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PROCEEDINGS OF THE SECOND 2010 EVIAN WORKSHOP ON LHC BEAM OPERATION

Evian, 7th to 9th December 2010

Edited by
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LHC Beam Operation Workshop

Evian 7-9 December 2010

The principle aims of the workshop are to review 2010 LHC beam commissioning and beam operations experience, and to look forward to the operation of the LHC in 2011.

Issues addressed will cover: operation from injection to stable beams; beam measurements and observations versus expectations; problems encountered; the performance of software and controls; the performance of the machine protection system; and necessary improvements across the board. The readiness of the machine as a whole for operation with high stored beam energies will be discussed.

The operations plan for 2011 will be presented and discussions will address the strategies for increasing luminosity, increasing intensity and other measures pertaining to the luminosity targets of 2011.

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The individual authors are both thanked and congratulated for their high quality contributions, written during a very busy period.

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†no written contribution

WORKSHOP INTRODUCTION

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Abstract

The main achievements of 2010 are briefly recalled. The year saw the completion of initial proton commissioning, a phased increase in beam intensity and the delivering of a respectable integrated luminosity total. The year finished with around a month's ion run, which also went well. A brief attempt is made at identifying the main contributory factors to the year's success

INTRODUCTION

2010 was the first full year of LHC commissioning and saw a number of important operational milestones. These included: first collisions at 3.5 TeV; commissioning of the squeeze; the move to physics with nominal bunch intensity; the move to bunch trains followed by the phased increase in intensity. In the end a peak luminosity of 2 x 10^{32} $cm^{-2}s^{-1}$ was achieved with an integrated luminosity of 6 pb^{-1} per day delivered in the final week of proton operations. The year culminated in a successful ion run.

The progress in 2010 was impressive and as a kick off to the workshop it might be worth asking what where the key contributory factors to this success.

2010 - OVERVIEW

The clear priority of the year was to lay the foundations for 2011 and the delivery of 1 fb^{-1}. The peak luminosity target was 1 x 10^{32} $cm^{-2}s^{-1}$. It was clear that we had to gain solid operational experience of injecting, ramping, squeezing and establishing stable beams; this was done although not without some issues. A period of steady running at or around 1 MJ for an extended period was used to fully verify machine protection and operational procedures before performing a safe, phased increase in intensity with validation and a running period at each step.

The main milestones of 2010 commissioning are outlined in table 1.

Table 1: main commissioning milestones 2010

Date	Milestone
28th February	Injection of both beams – rough RF capture
30th March	First colliding beams at 3.5 TeV
March	Initial commissioning leading to first collisions
April	Squeeze commissioning
May	Physics 13 on 13 with 2 x 10^{10} ppb
June	Commissioning of nominal bunch intensity
July	Physics 25 on 25 with 9 x 10^{10} ppb
August	3 weeks running at 1 – 2 MJ
September	Bunch train commissioning
Oct - Nov	Phased increase in total beam intensity

OF NOTE

Some significant figures from 2010 are shown in table 2.

Table 2: Some 2010 records (data courtesy of Atlas)

Peak stable luminosity	2.07 x $10^{32}$$cm^{-2}s^{-1}$
Maximum luminosity delivered in one fill	6.3 pb^{-1}
Maximum luminosity delivered in one day	6.0 pb^{-1}
Maximum luminosity delivered in 7 days	24.6 pb^{-1}
Maximum colliding bunches	348
Maximum average events/bunch crossing	3.78
Longest time in Stable Beams – one fill	30.3 hours
Longest time in Stable Beams – one fill	22.8 hours (94.9%)
Longest time in Stable Beams – one fill	69.9 hours (41.6%)
Faster turnaround (protons)	3.66 hours
Maximum stored beam energy at 3.5 TeV	28 MJ
Maximum stored beam energy in physics	24 MJ

Key features of the year's run include:

- Excellent single beam lifetime
- Ramp & squeeze essentially without loss
- Optics very close to model (and correctable)
- Excellent reproducibility
- Better than nominal beam intensity and beam emittance from the injectors
- It was possible to collide nominal bunch currents with smaller that nominal emittances with no serious problems from head-on beam-beam.
- Excellent cleaning and control of beam losses. There were no accidental beam induced quenches above injection energy.

DEEP PREPARATION

At least part of the excellent performance may be attributed to measures taken during magnet production, and subsequent installation.

- The major effort that went in steering the field quality in the main dipoles during the production phase, see for example [1].
- Dipole magnet sorting which took as a first priority sorting according to dipole geometry and a second sorting with respect to field quality (b1 and b3). See for example [2].
- Magnet model (FiDeL) representing 10 years of measurement, dedicated instrumentation and associated R&D, 4.5 million coil rotations, 50 GB of magnetic field data, a number of Ph.Ds. and master theses, 2 years of data pruning and modeling, collaborations resulted in the most complex and comprehensive field forecast [3].
- A full and very thorough survey and alignment campaign.
- The vacuum groups have delivered excellent pressures, and also excellent installation that despite

problems (e.g. the PIMS issues) has delivered better than expected aperture. The latter also owes thanks to survey and the careful magnet sorting and quality control.

UNDERPINNING

The LHC is a hugely complex machine. Machine availability depends on a number of critical systems, which provide the base on which beam based operation fully depends. These systems include the Quench Protection System; power converters; the feed-boxes and current leads; vacuum; magnet instrumentation; cryogenics; and access system.

The cross product of MTBFs of some huge systems has been surprisingly good.

- The **Quench Protection System** saw a massive upgrade program following the incident in 2008. Despite extremely tight deadlines and some inevitable teething problems, the system performed well in 2010 and impacted little on machine availability while performing its critical role.
- **Cryogenics** saw 90% availability with all faults included (since 1st April 2010) and 98.5% availability outside technical stops since 1st July [4].
- The **Power Converters** have provided very good reliability and availability. There is an appropriate level of control, accuracy, and the tracking performance and stability have been truly excellent.

PREPARATION

More near term preparation saw a three major thrusts: a series of transfer line and injection tests with beam; a comprehensive program of hardware commissioning; and a full program of dry runs leading into a thorough machine checkout phase.

The beam tests start in 2003 with the first extraction into TT40. Although modest the test saw the operational use of the LSA software for the first time and experience with LHC type beam instrumentation. This was to set the pattern for the coming years, which saw beam successively down TI8, TI2 and in 2008 in the LHC itself for the first time [5].

The hardware commissioning program was a major inter-departmental effort which saw systematic testing of all cold circuits and associated systems. The resultant performance of the magnetic circuits and associated protection systems is testament to the diligence that was brought to bear.

The dry runs and machine checkout program saw a full run through and tests of: extraction; transfer lines; injection; synchronization; injection sequencing; timing; beam interlocks; collimators; high level vacuum control; software interlocks; beam instrumentation; beam dumps; cold circuits as available; magnet model; sequencer; alarms; controls infrastructure; logging; databases; high level software (LSA); optics; orbit software etc.

EXPERIENCE AND TIME

It has to be note that delay has helped as well. The further delay to full operations caused by the September 19^{th} 2008 incident provided a chance to go around the operational and other loops again. A lot was learnt from the 2008 injection and initial commissioning period and the follow-up on lessons learnt was very thorough. We saw the deployment of a more robust and sensitive nQPS system and rationalization of a number of issues. Good understanding of the splice issues followed. On the beam operations side instrumentation, controls and equipment systems all took advantage of the extra time to establish an “unprecedented state of readiness”. It seems appropriate to quote Nietzsche’s familiar “What does not kill me, makes me stronger.” Even given that, the seriousness of the incident must not be underestimated.

OPERATION WITH BEAM

Excellent performance has been made possible by solid foundations provided by specific groups. These will be covered later in this workshop but include:

- Beam Interlock System;
- Beam based feedback systems (tune, orbit);
- Collimation;
- RF;
- LBDS;
- Injection system and associated protection.

Software and controls

Again benefiting from the delay, the deployment and debugging of systems on the injectors has helped the controls and software environment act as an enabler rather than another challenge to be wrestled with. The use and excellent performance of: databases; high-level software (LSA and others); a reliable and functioning controls infrastructure; a post mortem system have helped allow effective commissioning of the LHC.

Beam instrumentation

Truly an enabler, the excellent performance of the beam instrumentation, in particular the large distributed systems (BPMs and BLMs) have contributed to greatly to the fast progress. Also of note is the rapid assimilation into regular operations of the tune and orbit feedback systems which have proved vital in the ramp and squeeze.

Table 3: Overview of instrumentation performance

System	Performance overview
BPMs	In general very good. Capture mode enabling multi-turn acquisition and analysis. Enabled operational deployment of orbit feedback.
BLM	Excellent performance delivering fully operational system.
DBCT FBCT	Along with lifetime measurement, the systems were commissioned and operational. Some issues with implications for luminosity calibration.
BTV	Fully operational
BWS Wire scanners	Operational, calibrated and giving reference measurements.

Abort Gap Monitor [AGM]	Operational. Cleaning tests encouraging.
Synchrotron Light [BSRT]	Commissioned and working well. Proving difficult to calibrate reliably.
Tune	BBQ FFT used routinely from day one: tune, coupling, and chromaticity. Used for tune feedback in the ramp and squeeze. PLL – good progress, feedback not operational.
Chromaticity	Measured using: standard delta RF method; semi-automatic BBQ peak analysis; and radial modulation.

21ST CENTURY TECHNOLOGY

The LHC is the first large particle accelerator to be born in the 21st century. As such it has been able to leverage a wide range of modern technologies, which have undoubtedly helped a rapid and safe start-up. It is true that the technologies themselves don't provide understanding but:

- they do help in data acquisition (front-end processing power, middleware, data transmission);
- they do help in the deployment and modification of complex systems (e.g. FPGAs);
- they do help in time critical processes (real time systems, sheer processing speed);
- they do help in software engineering and provision of appropriate high level software (e.g. analysis, language, IDEs, version control, databases etc.)
- they do help in vastly improved data storage and subsequent data availability.

TEAMWORK

Other contributory factors include excellent collaboration between teams than span the whole of CERN. From access, safety, radiation protection to accelerator physics remarkable commitment has been shown to get the LHC up and running under what were very difficult circumstances.

INTELLECTUAL CONTINUITIY

The experience gained on LEP in a wide number of domains has clearly helped. The injector teams are very experienced and were well prepared to deliver the necessary LHC beams.

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DISCUSSION SUMMARY OF SESSION 1
LHC BEAM OPERATION:
REVIEW OF 2010 AND SETTING THE SCENE FOR 2011

R. Bailey (Chairman) and G. Papotti (Scientific Secretary), CERN, Geneva, Switzerland

Abstract

This paper summarizes the discussions that originated in the first session of the the LHC Beam Commissioning Workshop, which was held in Evian on Decemeber 7 to 9, 2010. Title of the session is “LHC beam operation: review of 2010 and setting the scene for 2011”.

INTRODUCTION

The first session of LHC Beam Commissioning Workshop included the following presentations:

- **Performance and results** by Massimiliano Ferro-Luzzi (PH-LBD);
- **Operational efficiency** by Walter Venturini Delsolaro (BE-OP);
- **The LHC RF: Operation 2010 and Plans for 2011** by Philippe Baudrenghien (BE-RF);
- **Beam Quality and availability from the injectors** by Giulia Papotti (BE-OP);
- **50 and 75 ns operation** by Gianluigi Arduini (BE-ABP);
- **Intensity ramp-up** by Mike Lamont (BE-OP);

The summaries of the discussion that followed each presentation are given.

PERFORMANCE AND RESULTS (MASSIMILIANO FERRO-LUZZI)

Brennan Goddard: When did you find the Abort Gap Keeper a limitation? *Massimiliano Ferro-Luzzi:* Mostly towards the end of the proton run, when the machine was rather full.

- -: Can the Abort Gap Keeper change? *Brennan Goddard:* If we change it, that would not allow the 4-bunch injection, for example. *Jörg Wenninger:* We would run into the risk of not being fully protected.

Mike Lamont: Concerning LHCb, is a single beta star the best solution? *Steve Myers:* Separating the beams might give problems due to beam-beam tune shift. The first few months we could run as last year, explore beam-beam limits and then see what strategy makes the most sense, if smaller beta star or larger separation. *Ralph Assmann:* Running with separated beams is not ideal from the aperture point of view. *Roderik Bruce:* The aperture should be considered. *Steve Myers:* From the LEP experience: we used to run with 4 interaction points, when we went to 5 the lifetime dropped to zero. *Oliver Brüning:* A separation scheme corresponds to substituting one head on collision with one long-range interaction.

OPERATIONAL EFFICIENCY (WALTER VENTURINI DELSOLARO)

Walter Venturini: The analysis stopped on the 30th of November.

Bernhard Holzer: I am surprised by so many dumps triggered by the BLMs, should they not be the last line of safety in the philosophy of our Machine Protection System? It means we have losses without warning, and we have to rely only on the BLMs. *Jörg Wenninger:* The statistics should also be read as a function of time, not simply integrated over the year. In the beginning the operation was a bit more critical but we had only low intensity. There is a strong trend of what triggered the MP dumps as a function of the year: most of the faults during the ramp occurred during the first part of the year, and never in the second. But it is true that concerning the UFO events, we rely on the BLMs, and later on the quench protection. *Rüdiger Schmidt:* The cause for the BLM triggers is mostly UFOs. Plus we have to remember that BLMs cover all losses, but obviously when possible we should detect the problems before, and dump the beam before it is affected.

Richard Jacobsson: Are there any statistics for dumps at injection? *Walter Venturini:* Not here, I looked only at events after the start of the ramp, cases for which, once we lose the beam, we have to go through the whole cycle again.

Steve Myers: We should use the Hubner factor (integrated luminosity divided by peak luminosity and the scheduled time for physics), that would give the physics target for the year. In order to find the scheduled time for physics we could look at the slides from the 8:30 meetings and see when physics was planned. *Jörg Wenninger:* Also, November was probably a good period to get an indication for statistics, as we were running mostly for physics, with a reduced program of machine developments.

THE LHC RF: OPERATION 2010 AND PLANS FOR 2011 (PHILIPPE BAUDRENGHIEN)

Brennan Goddard: If we have cavities that trip, the abort gap will fill up. We need indications about when to dump.

Philippe Baudrenghien: We had in one case 3 cavities that tripped at the flat top, with 15% of nominal intensity, and the abort gap cleaned naturally, on a timescale of about 15 minutes. We should take also that into account. It is worst to dump soon, than to let it clean naturally. In that case, we need a system that does some kind of supervision, and looks at the abort gap filling rate and has us wait a bit before the dump. *Jörg Wenninger:* We should either dump immediately, or keep it. It would make no sense to dump after some time: if it survived 15 minutes, then it can survive another hour. *Oliver Brüning:* The problem is if something else happens while we are waiting for the abort gap natural cleaning. You have to be ready to dump at any time. *Ralph Assmann:* It is not a safety issues, anyway we must always be prepared for an asynchronous beam dump. Of course, in case of dump, we cannot exclude the possibility of a quench. *Philippe Baudrenghien:* With 12% nominal intensity, we get 200 kV induced voltage in the idle cavities (the power converter trips, but the cavities are almost on tune and have enormous impedance, and the beam goes through them - also fortunately the bunch lengthens). Even with half nominal intensity, we get 2 MV and cavity trips should not be a problem. Above half nominal, the cavity is not safe as is has not been conditioned for such high voltage, so we have to protect it from sparking. *Ralph Assman:* Another option is to close slightly the collimators, so to make the natural cleaning faster. *Elena Chapochnikova:* From calculation, the cleaning time constant is about 18 minutes, which is in good agreement with the observed 15 minutes.

Steve Myers: When designing the LHC, Landau cavities were considered. Do we think we need them now? Would you consider them to keep the beam stable if we trip a cavity? *Elena Chapochnikova:* We might need Landau cavities if we find that the beam is unstable when we increase the intensity. In fact with the feedbacks, we can stabilize the beam and damp any coupled bunch instabilities inside the bandwidth or any higher order modes of the cavities. If the instability is due to other impedance lines in the ring, which are not related to the fundamental impedance of the cavities, then the feedback will not be effective and we would need the 800 MHz cavities.

BEAM QUALITY AND AVAILABILITY FROM THE INJECTORS (GIULIA PAPOTTI)

Anthony Rey: We should not forget that even if the MMI gets upgraded, the electronics behind it will not change, so limitations will remain, for example for the number of slots available to store data. The integration into LSA, including testing, will take a long time, so it will not be for next year.

Alick MacPherson: What about the PS 80 MHz cavities, is there anything particular to the ions? They seem to have operated worse in November. *Steve Hancock:* We have not had "normal operation" with these cavities, and also there is nothing special with ions. There is no reason why cavities should operate worse with ions than with protons.

Stefano Redaelli: Concerning the variation shown in the SPS transverse emittance measurement, do we know if it is real or only a measurement problem? *Giulia Papotti:* That was exactly my point in asking for the measurements. *Brennan Goddard:* We have measurements over an hour or so in the transfer lines, and they were reproducible. *Stefano Redaelli:* So we have to rely on LHC measurements.

Ralph Assmann: It would be nice to have a display that tells us, in case of lower than expected intensity injected in the LHC, were the beam is lost down the injector chain. *Giulia Papotti:* There was also a proposal for looking at losses during the SPS ramp, and possibly interlocking extraction in case they are too high.

Paul Collier: The SPS BQM stopped about 20% of shots from getting into the LHC. It would be interesting to understand how much of that is due to cycle-to-cycle variation and what is setting up problem. *Giulia Papotti:* The time for injectors setup included in the statistics should be minimal. The statistics were taken in Injection Probe and Injection Physics beam modes only.

Paul Collier: Do we have an idea about the stability of the injectors, over a certain period of time? How many shots are good and how many shots are bad? *Giulia Papotti:* Thinking back at the most recent days we had some problems with the longitudinal blow up, that is one example. *Jorg Wenninger:* Additionally it depends on how tight you set the thresholds. If you relax them a bit, you will get more positive statistics. Sometimes we allowed bunches to be a bit longer for example. *Anthony Rey:* From the experience of this past year, when the SPS BQM started triggering repeatedly, it was hiding some other problems that were developing somewhere else. For example 2 or 3 times the scraper was starting to heat up and break, sometimes it was reliability with the PS or problems with the source. Often when the BQM was continuously triggering it was a warning for a future problem. But we also had long periods in which the parameters were stable.

Malika Meddahi: We need procedures or checklists. We lost many many hours at the LHC due to the fact that the beam was not correctly setup at the injectors. *Giulia Papotti:* What I think the operators like about the SPS BQM is that they can see "all green", that is how they know the beam is ok, at least longitudinally. But for transverse size, for example, you have to fly the wire. *Malika Meddahi:* Also, you can prepare the beam at the injectors while the LHC is in coast, to save time later. *Giulia Papotti:* But if you start too early, then that is at the expense of SPS physics time. *Jörg Wenninger:* And things might change again by the time the LHC is ready to inject. It is difficult to say how long the setup will take.

Bernd Dehning: A comment on the wire scanners. The calibration of wire scanner in the PSB, PS and SPS where checked by the operation team. Scanners with a relative difference of 10% to the reference instruments are regarded as good and no action is required. PSB: check in September, two of the scanner will be replaced. PS: check in

September 2009, all scanners were regarded to have required performance. SPS: 416 and 519 where checked in August 2009 and have had the required performance. *Giulia Papotti:* That was my impression, the rest of the SPS wires should be reviewed next.

Paul Collier: When working on the LHC design report, the idea of dedicated LHC filling came from concerns about shot-to-shot stability. This year we were running with many cycles pasted together in the SPS supercycle, but we should see if dedicated filling could improve the cycle-to-cycle reproducibility. *Jörg Wenninger:* In fact there is a suspicion that the issues we had with stability in the transfer lines might have been due to the different order of the cycles in the SPS supercycle. *Elena Chapochnikova:* It has to be noted that when this year we had SPS Machine Developments which simulated dedicated LHC filling we had many limitations as for example MKE heating, outgassing, etc which prevented us from having many consequent cycles.

50 AND 75 NS OPERATION (GIANLUIGI ARDUINI)

Ralph Assmann: What about the emittance blow up? We are used to seeing it at the flat bottom. *Gianluigi Arduini:* Normally we had 0.2/0.3 μm/hour at the flat bottom with the transverse feedback on. Here we had twice the injected emittance after a few hours, which is not compatible with the usual phenomenon. Another proof is that we can clearly see that the last injected batches did not blow up as much.

Massimiliano Ferro-Luzzi: The 75 ns beam is stable until how many bunches? Could we think of doing physics with it, to start with? *Gianluigi Arduini:* The emittance blow up would be 30-40%, and if we started with smaller emittance it would be even worse. With 50/75 ns the incoherent blow up instability is worse. *Steve Myers:* If we need to relax interlock thresholds, which we needed to do this year for scrubbing at 450 GeV, but we should think and worry about Machine Protection and stored energy. That is one more reason to scrub at injection.

Steve Myers: Did you see a strong bunch length dependence? *Gianluigi Arduini:* In the ramp we can see the dependence on bunch length, but it is small. In the ramp we can also observe the effect of synchrotron light, and that is more important.

Gianluigi Arduini: We should try and see whether 25 ns is much worse. Why not to scrub at 25 ns bunch spacing? *Ralph Assmann:* Maybe it would be most efficient to scrub with 25 ns beams. *Paul Collier:* We could also think about scrubbing with 50 ns and then 25 ns beams.

Brennan Goddard: We should also take into account that we will need about 1 week to be able to inject 100 bunches at a time.

Tiziano Camporesi: What about interleaving scrubbing periods with physics? *Gianluigi Arduini:* It would make scrubbing much less efficient.

Steve Myers: What about synchrotron radiation? *Gianluigi Arduini:* For beam 2 we can observe cleaning also for synchrotron light, it seems. But it might be different areas at 3.5 TeV.

Brennan Goddard: When would you do the scrubbing run? *Gianluigi Arduini:* I would plan it right away, I would not wait until we need it. *Ralph Assmann:* But remember that in that case we need the final orbit, the final collimation setup etc. *Jörg Wenninger:* Plus if then we change the crossing angle... *Gianluigi:* No deterioration was observed when collapsing the separation bumps.

Martin Aleksa: Would it be possible to get data at the same time, while scrubbing? *Gianluigi Arduini:* We would anyway not be able to ramp 900 bunches early on, and it would be bad data, with high background for example.

INTENSITY RAMP-UP (MIKE LAMONT)

Rüdiger Schmidt: Maybe we should think about whether we should have moved to 1-2 MJ later, instead of earlier.

Ralph Assmann: Another point is that during the intensity ramp up, we kept the filling scheme for 3 fills, but I have the impression that we learned nothing from the 2nd and 3rd one. *Jörg Wenninger:* In fact, for example e-cloud came right away, at the first fill.

Ralph Assmann: In the case of the BBQ outage, we would have had losses on the collimators and that would have been caught by the BLMs. *Giulia Papotti:* But also remember that the one time the outage happened at the flat bottom, the ramp was not launched, as getting through the snapback might have been a problem.

Ralph Assmann: We should also think about the recovery from the Technical Stop. We always did one test ramp, but should we have done more tests? *Mike Lamont:* Maybe for example more BIS checks. *Rüdiger Schmidt:* We should improve our tracking of changes.

Steve Myers: It is important to have a plan, a strategy, but also we need flexibility, in case something unexpected happens. *Jörg Wenninger:* We have to foresee the possibility to change the plans, but not too often, twice per week would not be good for example.

Jörg Wenninger: Also remember that next year we will have experience, but also a new machine. *Ralph Assmann:* We have more elements now, as we had them towards the end of the year. When we started we did not know how long the collimator setup would be valid for, for example at Tevatron they re-do it every day. Now we have an idea. Additionally we had no quenches at 3.5 TeV... So for ions we could speed up, and we went up in intensity one fill per step, and that went very well. Maybe we could think of a similar strategy also for the next proton run.

Jörg Wenninger: We could for example foresee to go up to 200 bunches relatively fast, but slower from then on.

Stefano Redaelli: One important change that determined more reproducible conditions of the orbit in the IPs was that in September we moved to an absolute collision reference. After that, we did not have anymore large drift of

1-1.5 mm fill-to-fill and we gained confidence to increase the intensity. *Steve Myers:* When we started with bunch trains, we redid the whole machine. Same for ions, and it went even better. *Stefano Redaelli:* We should try and go for one reference, possibly one crossing angle. That would avoid some of the errors done this year and due to the change of orbit feedback settings.

Rüdiger Schmidt: Concerning the number of bunches to be increased faster. . . Let us be careful, and not exaggerate with confidence in Machine Protection.

Steve Myers: How many dumps depended only on BLMs? *Jörg Wenninger:* About 15, mostly due to UFO events. *Rüdiger Schmidt:* Also remember that if in this case the BLMs would have failed, then the losses would have either gone down, or we would have quenched, so in both cases the situation would have been saved anyway.

Martin Aleksa: Where do we stop, how many bunches maximum will we have? *Mike Lamont:* We stop at 900 bunches.

Brennan Goddard: This year we have the reviews, which turned out to be very useful. But we should also set dates to check that the recommendations have been followed up.

Gianluigi Arduini: We might have another problem. Instabilities might not generate quenches only. For now we had cases with risetimes of about 100 turns or one tenth of a second. In this case it would be faster than UFOs. *Ralph Assmann:* The BLM system is there also to protect for these eventualities.

Paul Collier: We should consider starting the year with 150 ns spaced beams.

Steve Myers: Also we should first get the machine in the final state, concerning beta star, crossing angles etc. Changing parameters is dangerous and time consuming.

Serge Claudet: One more thing to be pointed out. In case the e-cloud deposits energy on the beam screen we have to be aware that we have weaknesses there. We have 450 loops for beam screens: about 8% are just about ok, for 1-2% we have no ideas were the helium goes. These last cases are thermally coupled, but we have no confidence that they could react in case of energy deposition. We will try and reduce their number during the Christmas break. *Gianluigi Arduini:* That is even one more reason to scrub at low energy.

DRIVING THE LHC – SESSION 2

G. Arduini (Chairman) and M. Pojer (Scientific Secretary), CERN, Geneva, Switzerland

Abstract

The main aim of the session is the identification of improvements in procedures and software tools to enhance the efficiency in running the LHC with beam and favour the analysis and understanding of its performance and performance limitations.

HOW TO IMPROVE THE TURN-AROUND, S. REDAELLI

A minimum theoretical turn-around time was estimated in the order of 2h. The reality showed a much higher average of 4h27 min, which is nevertheless well below what other machines obtained after years of operation. The minimum turn-around time was 2h45m last year.

Only the physics fill with injection of trains were considered in the analysis (29 good fills ending in Stable Beams).

In terms of average time spent in the different beam modes, these are the estimated values: injection 3h (with some outliers above 6h and most between 1 and 4h, with no significant improvement with experience), ramp preparation 0.14h, energy ramp 0.43h, flat-top 0.13h, squeeze 0.56h and adjust 0.22h. A series of suggestions were presented to try and reduce downtime in each of the phases.

Proposals for improvements

Injection.

1- LHC beam setup in the injectors: improve the communication, also with early requests; finish the beam setup in the pre-cycle; check beam availability/quality before dumping.
2- Over-injection and: leave the pilot in slot 1, without over-injection; or move the pilot in the slot of the second train to avoid having the machine empty in case of over-injection with no beam coming from the SPS. An SPS super-cycle featuring two cycles for the pilot beam and the physics beam would also reduce the time required to switch from pilot to physics beam. During the discussion it was noted that this will impact the availability of the SPS for fixed target physics.
3- Injection Quality Checks (IQC): need faster response. During the discussion it was noted that the issues with the BPM and BLM data were fixed. Separate injection request of one beam from the IQC result of the other one; realistic thresholds for IQC parameters.
4- RF loops: set well-defined limits on the allowed loop errors and define a clear procedure for corrections.
5- Setup of pilot beams: the decay of the b3 in the dipoles at the injection plateau should be compensated to minimize the setting-up time (chromaticity correction).
6- Tools: automatic logbook entries for images.

Ramp Preparation.

1- Perform the setting incorporation after switching FBs on.
2- b3 compensation would avoid the verification of the chromaticity before the start of the ramp which is difficult with high intensity beams.

Energy ramp.

There is not much space for improvement, unless reducing the 400s decay time. It was noted that the combination of part of the squeeze with the end of the ramp would avoid stopping for allowing the decay at the end of the flat-top as this would be included in the last part of the squeeze.

Flat-top.

1- Start incorporation and FB preparation during the ramp.
2- Establish a policy for the chromaticity measurements at the end of the flat-op and at the end of the squeeze. This issue would be solved if we combine the end of the ramp with the beginning of the squeeze.

Squeeze.

1- Remove stopping points.
2- Use the same orbit reference through the squeeze or a dynamic reference is made possible for the orbit FB.
3- New studies are ongoing to optimize squeeze time.

Adjust.

1- Reduce the parallel beam separation during the ramp would increase aperture and reduce the time to bring the beams in collision.
2- Declare Stable Beams before luminosity scans.

Also the time needed for handshakes was estimated: 13 min for dump and 11 min for adjust. Do we need the dump handshake at all?

SOFTWARE AND CONTROL ISSUES, D. JACQUET

Reactivity and flexibility have been the secret for the impressive amount of well working applications, but still much has to be improved.

Many improvements were requested, aimed at reducing turn-around and down time, improving efficiency, minimizing risk of error and helping in diagnosing problems.

Equipment control.

- TCDQ: it happened a few times that they stayed armed, reporting idle and then moved unexpectedly. A new software version of the PLC is being implemented.

- RF: interlock details are needed, plus signals for diagnostics.
- Power converters: not efficient to restart a few power converters that tripped. It was requested to implement some tool into the sequencer to allow restarting only the tripped power converters so to avoid using the equipment stat application.

Injection.

- Problems have been reported with the publication of the circulating bunch configuration problem in case of BCT measurement problem, this was frequently observed during the ion run:
  - check Beam Quality Monitor (BQM) measurement versus DB before injection to prevent over-injection;
  - cross-check with ring BCT;
  - it was noted that it will be possibile to set the circulating bunch configuration with the measured bunches in the LHC BQM.

LHC sequencer.

A new GUI was developed mainly to solve issues of flexibility and ergonomics. Still some improvements to do for the check list panel or to interactively set a parameter.

Machine state application.

It is in the debugging phase, with check of transition already operational. In the future, the behaviour of certain control software (LSA, Sequencer) should be constrained by operational state (e.g. state should influence the LSA settings or sequencer tasks that can be used).

LSA-settings management.

Problems have been encountered in the generation of functions with too tight points or too large acceleration rates leading to trips induced by the Quench Protection System. Add verifications of the acceleration rates and distance between consecutive points at the generation level would help. The incorporation mechanism will have to be as well revised, to allow for more sophisticated rules, capable, for example, of including snapback and dynamic b3 corrections.

Alarms.

Too many alarms are always displayed. The list and level of alarm should be reviewed by a joint group of equipment, operation and controls experts. Mode-dependent alarms should be introduced.

Diamon.

Not clear to detect and identify problems: need to work on the configuration and on the hierarchy between application, middletears, proxy and front-ends.

Others.

- Front-ends have still too many crashes.
- Orbit and tune feedbacks should follow a dynamic reference (function).
- Sequence editor should be more user-friendly and allow for track changes and rollback.

CAN WE IMPROVE THE MAGNETIC CYCLE/MODEL AND THEIR EFFECT, E. TODESCO

In 2010 four combinations of pre-cycles were used. Only in September operation was performed with the nominal ramp rate of 10 A/s, with same parameters for physics cycle and pre-cycle. The present difference from the nominal 7 TeV cycle is the energy. The lower energy implies a smaller decay and snapback (about half). During operation, only in 3% of the cases, the machine was not properly pre-cycled; in 54% of the ramps, the previous physics cycle was used as a pre-cycle. This means that, since the pre-cycle takes 90 min, on average the time used for pre-cycle was 45 min, mainly dominated by the MQM-MQY.

Measurements performed in SM18 showed that, after 30 minutes, most of the b_3 decay has taken place, on the other hand beam measurements have shown that the magnitude of the decay matches the magnetic measurements (leading to a change of 10 to 15 units in chromaticity) but lasts 20 times longer.

Chromaticity correction is normally performed using lattice sextupoles (MSF/D) whereas the sextupole spool pieces (MCS) should be used. An automatic correction of the b3 decay is going to be implemented for the start-up.

During the ramp, the chromaticity changes as follows:

- ± 7 units, during snapback;
- ± 3 units, during the ramp;
- 7 units decay at flat-top.

Tracking precision is sufficient for operation, but it could be improved in the snapback part.

The tune decays at injection by 0.005 units over 1 h soon after the pre-cycle and should be included in the automatic correction.

For the hysteresis, there are two main issues: the IR quadrupoles during squeeze, when the current is ramping down, and the manual and FB trims on the correctors. At present the hysteresis branch is changed when the current direction is changing. This has some drawbacks, as the change of branch also happens with very small changes of current, which has resulted in a discrepancy between measured and expected beta beating corrections after incorporation of the trims in the squeeze. Since the impact of hysteresis is small and can originate, if neglected, a beta beating smaller than 10%, the proposed strategy is to remove the actual branch correction.

WHAT DO WE NEED TO UNDERSTAND AND OPTIMIZE THE LHC, O. BRÜNING

The expected main performance limitations for the operation are: electron cloud effects, UFOs, beam-beam effects, faults and overall efficiency.

E-cloud effects.

Electron cloud effects have been observed: vacuum pressure rise, instabilities and emittance growth along bunch trains, additional heat loads in the beam screens. Vacuum fixed-displays are available but it would be helpful to have windows with locations and vacuum values for the top 10 pressure maxima. Displays showing the heat load on the beam screens along each sector during scrubbing are required to be able to evaluate the effectiveness of the scrubbing and adapt the beam parameters accordingly. Bunch-by-bunch emittance displays should be available online, showing the evolution of the emittance along the bunch train as a function of time.

Unidentified Falling Objects.

The rate of this kind of events observed during the year resulted to be proportional to the total beam current (number of bunches), with no preferred location. No UFO was observed at injection, while most of them occurred below the BLM threshold.

For the monitoring of the UFOs, a display of the number of UFO events over a fill should be implemented, even for losses below BLM threshold, plus a histogram of their occurrence along the machine.

Beam-beam.

An online display of the tune diagram with bunch-by-bunch tune shift and lifetime could help to adjust the working point in collision.

For the tune and closed orbit variations along a bunch train, bunch-by-bunch orbit and tune measurements are essential for understanding the long-range beam-beam effects.

Performance monitoring.

Online statistics spread-sheets should be filled as a standard procedure, to monitor performance evolution. The statistics should include all beam parameters, the initial and final luminosity, the fill length, the reason for dump. For the whole week, the number of fills, the efficiency and the turnaround should be added as well.

Other suggestions.

A series of other suggested improvements are:

- routines for QPS reset made available for LHC operators
- emittance monitoring tool for beam quality at the injectors and time evolution
- flags/statistics for “hump” activity
- in Timber, possibility of cross-check of different variables, functionality to display vectors and general statistics pages (fault statistics and key statistics).

SESSION 3: BEAM DIAGNOSTICS AND FEEDBACK SYSTEMS SUMMARY

J. Wenninger (Chairman) and R. Alemany (Scientific Secretary), CERN, Geneva, Switzerland

BUNCH BY BUNCH MEASUREMENTS AT LHC (BY T. LEFEVRE)

Eleven instruments can provide bunch-by-bunch measurements at LHC. Nine of them can do it in parallel to normal continuous beam observation (limitation on beam size monitoring at the moment). Most of the systems are still under commissioning and many improvements can be foreseen. Only half of the monitors have operational applications for the moment. After the presentation, the BI group asked the question if this is covering all needs. Issues to be follow up for the 2011 start up are listed per instrument in Table 1, as well as proposed upgrades for short or long term.

FEEDBACKS: STATUS, OPERATIONAL DEPENDENCIES AND OUTLOOK FOR 2011 (BY R. STEINHAGEN)

Table 2 presents the outstanding issues and the proposed solutions.

TRANSVERSE DAMPER OPERATION (BY W. HOFLE)

After a successful commissioning of the LHC transverse dampers during 2010, the list of actions to be done for consolidating the system during 2011 is presented in Table 3.

LHC BPM SYSTEM: STATUS, MEASUREMENT RELIABILITY AND OUTLOOK FOR 2011 (BY E. CALVO)

In Table 4 the outstanding issues and the proposed solutions for the beam position monitoring system are presented.

CAN WE GET A RELIABLE TRANSVERSE BEAM MEASUREMENT (BY F. RONCAROLO)

The following systems were review: wire scanners, synchrotron light monitor and ionization gas monitor. In Table 5 the outstanding issues and the proposed solutions for consolidating the systems in 2011 are presented.

Table 1: Issues and proposed short and long term upgrades for the different instrumentation.

Fast Beam Current Transformer	
Issue	Upgrades for 2011
Calibration procedure in HIBW not accurate and not understood	Studies on going
Residual offset (≈$5^{\times}10^{8}$ charges)	
Bunch length dependence	
IP6 FBCTs: strong interference between the FBCTs and sputter ion pumps DC-DC converters: degrades measurement performance	
IP6 FBCTs: sometimes do not catch data when beam dump triggered: related to late triggering of acquisition	Cable installation on-going to get hardware triggering
Beam Position Monitors	
Issue	Upgrades for 2011
	Define persistent storage strategy for **BPM bunch-by-bunch orbit data**
	BPM bunch-by-bunch capture data: In the front end, provide turn by turn data averaged over all bunches and return it as a new

	field/property (to be discussed) to be used by YASP/ IQC
	BPM bunch-by-bunch capture data: for few selected devices, installation of dedicated DABs (higher memory 512k) on the less used VME systems in SR1 (BPME) and possibly SR5 (TOTEM)
Beam Quality Monitor	
Issue	Upgrades for 2011
	Multiple acquisition : looking for longitudinal oscillations and stability
	Limitations to be investigated: how fast and how many turns
Longitudinal density monitor	
Issue	Upgrades for 2011 (*long term*)
Dynamic range can be 2000 but needs long (>10mn) integration time	*Work on an optimized algorithm to compensate for after pulsing?*
Average bunch length could be determined much faster (specification: 10ms) by combining bunch data	Software fix so can run in parallel with the slower full-ring profile.
	Installation of a permanent Longitudinal Density Monitors in the BRST telescope for B1 ➔ DONE
	Both beams are to be integrated into FESA and logged
	An optically gated detector is under development which will increase the dynamic range of the system
Wire Scanners	
Issue	Upgrades for 2011
Preliminary comparison between the Turn and 40MHz acquisition measurements within 10% emittance	
During 2010 run attenuation was not enough for profile measurement of nominal bunches (>2 slot delay to avoid saturation)	Reduction of signal amplitude by lowering pre-amp gain ➔ DONE
50 ns spaced bunch pattern measurements have crosstalk	*Check relation between pre-amp gain and crosstalk:* *- Systematic comparison between acquisition modes & reproducibility with beam* *- Implementation/ validation Photo-Multiplier saturation detection as for the PSB*
Beam Synchrotron Light Telescope	
Issue	Upgrades for 2011
Relatively long scanning time : tens of minutes	Install two fast cameras providing turn by turn and bunch by bunch measurement ➔ DONE
Limitation in light intensity for ions at injection energy	
	Both beams are to be integrated into FESA and logged
	OP application with slot scan ? for the moment only available in the expert tool
Schottky	
Issue	Upgrades for 2011
Proton signals not useable during ramp	
Longitudinal blow-up destroys the signal	
	Consistency of emittance & dp/p still to be verified
	Incorporate automatic bunch cycling on selected bunches in GUI (currently via expert program)
	Add electronic pick-up centring to try to reduce coherent signal levels
BRAN	

Issue	Upgrades for 2011
BRANB and BRANP counting mode is the only available mode	
Bunch-by-bunch luminosity already relatively high due to pile-up	pile-up correction
Absolute calibration not yet reliable	better calibration
BRANA has a pulse height mode for the high multiplicity, but it is not working yet, may be limited to lumi > 10^{33}	
Some leakage in neighbour slots for short bunch spacing, 25ns filling would lead to errors in the bunch-by-bunch	
BRANP is not radiation hard and will have to be removed before next run as remote handling is not possible with the present detectors	Only BRANA system, which is not well suited for very low luminosities (<10^30) *In collaboration with LHC-f a new rad-hard scintillator will be tested on one side of IP1, details still to be worked out*
Due to interference with ALICE ZDC the BRANB in IP2 cannot be used with ions	
Fast Beam Loss Monitors	
Issue	Upgrades for 2011
	One BLM in point 2 & 8 for injection snapshot measurement triggered by injection sequencer
	Two BLM in point 7 for UFO observation triggered by PM

Table 2: Issues and proposed short and long term upgrades for the feedback systems.

Feedback	
Issue	Upgrades for 2011 (*long term*)
Sextupoles and MCBX are currently not used, may become critical for orbit stability with small beta*	
Unannounced IT kernel updates and denial-of-service attacks during beam operation ➔ caused beam dumps	Better coordination, make them during technical stops
Tune-PLL operation OK but not as robust as the previous one (e-blow-up)	
Transverse damper/abort gap cleaning interference: **- High gain ADT has limited impact on the emittance but affects significantly Q and Q' resolution and measurement bandwidth**	- Lower ADT gain after injection until end of squeeze - High ADT gain for first N-turns after injection, then lower again *- Dead-band in ADT gain function masking oscillations below noise floor ➔ simulation, test with beam and firmware update required* *- High ADT gain & Q-PLL exciting ~30+ dB above 10x lower ADT noise-floor ➔ flexibility of noise reduction needs to be demonstrated; commissioning time required (e.g. in parallel to loss maps)* *- Off-resonance excitation and one-turn-phase-advance measurement ➔ needs additional HW(possibly pickups) and further feasibility tests with beam*
Operational failures	Improved integration and automatization via LHC sequencer
	Dynamic orbit reference: needs further test and

	integration into LSA, sequencer and YASP
	Automatic feedback gain-scheduling (see slide 4)
	Energy feedback (see slide 4)
All ramps in 2010 exceeded the initially required Q', sometimes systematically Q'<0 (reluctance from OP and coordinators to measure and fix)	
Q': Remaining fill-to-fill variations still large compared to target Q'ref=+2±1; do we need to care about these variations?	
Feedbacks used systematically as replacement of feed forward. Safety margin diminishes if underlying systematic perturbations and potential problems are not followed-up and incorporated into feed-forward.	*Feedbacks shadow systematic machine problems* ➔ *seek for robust long-term solutions*
Need logging of all feedback system actions to monitor and identify potential problems and to facilitate feed-forward	To be followed up, same request by SIS and sequencer. Global action?
Single and coupled bunch instability = f(Q'): higher modes have been seen by BBQ and head-tail monitor, are these modes responsible for emittance blow-up?	More controlled experiments at 450 GeV and flat top

Table 3: Proposed short and long term upgrades for the transverse dampers system.

Transverse damper
Upgrades for 2011 (*long term*)
Automatic loading of settings for the different operation modes: bunch trains, different bunch intensities and bunch spacing
Improve frequency response and adapt the bandwidth as a function of bunch spacing
Fine adjustment of phase and delay to improve precision
Commission the vector sum as a more robust scheme with respect to tune variations
Program damper gain with a normalize function (scales with energy) in physical units, e.g. damping time
Improve multi-bunch acquisition to more than 8 bunches
Define the logging variables to be used as post mortem
Move to standard operation the beam cleaning (abort gap / injection slot)
Improve the abort gap cleaning pulse shape
Damper commissioning during squeeze
Work on compatibility with tune feedback (witness bunches ?)
Feasibility study of on-line tune measurement from residual feedback signal
Develop and test a scheme for a controlled emittance increase to be used for example to generate loss maps for collimation setup and verification
Study the noise properties of the system and propose improvements to be implemented during a long shut-down

Table 4: Issues and proposed short and long term upgrades for the beam position monitoring system.

Beam Position Monitors	
Issue	Upgrades for 2011 (*long term*)
(Only) 3% of channels disabled on OFC. 75% correspond to BPMs close to the IR with long coaxial cables (deported electronics) and coupled noise and/or ground loops	Cable adapters will be installed this XMAS stop. Expect to reduce RMS noise in many channels.
With I_{beam}>2e10 p/bunch, B1 bunches can trigger B2 channels and vice versa. During 2011 commission Synchronous orbit mode (bunch mask) will reduce this problem	Synchronous orbit (currently only asynchronous mode is available): Only bunches from selected slots averaged (225 turns). Initially the mask allows one or all bunches. It requires the phase adjustment of each channel in the DAB module. Output from both modes are read-out, calibrated and transmitted at 25Hz to OFSU system (YASP update 1Hz) – choice of mode

Long term stability is limited by ambient temperature dependence giving rise to systematic offset in the position measurement. Average value: 2.2 ADC bins/°C (➔ARC BPM = ~50 um/°C). ΔTemp in 24h varies from day to day but can be up to 6°C. Although an expert application was develop to correct for this temperature dependence, remains two issues which limits the efficiency of the method: - **The fan speed reduction allows for calibration in small dynamic range (5 - 6°C)** - **Error non-negligible if temperature too far from the measured points (non-linear behaviour)**	- Add to LHC sequencer standard BPM calibration - Remove long term accumulated temperature variations ("Reset effect"). *Long term, plans to implement "temperature regulated racks".* *First prototype received beginning of next year.* *Complete replacement during long shutdown (2012? / 2013?).*
Against BPM errors and faults two actions have been already put in place. It remains to be integrated into the system: **- Pre-checks with Pilot and Intermediate beams** **- Forced slow COD-driven betatron oscillation with rotating phase** **- Idea: "Every non-moving position reading indicates a dead BPM"** **- Test the complete acquisition chain (including monitors and cabling).** **- Tests also calibration factors**	
A decision has to be taken whether to remove or not the intensity monitors since they are not used	During the 2010-2011 Xmas shut-down the intensity monitors at the IP will be removed

Table 5: Issues and proposed short and long term upgrades for the beam profile monitors.

Wire scanner	
Issue	Upgrades for 2011 (*during 2011*)
Wire scanner quench test has shown that we can go a factor 3 higher at 3.5 TeV (from wire damage and quench threshold), but BLM thresholds would dump.	Update interlock values to allow safe scans at higher intensities (proposed a factor 1.5 if one does not want to change BLM thresholds). Damaged wire from quench test will be replaced.
Commissioning of bunch-by-bunch	Operational in 2011
	Systematic studies on saturation levels
Beam synchrotron light telescope	
Issue	Upgrades for 2011 (*during 2011*)
Resolution/Accuracy: apart from proton fill with small emittances, system is above resolution limit, however relative variations are reliable.	*Need to study further the absolute and relative calibration. More simulations are needed, laboratory work, beam based measurements during MD*
At the moment correction factors on beam size are not applied to the logged data, has to be done off-line. Correction factors changed during the year as the system was optimized (alignment, focusing, S/N)	Logged corrected beam size values (including evolving correction during the year)
Bunch-by-bunch is only available on demand to the BI expert	*OP application with options for bunch-by-bunch*
	Intensified fast cameras test: turn-by-turn, bunch-by-bunch (few minutes to scan many bunches)
	Improve automatic settings: feedback on position, automatic focusing vs. energy
Ionization gas monitor	
Issue	Upgrades for 2011 (*during 2011*)
	Remote camera gain and gate control

	Gas injection remote control
It is still in commissioning phase, therefore logged beam sizes sometimes are affected by profile fitting failures. One should look carefully into logged profiles and perform off-line fit	Absolute calibration to be studied in detail to complement cross-calibration with bumps

DISCUSSION SUMMARY OF SESSION 4 MACHINE PROTECTION SYSTEMS

A.L. Macpherson (Chairman) and B. Goddard (Scientific Secretary), CERN, Geneva, Switzerland

Abstract

This paper summarises the discussions that followed the presentations of the "Machine Protection" session of the the LHC Beam Operation Workshop, EVIAN2010.

INTRODUCTION

The fourth session of LHC Beam Commissioning Work- shop was dedicated to the analysis of the Machine Protection Systems and included five talks:

1. **Do we understand everything about MP system response?** by Markus Zerlauth
2. **LBDS and abort gap cleaning** by Chiara Bracco
3. **How low can we go? Getting below 3.5 m β*** by Roderik Bruce
4. **Injection protection: are we taking it seriously, how can we make it safer?** by Verena Kain
5. **The Human Factor** by Alick Macpherson

For each presentation of the session, summaries of the discussion that followed the presentations are given.

THE MACHINE PROTECTION SYSTEM

After a review of performance and analysis of the Machine Protection System (MPS), the following was noted.

• For the Post Mortem analysis it was asked if the analysis was documented, as there is a request to have the EiCs have more involvement in the PM analysis/result checking. It was acknowledged that for 2010 the PM analysis was expert driven, and was done via Excel spreadsheet analysis. For 2011, it is planned that both the online and offline process be more streamlined, and that the operations team take more of a role.

• For the online Post Mortem it was requested that the application be updated to allow for the EiC to edit the PM comment field after sign-off, so that for a PM that is signed off, the reason for the dump can be updated if needed.

• One significant change to the MPS in 2011 is the upgrade of the Safe Machine Parameters (SMP). This upgrade will provide completely new SMP flags and as such the SMP needs full commissioning at startup, including the management of critical settings.

• For 2011 operations, it will no longer be possible to disable the post-mortem above injection energy.

• It was also noted that that we should move to a procedure where the PM offline analysis has to be confirmed before re-filling is permitted. However, this requires the streamlining of the offline analysis.

• The speaker noted that the "false dumps" or MPS trips in 2010 have been related to hardware issues, and that these should have been addressed for the 2011 run.

• For the dumps related to single event upset issues, a clear plan of attack has not yet been made, but for the FGCs, statistics of SEUs is being collected and assessed.

• Finally, it was observed that for 2010, the QPS and UFO detection, the dumps were handled correctly with quenches avoided.

LBDS AND ABORT GAP CLEANING

Following the presentation of the performance and analysis of the Beam Dump System and Abort Gap Cleaning, the following was noted.

• In 2010, the one asynchronous dump with beam was due to a component failure in a trigger fan-out on the MKD generators, and this failure was contrary to the fail - safe design. The trigger logic is being updated, but it was noted that the SIL level assessment level for asynchronous dumps is not not able to cover everything. Each new exception needs careful followup and diagnostic on a case by case basis, and the results fed back into the design.

• The issue of the protection of TCDQ during operation with nominal bunch beams was discussed, and there is an identified risk that the TCDQ could be damaged during an asynchronous dump of nominal 25ns bunch beam, with the damage threshold set at 28 bunches. This problem has been identified, but it was stated that it can be resolved only by means of an upgrade in the long shutdown, and so prohibits using 25ns beam with nominal bunch intensities

• For the 2010 Ions run, it was noted that the synchrotron light monitor was only able to provide images above 650-700 Z GeV, but this limitation should be corrected for the 2011 run.

• It was observed that abort gap filling is potentially part of normal operation, and so abort gap monitoring has to be taken into account when preforming programmed beam dumps. In addition, during a fill, abort gap monitoring and abort gap cleaning should be invoked as part of standard operational procedure for the 2011 run.

• It was commented that at present there is no SIS interlock on the abort gap population, and this should be corrected.

GOING BELOW 3.5 M β*

Results from the estimation of available triplet aperture and the margins in the cleaning hierarchy were presented, and the implications for running at reduced β* were presented; the following issues were discussed.

• It was noted that as the squeeze is limited by available triplet aperture, and the proposal for 2011 running with reduced β* includes a reduced separation of 0.7mm at the

IPs in order to gain aperture, there is a need to have a full mapping of the triplet aperture.

• The speaker indicated that the β* reach down to 1.6m was based on conservative scaling of the available aperture, with the margins taken from the triplet settings at the end of the 2010 run.

• It was commented that in 2011, the ALICE luminosity levelling is to be treated differently to that of the Luminosity levelling in LHCb. ALICE will run with unsqueezed beams, while LHCb is to run with squeezed beams and the luminosity levelling potentially done by partially separating the beams.

• In the cases of reduced β*, luminosity levelling, and luminosity scans, it was acknowledged that a good knowledge of the triplet aperture, control of the β-beating to below 10%, and adherence to the collimation hierarchy (with regular validation of the leakage on to the TCTs) is required.

• It was also mentioned that if the procedure for luminosity levelling is to be established in LHCb, then it should be such that it is also applicable at ATLAS and CMS if needed.

• For both the squeeze and for Van der Meer scans in 2011 the movement of tertiary collimators is being done by functions rather than discrete steps, which will not only simplify the operational procedure, but also improve the degree of protection due to the TCTs tracking the beam. However, care must be taken in the implementation for the Van der Meer scans due to reduced aperture an the potential loss of collimator hierarchy during a scan.

• Due to the issues with commissioning and operating with reduced β*, the aperture meter is seen as a necessary tool for 2011 operation, and it was noted that the meter must take into account the actual machine optics and settings. Further, clear operational procedures need to be defined for the operational scenarios where that aperture meter shows that the aperture margin is compromised, or if operator applied trims risk breaking the collimator hierarchy. As yet, no proposal for the definition of such operational procedures or checks has been discussed

• Finally, it was commented that with either the movement of the TCTs or large β-beating at the TCTs, the leakage onto the TCDQ may be increased, so it was noted that in addition to the validation of the β-beat and movement at the TCTs, the TCDQ settings should be re-checked

INJECTION ISSUES

A detailed presentation of the injection process was given and set of improvements discussed. In the post presentation discussion, the following points were raised.

• Some degree injection oscillations is beneficial for maintaining the required emittance, but as the transverse damper is working well, tight constraints need to be kept on the transfer line collimators. However, it was re-iterated that the degree of acceptable injection oscillations needs to be coupled with the IQC surveillance, which interlocks on large oscillations.

• For the orbit interlocking, tight SIS interlocks on orbit has to be reconciled with fact that something in the TLs keep changing and the trajectory drifting

• It was noted that the proposal for an intermediate injection (8 bunches) can be used as a means of checking injection oscillations on the high intensity beams from the SPS, and should be seen as a way of validating the MPS settings for injection prior to filling the LHC.

• It was commented that the example of heavy losses at injection due to loss of timing synchronisation resulting from a glitch of the GPS timing receiver for the master clock did not interlock and block further injections. This issue is to be addressed over the shutdown.

HUMAN RISK FACTORS

The 2010 run and general machine operation were discussed in terms of the human risk factor with the focus on both machine protection as well as standard operation. The following was was noted from the post-presentation discussion:

• A number of issues and operational weaknesses resulted from insufficient communication or the poor passage of information. For equipment teams and experts, it was mentioned that the operations would benefit from an improved means by which information could be passed to the shift crew - especially if the experts are in a remote location (eg SR4).

• When there is beam in the machine, the access to low level applications such as Equip State should be reduced to remove the risk of inadvertent operator errors that could compromise the machine protection. It was noted that there is very little protection against commands that take the machine outside a predefined machine protection envelope, but that such an envelope is difficult to define and to maintain. For 2011, the suggestion is to move to an increased reliance on the LHC Sequencer and State Machine during routine operation.

• It was re-iterated that within the control room, clear lines of communication must be maintained across the LHC and the injectors, as there is the potential for both a loss in efficiency and compound operational scenarios, which whilst normally protected against by MPS, could lead to unnecessary risks.

DISCUSSION SUMMARY OF SESSION 5: BEAM LOSSES

R. W. Aßmann (Chairman) and S. Redaelli (scientific secretary), CERN, Geneva, Switzerland

Abstract

This paper summarizes the discussions that followed the presentations of the "Beam Losses" session of the the LHC Beam Operation Workshop, EVIAN2010.

INTRODUCTION

The fifth session of LHC Beam Commissioning Workshop was dedicated to the analysis of beam losses and included four talks:

1) **Multi-turn losses and cleaning**, by Daniel Wollmann (BE-ABP);
2) **Injection and extraction losses**, by Wolfgang Bartmann (TE-ABT);
3) **Losses away from collimators: statistics and extrapolation**, by Barbara Eva Holzer (BE-BI);
4) **BLM thresholds: limiting locations**, by Annika Nordt (BE-BI).

For each presentation of the session, summaries of the discussion that followed the presentations are given.

MULTI-TURN LOSSES AND CLEANING (D. WOLLMANN)

B. Goddard asked if the beam loss maps used for inefficiency calculations weight in the same way the BLM readings at the collimators and at the magnets. *D. Wollmann* reply that for the final intensity reach estimate, appropriate BLM factors are taken into account for the different element types.

F. Zimmermann asked if the ratio of loss peaks in IP7 and IP3 are correctly predicted by simulations in the case of betatron losses. *R. Assmann* replied that they agree within a factor ≈ 2.

O. Brüning asked if the hierarchy violation in IP3 was caused by a positioning error of the collimators. *D. Wollmann* replied that this is not the case: the collimators were correctly sent back to the same positions within the mechanical accuracy. He also pointed out that the machine was never at risk because the provided efficiency with hierarchy violated was still acceptable. *R. Assmann* commented that the radiation resistance of the warm magnets in IP3 could have been compromised in case of larger stored energies because only the magnets downstream of the primary collimators are protected with passive absorbers.

S. Fartoukh asked if the hierarchy violation was caused by an error at the primary or at the secondary collimator. *D. Wollmann* replied that this is not clear because the source of the problem was not identified.

As the estimated intensity reach from the collimation system is well above the goal for 2011, *M. Ferro-Luzzi* asked if there are other immediate limitations on the luminosity reach. *R. Assmann* stated that the 2011 goals should not be compromised. We have collimators dedicated to the absorption of the physics debris that have not yet been used but are fully operational and will be used if the debris from the IP will become an issue.

Having seem the excellent performance of the system, *O. Brüning* asked if we really need an upgrade of the system. *R. Assmann* replied that at 7 TeV the margins will be reviewed and also reminded that the losses for ion beams are worst.

B. Goddard suggested to review offline the issue of non reproducibility of vertical losses in IP6 because there we only have horizontal collimators. Why should we have vertical losses? *S. Redaelli* stated that for vertical losses at the primary collimators of IP7 there is also a leakage for the horizontal plane that induced losses in the collimators of IP6 as well.

R. Schmidt suggested to fold the latest updates on the quench estimates for different integration times onto the cleaning results presented by D. Wollmann. *B. Dehning* reminded that the new calculations will only affect the long running sums whereas the short one should be correct.

J. Uythoven asked if one should expect a different behaviour for smaller β^* values. *D. Wollmann* replied that the betatron cleaning from IP7 should remain unaffected so the conclusions should not change (provided that the triplet magnets are locally protected in an appropriate way by the tertiary collimators).

INJECTION AND EXTRACTION LOSSES (W. BARTMANN)

R. Assmann asked why the injection loss projections as a function of the number of bunches is not linear. *W. Bartmann* replied that the measurement with more than 24 bunches were taken without re-optimization of the injection collimator settings. *M. Sapinski* warned that the BLM thresholds were not the same for the various data taking and strongly recommended to make sure that this is properly taken into account.

P. Collier asked if it is clear why uncaptured beam at the SPS is seen in the LHC. This could only be explained by a mis-match between SPS extraction kicker and LHC injection kicker. To be checked.

B. Dehning asked if the factor 3 improvement of TDI losses from the shielding will be enough. *W. Bartmann* replied that this will not be the case. *B. Goddard* warned that the simulations that predicted this value are preliminary and the final figures should be considered. *B. Dehning* stated that a beam-based validation of the improvement factor from shielding predicted by simulations should be addressed as soon as possible. Dedicated beam time should be foreseen for tests with beam.

G. Arduini commented that the scaling of losses versus bunch number must take into account the fact that so far we used smaller emittances than nominal. This will not be possible anymore with many more bunches per train.

G. Arduini also asked how we will make sure that the abort gap cleaner, proposed as a way to clean the space of the next injection train, will not act also on the already filled bunch slots. *W. Hofle* replied that he has established a procedure for that. This method will have to be stamped by the machine protection panel.

J. Wenninger pointed out that the "BLM sun glass" has not been discussed yet at the machine protection meeting and therefore it should be considered just as a proposal at this stage. *W. Bartmann* confirmed that this is the case.

R. Jones asked how much should one open the injection collimators in order to reduce the loss spikes. *W. Bartmann* replied that clearly opening collimators is an effective way to reduce losses: 0.5 σ reduces the losses by about a factor 3. *R. Assmann* commented that one could also increase significantly the thresholds of the TCTV collimators for the short integration times. *R. Schmidt* suggested to consider also the possibility to increase the thresholds of the superconducting magnets in the injection regions. We should not be too afraid of the quenches!

W. Hofle reminded that, as he stated in his presentation, the present mechanism to clean the injection slot has a problems that require follow-up if the area to clean is 8 μs.

LOSSES AWAY FROM COLLIMATORS: STATISTICS AND EXTRAPOLATION (B.E. HOLZER)

Bernhard Holzer asked if the degradation of the signal experienced with some of the ionization chambers was caused by radiation damage. B.E. Holzer replied that the problem was identified as a bad soldering and is therefore independent of the beam.

P. Collier pointed out that, as no UFO was observed at injection energy, one should think of a mechanism that only produces them at top energy. The theory of the dust might not be appropriate. Clearly, we do not have yet a satisfactory physics model. *O. Brüning* suggested that the dependence on the synchrotron radiation should be taken into account. *T. Camporesi* proposed to consider the possibility that single halo protons hit directly the aperture. Other ideas were proposed: looking in detail in the ramp data to see when UFOs appear (*R. Assmann*), study the correlation with primary collimator settings (*S. Fartoukh*).

BLM THRESHOLDS: LIMITING LOCATIONS (A. NORDT)

B. Goddard asked if the pressure rise seen in case of losses at the collimators is real of could come from noise in the electronics. *A. Nordt* replied that she does not have this information.

J. Jowett stated that it would be interesting to perform a similar analysis of beam losses and pressure levels also for the ions.

P. Collier asked if there is a rationale for the change of BLM thresholds. *R. Assmann* commented that the purpose of this talk was indeed to identify locations for which a safe change of thresholds makes sense. *A. Nordt* pointed out that all the changes applied in the machine are subjected to a strict EDMS approval procedure.

F. Zimmermann suggested to check if there is a correlation between critical loss locations and β^* values.

H. Burkhard stated that the interaction of proton beams with the rest gas is well known and the losses could be compared with simulations.

DISCUSSION SUMMARY OF SESSION ON LUMINOSITY PERFORMANCE

M. Meddahi (Chairman), V. Kain (Scientific Secretary), CERN, Geneva, Switzerland

Abstract

The discussion during the session "Luminosity Performance" is summarised in the following.

CAN WE GET RELIABLE ON-LINE MEASUREMENTS OF THE TRANSWERSE BEAM SIZE? FEDERICO RONCAROLO & EMITTANCE PRESERVATION – VERENA KAIN

Due to time constraints the presentation on "Can we get a reliable on-line measurements of the transverse beam size?" from session Beam Diagnostics and Feedbacks was combined with the presentation on "Emittance Preservation".

B. Goddard asked whether the turn-by-turn matching screens will be available for the 2011 start-up. E. Bravin answered "probably not". They will come during the run. M. Lamont asked whether from the data of the experiments the stronger vertical blow-up in beam 2 could be seen. V. Kain answered that during the beginning of the 150 ns run the vertical luminous region data follows the beam size of beam 2, which is larger than beam 1 before the ramp. Towards the end of the 150 ns run the vertical emittance from the luminous region becomes smaller (around 2.5 μm), as does the vertical beam size at injection. The reason for that is not clear, G. Arduini mentioned the timing in of the beam 2 injection kicker. That however would only affect the first bunch and does not seem to be the explanation. S. Redaelli asked whether the effect of the nominal optics at the wire scanners and BSRTs for calculating the emittance instead of the measured optics has been evaluated. F. Roncarolo answered "no".

BEAM-BEAM – WERNER HERR

The matching between the two beams is important for beam-beam effects, W. Herr answered to O. Brüning's question. O. Brüning then added that time will have to be spent on correcting β^* and equalising the emittances. W. Herr also commented that from the 2010 experience we know that the effect of the beam-beam separation is less severe than expected, however PACMAN seems to be stronger than previously thought. Concerning the beam-beam limit, it was asked whether it originates from head-on or long range effects. W. Herr answered that at the moment the LHC is head-on limited, but later the beam-beam effects will most probably be long range dominated. W. Herr stressed that the observed sudden losses were clearly related to luminosity scan, and only observed at the time we were applying a tune split.

S. Myers asked if we can do better on head-on tune shift? W. Herr answered "yes, we have to try to push it as much as possible". S. Myers said that MDs should be planned to understand the beam-beam limit.

STRATEGY FOR LUMINOSITY OPTIMISATION – SIMON WHITE

A similar tool as for luminosity optimisation could be useful also for "distance scale calibration". The interest of having a feedback every few minutes on luminosity optimisation, like at PEP II, was also mentioned by Witold Kozanecki. W. Herr replied that shaking the beam over and over again would cause emittance growth. Violating the collimation hierarchy during VdM scans was mentioned several times. R. Schmidt commented that the violation of the hierarchy is not as problematic as exposing the triplet. R. Assmann remarked that VdM are not too worrying as they are only done under special circumstances following special procedures. For the automated tools, limits on the correctors should be in place. It was also stressed that maintenance and development of the software is to be taken into account as Simon White is leaving.

THE LHC OPTICS IN PRACTICE – ROGELIO TOMAS

J. Wenninger asked for a possibility to have the results of the beta-beating online in the control room for comparison. A solution will be put in place for next year's start-up. R. Assmann asked whether any effect of "aging" will be expected for the extremely reproducible LHC optics. The LHC will not be re-aligned for the next run. This will be followed up at the LMC. E. Todesco wanted to know whether hysteresis was seen to be a big issue. R. Tomas Garcia replied that currently this is not the biggest error. For the next year all the trim quadrupoles should be driven during the squeeze to make the corrections effective. F. Zimmermann remarked that for the coupling correction at $\beta^* = 2$ m, some of the correctors are already reaching their limit. R. Tomas Garcia answered that local correction using the triplet correctors will be needed there. B. Dehning asked for an estimate of the systematic errors of the beta-beating measurements. This can only be fully answered with k-modulation as cross-check.

HUMP: HOW DID IT IMPACT THE LUMINOSITY PERFORMANCE? – GIANLUIGI ARDUINI

S. Myers asked whether it would be possible to find a working point away from the hump. G. Arduini answered that the hump has a varying frequency, all frequencies from 0 – 0.5 are affected. G.Arduini also insisted that the Hump buster is used more frequently

LHC BEAM PARAMETERS: PUSHING THE ENVELOPE – ELIAS METRAL

E. Metral mentioned a minimum emittances of 1.5 μm in case of 2 batch operation from the booster. B. Goddard remarked that the machine protection implications for such small emittances should be investigated.

WRAPPING UP: DISCUSSION SUMMARY

M. Meddahi, CERN, Geneva, Switzerland

2011 PARAMETERS AND LHC BEAM OPERATION PLANS – JOERG WENNINGER

Steve Myers expressed his surprise regarding the number of remaining 2011 Physics days (125 days for a total time of 260 days) and asked that this is again reviewed. Jörg Wenninger added that all special demands implying a re-set up of the LHC –and injectors- will take time and will even cut more into the Physics days.

Concerning the 2011 ion run, if a normalisation run corresponding to 4 TeV is performed, it was proposed that another one is done at the same time for the 2013 energy – so setting up for two special energies, but only once and for all.

Werner Herr clarified that keeping alternating crossing scheme in IP1 and 5 is highly important in order to compensate for long range beam-beam effects. This is less important for the other IPs.

Jörg Wenninger said that the criteria for the large increase of bunch number needs further discussion. 3 weeks in total have been accounted for the increase of number of bunches.

Massimiliano Ferro-Luzzi proposed to start with 150 ns bunch spacing –w.r.t. to the proposed 75 ns- to restore the 2010 conditions. Jörg Wenninger said that every time the beam parameters are changed, it is reflecting in the time it takes to restore the same conditions. So the less changes are done, the more will be gained in Physics operation. The scrubbing run will already imply a bunch spacing change (50 ns). With 75 ns bunch spacing operation, a total of 1-3 fb^{-1} is at reach.

Massimiliano Ferro-Luzzi said that an alternative scenario could be to start with 150ns bunch spacing operation, perform the scrubbing run with 50 ns and continue with 50 ns operation for Physics. It was argued that 75 ns is not given yet and 50 ns will be even more difficult.

It was said that a single Pilot would become a batch of 16 bunches at the considered luminosity. This would be an argument to go to 50 ns. Steve Myers reminded that the experiments always said that they can take whatever pilot intensity we can provide them.

Ralph Assmann reminded that in the middle of the LHC run, a collimator set-up would most probably be needed. This is to be taken into account in the overall planning.

Django Manglunki reminded that the 2010 ion run was performed with 50% more intensity than nominal. However, if the number of bunches is increased in 2011, there will, of course, be much less intensity per bunch.

It was reminded that the machine aperture is to be measured at 450 GeV, this is important for the β* reach– it was scheduled for this year and was not done.

WORSHOP SUMMARY – MIKE LAMONT

Mike Lamont highlighted the main points of each the presentations made during the workshop. Mike Lamont thanked all the teams involved in the LHC operation for their excellent work. Some of the humoristic moments during the 2010 operation were highlighted.

The actions gathered during the workshop will be summarised at Chamonix, together with the name of a responsible person for follow-up and a time schedule for the implementation.

CLOSING REMARKS– STEVE MYERS

Steve Myers said that many actions have been gathered during this fruitful workshop and follow-ups are to be done within the new operations committee and LMC.

The possible issues with 900 bunches and 75 ns bunch spacing operation are:

- Electron clouds, with the interrogation concerning the cleaning at 450 GeV being sufficient for 4 TeV operation (additional effect of synchrotron light when reaching ~1.5-2 TeV) and therefore a possible need to scrub with 25ns;
- UFOs: what are they? Why is there an energy dependence (no UFOs at 450 GeV);
- Machine protection with ~100 MJ.

Steve Myers asked to consider luminosity levelling -by reducing the β*- in all IPs, not only for LHCb.

Steve Myers proposed that the “LEP efficiency factor” concept is used as well for the LHC efficiency calculation.

When pushing the beam parameters to their limits – emittance of 1.5 μrad, head-on beam-beam tune shift of 0.01, bunch intensity of 1.5e11p, β* = 1.5m-, the luminosity reach could be between 3 to 5 fb^{-1}.

Steve Myers was surprised to hear that no check of the LHC alignment was scheduled during the shutdown and reminded that it was regularly performed in LEP.

Steve Myers pointed out that a combined ramp and squeeze is interesting and may be done.

2010 EXPERIENCE AND EXPECTATIONS FOR 2011

M. Ferro-Luzzi, CERN, Geneva, Switzerland

Abstract

A critical review of 2010 operation, as viewed by the LHC experiments, is given. An overview of the run is presented. Running conditions and procedures are reviewed with emphasis on issues and proposals for improvements.

INTRODUCTION

First, a brief review of the 2010 LHC run is presented, with emphasis on physics operation. Second, lessons from the 2010 run, as seen by the experiments, are listed and proposals for improvements are made.

SUMMARY OF 2010 RUN

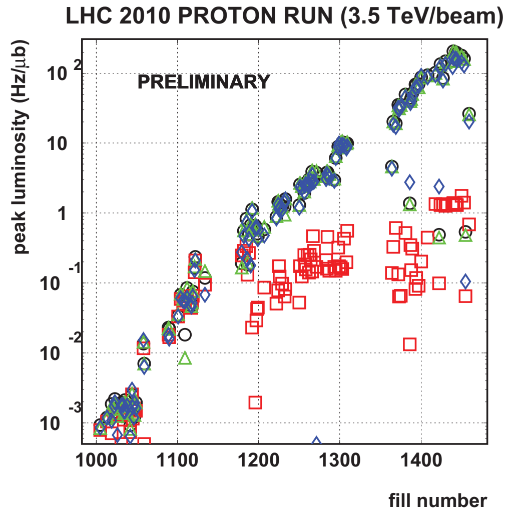
LHC proton operation started on February 28 and stopped on November 4. The LHC proton run can be divided in three phases:

- Phase 1: The initial phase started with commissioning to 3.5 TeV and first collisions at $\sqrt{s} = 7$ TeV. It proceeded with a first optics squeeze ($\beta^* = 2$ m at all IPs), and continued with an increase in the number of bunches (from 2 to 13) of small intensity (1 to $2 \cdot 10^{10}$ p). During this phase, physics collisions at 0.45 TeV/beam were also delivered, at injection optics and with close to nominal bunch intensities. The LHC physics fills of this phase are listed in table 1.

- Phase 2: After successfully testing physics collisions with nominal bunches at injection energy, the machine was prepared for collisions at 3.5 TeV/beam with $\beta^* = 3.5$ m at all IPs and with a small number of bunches of nominal intensity. The beam intensities and luminosities were pushed up by increasing the number of bunches from 3 to 50. This phase ended with a 1-month period of physics production with stable conditions and a stored beam energy of about 2 MJ (August). The LHC physics fills of this phase are listed in table 2.

- Phase 3: Finally, the machine was commissioned to work with bunch trains of 150 ns spacing (and nominal bunch intensities). The total number of bunches was increased from 24 to 368 (about 20 MJ per beam). A single test fill with 50 ns was attempted at the end. The LHC physics fills of this phase are listed in table 3.

The state of the LHCb dipole spectrometer and of the ALICE dipole and solenoid spectrometers are indicated in the tables. The polarity ('+' or '−') refers to the power converter polarity ('0' means 'off'). For IP2, the solenoid and dipole were always in the same state.



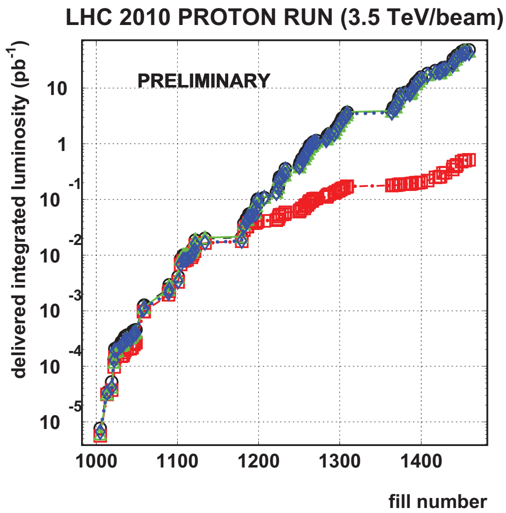
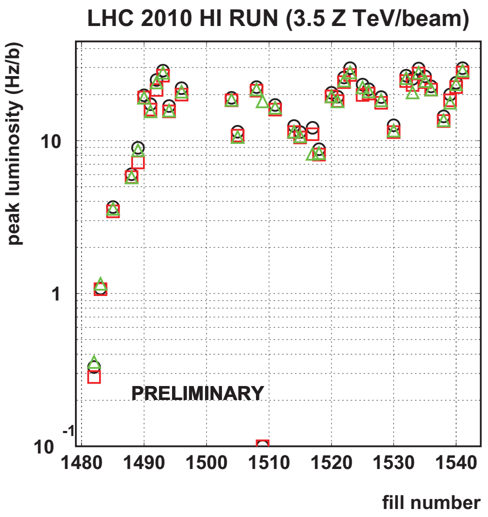


Figure 1: Overview of 2010 proton run. The top (bottom) graph shows the evolution of the peak (integrated) luminosity in the four interaction points. Symbols: ○ IP1, □ IP2, △ IP5, ◇ IP8.

There were six techical stops (starting on March 15, April 26, May 31, July 19, August 30, October 19) of 2 to 4 days during the proton run. During the ion run, a 3-day interruption of ion operation took place from November 17 to 20 to accomodate electron cloud studies with high intensity



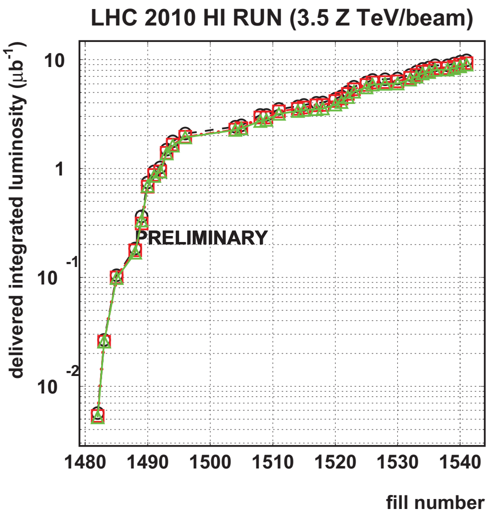


Figure 2: Overview of 2010 ion run. The top (bottom) graph shows the evolution of the peak (integrated) luminosity in the three interaction points. Symbols: ○ IP1, □ IP2, △ IP5, ◇ IP8.

proton beams (with 50 and 75 ns spacing).

An external crossing half-angle was introduced at IP1 (-100 μrad) and IP5 ($+100$ μrad) between the first and second phase. The angle at IP1 allowed LHCf to collect data with a different momentum coverage. The LHCf detector was dismounted during the July technical stop (the last 2010 physics fill for LHCf was fill 1233).

In order to facilitate operation with bunch trains, all IPs were set up with an external crossing angle between the second and third phase, An external horizontal crossing half-angle of $+100$ μrad in IP5 and of -100 μrad in IP8 was used (for LHCb the polarity reversals were applied to the internal angle only). External vertical crossing half-angles of -100 μrad in IP1 and of ± 110 μrad in IP2 were used (for ALICE the polarity reversals were applied to the spectrometers and to the external angle).

Since fill 1190, IR2 was operated with a horizontal parallel separation of 3 to 4 nominal beam sizes ($\sigma_{\rm beam} \approx 60$ μm) to maintain a luminosity between $\sim 10^{29}$ Hz/cm^2 and $2 \cdot 10^{30}$ Hz/cm^2.

A number of special activities were organized:

- A few fills at $\sqrt{s} = 0.9$ TeV were delivered (1068, 1069, 1128) to complement the 2009 physics run and to test collisions with nominal bunch intensities. This allowed the experiments to collect several million events.
- A first series of Van der Meer scans was carried out in Phase 1, fills 1058, 1059, 1089 and 1090 [1], which yielded a direct luminosity calibration. A second series of Van der Meer scans was organized in Phase 3, this time during dedicated fills (1386 and 1422), to obtain a more precise luminosity calibration (at the level of 5%).
- Length scale calibration measurements for the Van der Meer scans were performed in fills 1393 (IP1), 1422 (IP8 and IP5), 1439 (IP5) and 1455 (IP2).
- Beam-based alignment of the TOTEM Roman Pots was done during fill 1359 and followed by a short data-taking period (of about 1 hour) with the pots positioned at about $7\sigma_{\rm beam}$ from the beam orbit. A second special data-taking period was delivered for TOTEM during fill 1455 (about 4 hours).
- During fill 1455, about one hour was dedicated to the technical test of a longitudinal scan. The phase between the beams was varied from -15 and +15 ns in steps of 5 ns (and 0.2 ns between -1 and +1 ns) . Possible applications of such scans are: longitudinal separation and collapse to collisions, measurement of the crossing angle and measurement of satellite bunch distributions.

The LHC ion run drastically benefited from the operational and commissioning experience of the proton run. Ion operation started on November 4 and stopped on December 6. The beam rigidity and the optics remained untouched ($E = 3.5$ ZTeV and $\beta^* = 3.5$ m), from the start of the ion run. Only the crossing angles were modified such as to give zero net angle in all IPs (IP1, IP2 and IP5), which is an advantage for interpreting data of the Zero-Degree Calorimeters (ZDC). The TCTVB collimators in IR2 were opened enough to not create any shadow on the ALICE ZDC. The bunch intensity was between 6 and $12 \cdot 10^7$ Pb from the first fill (thus exceeding 'nominal' intensity). The number of bunches was rapidly increased from 2 to 121, and later to 137. All LHC physics fills of the ion run are listed in table 4.

Van der Meer scans for luminosity calibration with ions were carried out in fill 1533 for IP1, IP2 and IP5. Note that

Fill nr.	Stable beams start	stop	E (TeV)	Filling scheme	Magnets IP8	IP2	β^* (m)
1005	Tue 30.03 13:22	Tue 30.03 16:29	3.5	Single_2b_1_1_1	+	-	11/10
1013	Wed 31.03 21:03	Thu 01.04 05:05	3.5	Single_2b_1_1_1	+	-	11/10
1019	Sat 03.04 04:23	Sat 03.04 07:23	3.5	Single_2b_1_1_1	-	-	11/10
1022	Sun 04.04 17:26	Mon 05.04 13:29	3.5	Single_2b_1_1_1	-	-	11/10
1023	Tue 06.04 02:44	Tue 06.04 14:59	3.5	Single_2b_1_1_1	+	-	11/10
1026	Wed 07.04 10:28	Wed 07.04 12:52	3.5	Single_2b_1_1_1	+	-	11/10
1031	Sat 10.04 06:13	Sat 10.04 15:47	3.5	Single_2b_1_1_1	+	+	11/10
1033	Mon 12.04 01:24	Mon 12.04 03:23	3.5	Single_2b_1_1_1	0	+	11/10
1034	Mon 12.04 08:54	Mon 12.04 17:25	3.5	Single_2b_1_1_1	0	+	11/10
1035	Tue 13.04 05:01	Tue 13.04 09:31	3.5	Single_2b_1_1_1	+	+	11/10
1038	Wed 14.04 05:50	Wed 14.04 10:53	3.5	Single_2b_1_1_1	+	+	11/10
1042*	Thu 15.04 06:22	Thu 15.04 08:54	3.5	Single_2b_1_1_1	+	+	11/10
1044	Fri 16.04 05:50	Fri 16.04 09:12	3.5	Single_2b_1_1_1	+	+	11/10
1045	Sat 17.04 05:55	Sat 17.04 14:58	3.5	Single_2b_1_1_1	+	+	11/10
1046	Sun 18.04 06:06	Sun 18.04 06:55	3.5	Single_2b_1_1_1	+	+	11/10
1047	Sun 18.04 11:28	Sun 18.04 14:39	3.5	Single_2b_1_1_1	+	+	11/10
1049	Mon 19.04 03:55	Mon 19.04 05:14	3.5	Single_2b_1_1_1	+	+	11/10
1058†	Sat 24.04 03:13	Sun 25.04 09:30	3.5	Single_3b_2_2_2	+	+	2
1059†	Mon 26.04 01:34	Mon 26.04 06:32	3.5	Single_2b_1_1_1	+	+	2
1068	Sun 02.05 14:33	Sun 02.05 21:44	0.45	Single_2b_1_1_1	+	+	11/10
1069	Mon 03.05 02:03	Mon 03.05 09:18	0.45	Single_2b_1_1_1	-	+	11/10
1089†	Sat 08.05 22:33	Sun 09.05 18:55	3.5	Single_2b_1_1_1	-	0	2
1090†	Mon 10.05 04:31	Mon 10.05 10:57	3.5	Single_2b_1_1_1	-	+	2
1101	Fri 14.05 12:57	Fri 14.05 23:39	3.5	Single_4b_2_2_2	+	+	2
1104	Sat 15.05 16:54	Sun 16.05 14:14	3.5	Single_6b_3_3_3	-	+	2
1107	Mon 17.05 06:27	Mon 17.05 15:25	3.5	Single_6b_3_3_3	-	+	2
1109	Tue 18.05 04:54	Tue 18.05 05:35	3.5	Single_6b_3_3_3	-	+	2
1112	Wed 19.05 06:10	Wed 19.05 07:33	3.5	Single_6b_3_3_3	+	+	2
1117	Sat 22.05 03:39	Sat 22.05 11:42	3.5	Single_6b_3_3_3	+	+	2
1118	Sun 23.05 06:05	Sun 23.05 12:34	3.5	Single_6b_3_3_3	+	+	2
1119	Sun 23.05 20:45	Mon 24.05 00:18	3.5	Single_6b_3_3_3	+	+	2
1121	Mon 24.05 15:01	Mon 24.05 17:27	3.5	Single_13b_8_8_8	+	+	2
1122	Tue 25.05 03:15	Tue 25.05 12:27	3.5	Single_13b_8_8_8	+	+	2
1128	Thu 27.05 15:07	Thu 27.05 16:03	0.45	Single_7b_4_4_4	+	+	11/10
1134	Sat 05.06 13:42	Sat 05.06 17:28	3.5	Single_13b_8_8_8	+	-	2

Table 1: All fills with STABLE BEAMS during the first phase of the 2010 LHC proton run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid. *The CMS solenoid was off during fill 1042. †Fill includes Van der Meer scans.

LHCb was switched off during the ion run (including the spectrometer bump).

In total, the LHC operated 1074 hours in STABLE BEAMS (851 hours with p and 223 hours with Pb) out of about 6600 hours. There were 147 fills with STABLE BEAMS (110 with p and 37 with Pb).

Figure 1 shows on the top graph the peak luminosity as a function of physics fill number. The peak luminosity increased from $8 \cdot 10^{26}$ $\mathrm{Hz/cm^2}$ to $2 \cdot 10^{29}$ $\mathrm{Hz/cm^2}$ (Phase1), then further to $4.6 \cdot 10^{30}$ $\mathrm{Hz/cm^2}$ (Phase 2) and finally reached $2 \cdot 10^{32}$ $\mathrm{Hz/cm^2}$ (Phase 3). The integrated delivered luminosities (2010 totals) were approximately $48\,\mathrm{pb}^{-1}$ (IP1), $0.5\,\mathrm{pb}^{-1}$ (IP2), $47\,\mathrm{pb}^{-1}$ (IP5) and $42\,\mathrm{pb}^{-1}$ (IP8).

Figure 2 shows the corresponding graphs for the ion run (LHCb switched off). In this case, the luminosity was increased from $3 \cdot 10^{23}$ $\mathrm{Hz/cm^2}$ to $3 \cdot 10^{25}$ $\mathrm{Hz/cm^2}$. The integrated delivered luminosities were approximately $9.9\,\mu\mathrm{b}^{-1}$ (IP1), $9.3\,\mu\mathrm{b}^{-1}$ (IP2) and $9\,\mu\mathrm{b}^{-1}$ (IP5).

Other yearly summary plots are available at the LHC Programme Coordinations site [2].

2010 LESSONS

Modus operandi: The early June experience with machine operation alternating between commissioning (at day time) and physics (at night) showed that this mode of operation had reached its limits (though its was useful during the initial phase). Subsequently, a clear separation between major commissioning steps and physics production was put in place, to the benefit of the LHC machine and LHC experiments. For 2011, such a separation between commissioning blocks (of several days) and physics production (of several weeks) should be maintained.

Technical stops: The impact of technical stops on operation, and in particular the recovery from a stop, was discussed elsewhere (see [3]). Originally, a 3-day stop every fourth week was planned for the LHC. From the 2010 experience, it seems that a space of 6 weeks between the start of two subsequent (4-day long) technical stops is acceptable. The frequency and length of such stops needs to be further optimized. The cooperation between the Technical Stop Coordinator and the LHC Machine Coordinator was strengthened in the course of 2010. This improved the supervision of interventions (hardware and software changes) and helped reducing collateral effects of technical stops on operation. Further strengthening of this cooperation will help minimizing the machine downtime.

Increasing stored beam energy: The increase of beam intensity (stored energy) in the LHC machine was driven by both machine protection aspects and operational considerations. The human factor and improvement of operational

Fill	Stable beams		E	Filling	Magnets		β^*
nr.	start	stop	(TeV)	scheme	IP8	IP2	(m)
1179	Fri 25.06 01:35	Fri 25.06 03:57	3.5	Single_3b_2_2_2	+	-	3.5
1182	Sat 26.06 19:28	Sun 27.06 10:15	3.5	Single_3b_2_2_2	+	-	3.5
1185	Tue 29.06 11:57	Tue 29.06 16:11	3.5	Single_3b_2_2_2	+	-	3.5
1186	Wed 30.06 08:15	Wed 30.06 10:36	3.5	Single_3b_2_2_2	+	-	3.5
1188	Thu 01.07 02:56	Thu 01.07 10:47	3.5	Single_3b_2_2_2	+	-	3.5
1190	Fri 02.07 05:40	Fri 02.07 06:27	3.5	Single_7b_4_4_4	+	-	3.5
1192	Fri 02.07 17:30	Fri 02.07 18:04	3.5	Single_7b_4_4_4	+	-	3.5
1196	Sun 04.07 00:46	Sun 04.07 01:35	3.5	Single_7b_4_4_4	+	-	3.5
1197	Sun 04.07 06:22	Sun 04.07 18:16	3.5	Single_7b_4_4_4	+	-	3.5
1198	Mon 05.07 02:28	Mon 05.07 13:43	3.5	Single_7b_4_4_4	+	-	3.5
1199	Mon 05.07 23:11	Tue 06.07 02:58	3.5	Single_10b_4_2_4	+	-	3.5
1207	Fri 09.07 04:16	Fri 09.07 10:17	3.5	Single_10b_4_2_4	+	-	3.5
1222	Mon 12.07 03:02	Mon 12.07 11:56	3.5	Single_9b_6_6_6	+	-	3.5
1224	Tue 13.07 05:08	Tue 13.07 14:59	3.5	Single_12b_8_8_8	-	-	3.5
1225	Wed 14.07 02:13	Wed 14.07 17:02	3.5	Single_12b_8_8_8	-	-	3.5
1226	Thu 15.07 04:19	Thu 15.07 13:15	3.5	Single_13b_8_8_8	-	-	3.5
1229	Sat 17.07 00:44	Sat 17.07 04:36	3.5	Single_13b_8_8_8	-	-	3.5
1232	Sat 17.07 19:19	Sun 18.07 01:11	3.5	Single_13b_8_8_8	-	-	3.5
1233	Sun 18.07 10:56	Mon 19.07 05:58	3.5	Single_13b_8_8_8	-	-	3.5
1250	Wed 28.07 22:28	Thu 29.07 10:35	3.5	Single_13b_8_8_8	+	-	3.5
1251	Thu 29.07 23:28	Fri 30.07 07:25	3.5	Multi_25b_16_16_16_hyb	+	-	3.5
1253	Fri 30.07 23:11	Sat 31.07 12:20	3.5	Multi_25b_16_16_16	+	-	3.5
1256	Sun 01.08 03:50	Sun 01.08 04:49	3.5	Multi_25b_16_16_16	+	-	3.5
1257	Sun 01.08 22:00	Mon 02.08 12:35	3.5	Multi_25b_16_16_16	+	-	3.5
1258	Tue 03.08 00:22	Tue 03.08 07:39	3.5	Multi_25b_16_16_16	+	-	3.5
1260	Wed 04.08 04:31	Wed 04.08 06:38	3.5	Multi_25b_16_16_16	+	-	3.5
1262	Wed 04.08 17:40	Thu 05.08 11:19	3.5	Multi_25b_16_16_16	+	-	3.5
1263	Fri 06.08 03:52	Fri 06.08 19:08	3.5	Multi_25b_16_16_16	+	-	3.5
1264	Sat 07.08 01:42	Sat 07.08 02:14	3.5	Multi_25b_16_16_16	+	-	3.5
1266	Sat 07.08 23:12	Sun 08.08 01:10	3.5	Multi_25b_16_16_16	+	-	3.5
1267	Sun 08.08 05:18	Sun 08.08 18:52	3.5	Multi_25b_16_16_16	+	-	3.5
1268	Mon 09.08 01:29	Mon 09.08 04:02	3.5	Multi_25b_16_16_16	+	-	3.5
1271	Tue 10.08 07:24	Tue 10.08 12:22	3.5	Multi_25b_16_16_16	+	-	3.5
1283	Fri 13.08 23:06	Sat 14.08 12:04	3.5	Multi_25b_16_16_16	+	-	3.5
1284	Sat 14.08 15:44	Sat 14.08 19:13	3.5	Multi_25b_16_16_16	+	-	3.5
1285	Sun 15.08 00:39	Sun 15.08 13:02	3.5	Multi_25b_16_16_16	+	-	3.5
1287	Sun 15.08 23:01	Mon 16.08 09:24	3.5	Multi_25b_16_16_16	+	-	3.5
1293	Tue 18.08 09:12	Tue 18.08 21:13	3.5	Multi_25b_16_16_16	-	-	3.5
1295	Thu 19.08 23:36	Fri 20.08 14:19	3.5	1250ns_48b_36_16_36	-	-	3.5
1298	Mon 23.08 00:52	Mon 23.08 13:50	3.5	1250ns_48b_36_16_36	-	-	3.5
1299	Tue 24.08 00:11	Tue 24.08 03:26	3.5	1250ns_48b_36_16_36	-	-	3.5
1301	Tue 24.08 17:35	Wed 25.08 07:53	3.5	1000ns_50b_35_14_35	-	-	3.5
1303	Thu 26.08 04:21	Thu 26.08 17:26	3.5	1000ns_47b_32_14_32	-	-	3.5
1305	Fri 27.08 06:11	Fri 27.08 09:41	3.5	1000ns_50b_35_14_35	-	-	3.5
1308	Sat 28.08 22:43	Sun 29.08 12:22	3.5	1000ns_50b_35_14_35	-	-	3.5
1309	Sun 29.08 18:17	Mon 30.08 05:35	3.5	1000ns_50b_35_14_35	+	-	3.5

Table 2: All fills with STABLE BEAMS during the second phase of the 2010 LHC proton run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid.

procedures shaped the 'learning curve'. Operation in 2011 and beyond will greatly benefit from the enormous experience acquired during 2010. In future years, intensity increase should be largely driven by the state of the machine protection system and by intrinsic performance limitations of the machine itself (such as e-cloud effects).

Filling the LHC: The LHC currently hosts seven approved experiments (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL) with diverse requirements on beam conditions. Filling the LHC in such a way that all experiments are adequately served is a challenge. Constructing filling schemes became increasingly complex toward the end of the 2010 proton run, mainly due to the following features:

- The use of an intermediate intensity batch ($< 10^{12}p$) before transfering a high intensity batch from the SPS imposed to use the same number of bunches per PS batch throughout the whole filling process. This is due to the fact that the number of bunches from the booster to the PS can not be dynamically driven by the LHC. For 150 ns operation, this precluded the use of 12-bunch trains from the PS. The implications were a small fraction of lost collisions (more train edges) and a reduced reach in total number of bunches as compared to 12-bunch trains. For future years, ideally, the LHC should be able to drive dynamically the number of booster bunches to the PS.
- The compulsory use of the intermediate intensity batch also introduced a difficulty in constructing well-balanced filling schemes. Besides the breaking of the four-fold symmetry, it also "consumes" 950 ns of the LHC circumference. Ideally, this batch should be dumped before starting the actual LHC filling, or it should be possible to inject a full intensity batch over the intermediate batch. Preferably, the deployed solution should work for any bunch spacing (150, 75, 50, 25 ns).
- The Abort Gap Keeper (AGK) window length was set

Fill nr.	Stable beams start	stop	E (TeV)	Filling scheme	Magnets IP8	IP2	β^* (m)
1364	Wed 22.09 16:54	Thu 23.09 06:37	3.5	150ns_24b_16_16_16_8bpi	-	+	3.5
1366	Thu 23.09 19:10	Fri 24.09 09:12	3.5	150ns_56b_47_16_47_8bpi	-	+	3.5
1369	Sat 25.09 09:38	Sat 25.09 11:05	3.5	150ns_56b_47_16_47_8bpi	-	-	3.5
1372	Sat 25.09 19:39	Sun 26.09 11:18	3.5	150ns_104b_93_8_93_8bpi	-	-	3.5
1373	Sun 26.09 21:27	Mon 27.09 09:58	3.5	150ns_104b_93_8_93_8bpi	-	-	3.5
1375	Tue 28.09 02:23	Tue 28.09 11:23	3.5	150ns_104b_93_8_93_8bpi	-	-	3.5
1381	Thu 30.09 02:25	Thu 30.09 05:28	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1386†	Fri 01.10 13:30	Fri 01.10 16:24	3.5	Single_19b_6_1_12_allVdm	-	-	3.5
1387	Sat 02.10 05:08	Sat 02.10 07:06	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1388	Sat 02.10 10:57	Sat 02.10 13:08	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1389	Sun 03.10 13:16	Sun 03.10 20:27	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1393‡	Mon 04.10 20:00	Tue 05.10 09:43	3.5	150ns_200b_186_8_186_8+8bpi17inj	-	-	3.5
1394	Tue 05.10 23:58	Wed 06.10 01:41	3.5	150ns_200b_186_8_186_8+8bpi17inj	-	-	3.5
1397	Thu 07.10 04:23	Thu 07.10 10:54	3.5	150ns_200b_186_8_186_8+8bpi17inj	-	-	3.5
1400	Fri 08.10 02:36	Fri 08.10 09:10	3.5	150ns_248b_233_16_233_3x8bpi15inj	-	-	3.5
1408	Mon 11.10 21:20	Tue 12.10 07:17	3.5	150ns_248b_233_16_233_3x8bpi15inj	-	-	3.5
1418	Thu 14.10 03:38	Thu 14.10 12:06	3.5	150ns_248b_233_16_233_3x8bpi15inj	-	-	3.5
1422†	Fri 15.10 13:14	Fri 15.10 18:27	3.5	Single_16b_3_1_12_allVdmB	-	-	3.5
1424	Sat 16.10 02:30	Sat 16.10 03:23	3.5	150ns_312b_295_16_295_3x8bpi19inj	-	-	3.5
1427	Sat 16.10 22:56	Sun 17.10 09:31	3.5	150ns_312b_295_16_295_3x8bpi19inj	-	-	3.5
1430	Mon 18.10 04:25	Mon 18.10 05:03	3.5	150ns_312b_295_16_295_3x8bpi19inj	-	-	3.5
1439‡	Sun 24.10 09:59	Sun 24.10 20:41	3.5	150ns_312b_295_16_295_3x8bpi19inj	+	-	3.5
1440	Mon 25.10 02:35	Mon 25.10 13:54	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1443	Tue 26.10 05:35	Tue 26.10 07:49	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1444	Tue 26.10 13:35	Tue 26.10 20:47	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1450	Thu 28.10 00:45	Thu 28.10 15:17	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1453	Fri 29.10 04:16	Fri 29.10 10:36	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1455‡	Sat 30.10 05:33	Sat 30.10 06:32	3.5	Single_5b_5_1_1	+	-	3.5
1459	Sun 31.10 01:24	Sun 31.10 07:25	3.5	50ns_109b_91_12_90_12bpi10inj	+	-	3.5

Table 3: All fills with STABLE BEAMS during the third phase of the 2010 LHC proton run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid. †Fill includes Van der Meer scans (and length scale calibrations). ‡Fill includes a length scale calibration.

to match the nominal transfer from the SPS of 288 bunches of 25 ns spacing, i.e. a length of about 8 μs (3200 LHC Rf buckets). The AGK prevented injection of the first bunch of a batch to fall in an LHC RF bucket larger than about 32040 ($35640 - 3200 - 400$, where the 400 comes from the abort gap). In practice, the longest proton batch used was about 5 μs (and 3.5 μs for ion operation). Therefore, the 8 μs AGK window introduced a dead space of at least 3 μs which, when combined with the four-fold symmetry requirements, created difficulties and limitations for constructing well-balanced filling schemes. For 2011 operation, it is likely that the transfer of full 8 μs batches will actually be used (for e-cloud scrubbing and for physics).
For the ion run, the smaller the dead space, the less collisions will be lost at IP2 (ALICE). Note that the possibility to rephase the abort gap near IP2 was discussed, but finally not implemented due to potential disruptions in the DAQ of some of the experiment. This option might be reconsidered for the 2011 Pb run.

- When the BPM sensitivity is set for high intensity bunches, the BPMs cannot measure low intensiy bunches (below $\sim 5 \cdot 10^{10}p$). For this reason, it was decided (initially) not to operate with schemes mixing high and low intensity bunches, as the trajectory of the latter bunches would have been invisible. This precluded the option of using the intensity of special bunches for adjusting the interaction rate at low-luminosity experiments (ALICE, LHCf, TOTEM). For IP2, the alternative method of parallel separation was used with great success. For TOTEM, a single test with small bunches was performed in the last proton physics fill (1459), showing no particular issues related to the small bunch. Since TOTEM is at the same IP as CMS, parallel separation cannot be used. For 2011, the use of a few small intensity bunches during physics fills would allow TOTEM to collect low pile-up data in parallel to high-luminosity production for CMS. This trick could be used as long as the small intensity bunches do not occupy space otherwise usable by high intensity bunches (for example, if operating at 400 bunches with 75 ns spacing).

- Much of the turn-around time was spent at LHC injection (2 to 5 hours ?). This was due to several reasons: loss of injection requests because of the management of injection checks, non-dedicated injector operation for LHC filling (long supercycle), lengthy beam checks at injection, handshakes with the experiments, etc. For details see [4]. For 2011, an improved treatment of injection requests/checks, dedicated operation of the injector complex for LHC filling, more automated beam quality checks, are expected to give a much reduced turn-around time for physics.

Polarity reversals: The spectrometer polarity changes interfered with beam commissioning and operation. In 2010, the LHCb dipole polarity was reversed 12 times. The ALICE dipole and solenoid polarities were reversed 5 times.

Fill nr.	Stable beams start	stop	E (TeV)	Filling scheme	Magnets IP8	IP2	β^* (m)
1482	Mon 08.11 11:19	Mon 08.11 20:02	3.5	Single_2b_1_1_0_1bpi2inj_IONS	0	-	3.5
1483	Tue 09.11 01:01	Tue 09.11 09:58	3.5	Single_5b_4_4_0_1bpi5inj_IONS	0	-	3.5
1485	Tue 09.11 22:49	Wed 10.11 12:43	3.5	500ns_17b_16_16_0_4bpi5inj_IONS	0	-	3.5
1488	Fri 12.11 00:53	Fri 12.11 06:39	3.5	500ns_69b_65_66_0_4bpi18inj_IONS	0	-	3.5
1489	Sat 13.11 01:04	Sat 13.11 10:41	3.5	500ns_69b_65_66_0_4bpi18inj_IONS	0	-	3.5
1490	Sun 14.11 00:32	Sun 14.11 08:21	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1491	Sun 14.11 18:04	Mon 15.11 00:38	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1492	Mon 15.11 07:42	Mon 15.11 08:44	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1493	Mon 15.11 12:48	Mon 15.11 22:04	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1494	Tue 16.11 02:28	Tue 16.11 09:00	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1496	Wed 17.11 00:33	Wed 17.11 06:14	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1504	Sat 20.11 23:00	Sun 21.11 06:16	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1505	Sun 21.11 11:00	Sun 21.11 13:05	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1508	Mon 22.11 01:36	Mon 22.11 09:49	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1509	Mon 22.11 14:06	Mon 22.11 15:16	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1511	Mon 22.11 21:59	Tue 23.11 08:00	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1514	Wed 24.11 02:04	Wed 24.11 08:31	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1515	Wed 24.11 14:01	Wed 24.11 17:00	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1517	Wed 24.11 22:02	Thu 25.11 03:34	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1518	Thu 25.11 06:58	Thu 25.11 08:06	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1520	Thu 25.11 18:11	Thu 25.11 23:58	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1521	Fri 26.11 05:43	Fri 26.11 09:51	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1522*	Fri 26.11 13:32	Fri 26.11 21:35	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1523*	Sat 27.11 03:59	Sat 27.11 12:23	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1525	Sat 27.11 23:54	Sun 28.11 09:51	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1526	Sun 28.11 13:22	Sun 28.11 18:59	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1528	Mon 29.11 02:05	Mon 29.11 03:41	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1530	Mon 29.11 14:54	Mon 29.11 17:06	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1532	Mon 29.11 23:56	Tue 30.11 08:05	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1533†	Tue 30.11 13:31	Tue 30.11 22:04	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1534	Wed 01.12 08:38	Wed 01.12 15:18	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1535	Wed 01.12 22:49	Thu 02.12 01:38	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1536	Sat 04.12 13:54	Sat 04.12 20:38	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1538	Sun 05.12 11:07	Sun 05.12 11:22	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1539	Sun 05.12 17:59	Sun 05.12 23:41	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1540	Mon 06.12 04:01	Mon 06.12 09:56	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1541	Mon 06.12 14:10	Mon 06.12 18:00	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5

Table 4: All fills with STABLE BEAMS during the 2010 LHC ion run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid. *The ATLAS solenoid was off during fills 1522 and 1523. †Fill includes Van der Meer scans.

In addition, ALICE, ATLAS, CMS and LHCb requested "field off" collisions (see tables 1 to 4). The LHCb reversal had little impact (one spectrometer magnet and fixed external angle, when present), while the ALICE reversals (two magnets and a changing external angle, when present) required more attention due to the fact that the solenoid introduces a trajectory change in the horizontal plane which is not compensated by dedicated magnets (contrary to the dipole spectrometer fields). The number of polarity change requests will be similar in 2011. Acquiring similar data sets in both polarities for every new type of beam conditions is important for understanding systematic uncertainties in the experiments. Making the polarity reversals as transparent as possible for operation is important. In addition, keeping the beam conditions (pile-up, luminosity) at IP2 and IP8 as stable as possible will also contribute reducing the number of change requests. For 2011, two settings of tertiary collimators in IR2 should be validated (corresponding to the two polarities).

IR2 tertiary collimators: The TCTVB collimators in IR2 created a shadow to the ALICE ZDC during proton operation. The collimators were opened for the ion run and should again be opened for the 2011 ion run. The final solution is to replace the TCTVB by a different type located further downstream of the current TCTVB (much like in IR1 and IR5). This change is already planned and should take place as soon as possible.

Bunch current measurements: The luminosity calibration measurements highlighted the importance for the experiments of the LHC beam instrumentation, most prominently of the Beam Current Transformers (BCTs). This triggered a joint machine-experiments activity to extract best results on the bunch population product normalisation [5]. A few issues were encountered during 2010:

- The DCCT did not behave as expected when bunch trains were introduced (150 ns spacing). This was traced back to a saturation effect in the DCCT amplifier cards.
- Given our current understanding, the DCCT scale factor is now the main source of uncertainty. Calibration studies, in particular assessment of stability, are becoming increasingly important for the experiments. Such studies have started at the end of 2010 and should be pursued.
- The FBCT exhibited a dependence on bunch length and beam position. This needs to be understood and corrected. The experiments (ATLAS in particular) offer a cross-check of the FBCT data by measuring the

relative bunch populations with their beam pick-ups (BPTX).

- The raw FBCT data (not zero-suppressed data) were initially not logged. Given the importance of these data for the luminosity calibration, they should be logged in 2011. This may help understanding the offset and linearity of the FBCT.

- Cross-comparison of the BCT systems A and B would also be desirable, at least during luiminosity calibration measurements. In general, it would be useful to have a mechanism to trace when a BCT system underwent a development period and when it was considered stable.

This joint effort should be continued in 2011 to bring the beam and bunch current measurements to their specified accuracy. In a recent workshop [6], it was concluded that a luminosity calibration accuracy smaller than 5% seems feasible and would have significant impact on physics results. This may require additional beam-based measurements for narrowing down systematic uncertainties (of BCTs, beam displacements, beam-beam effects, pile-up, etc.), see [1, 6] for a discussion. Further desired improvements on beam instrumentation are given below.

Longitudinal profile: Ghost and satellite charge measurement and/or control could become a limiting factor in the precision reach of the bunch current normalisation for luminosity calibration. The Longitudinal Density Monitor was deployed (for ring 1) during the ion run. Its potential to thoroughly address the ghost charge issue was demonstrated. The luminosity normalisation experiments would greatly benefit from the full deployment, commissioning and calibration of these devices for both rings.

Emittance measurements: Emittance measurements were used for estimating the emittance growth during the luminosity calibration measurements. If needed, a correction to the measured convoluted shapes was applied. They were also used for studying the evolution of the specific luminosity during a fill. Bunch-by-bunch measurements became available during the year. Flexibility and ease of use of such measurements could be improved. Ideally, a user should be able to rapidly change between single bunch or multi-bunch acquisition (on a pre-defined set on bunch slots). A file-driven bunch slot selection could be considered. In 2011, bunch-by-bunch emittance measurements will be crucial to understand beam-beam effects. Continuous and automated logging of the emittance of each bunch (e.g. with the BSRT) would be extremely valuable.
The experiments support the effort to perform a cross calibration of the various emittance measuring devices (wire scanners, beam-gas ionisation monitors, synchrotron light monitors). With decreasing β^* and beam emittances, the beam sizes at the IPs may well become of the order of the vertex resolution, which will render the extraction of beam sizes from vertex detector data less reliable.

Beam position in IRs: The stability and accuracy of IR BPMs was not yet at the level of the design specifications. This will become increasingly important in 2011, with the use of smaller beams, higher intensities, and for forward experiments (such as TOTEM and ALFA). In particular, the BPMWF monitors should be commissioned and calibrated.

Luminosity Scan application: The Luminosity Scan application was extensively used for Van der Meer scans and associated length scale calibration scans. However, new scan procedures were proposed (to understand systematics or to speed up the procedure) which were not compatible with the application functionality. It has been proposed to upgrade the application functionality such as to allow the user to encode the scan sequence in an input file. Such a modification would greatly enhance the flexibility and functionality. Additionally, the possibility to scan simultaneously at different IPs has been implemented in the course of 2010. This may greatly reduce the cost of Van der Meer scans. The data exchange protocol and possible (cross-IP) systematic effects are yet to be tested [1].

Scan range (envelope): The scan range of luminosity calibration experiments was defined on the basis of tertiary collimator margins and restricted to $\pm 3\sigma_{\rm beam}$ displacements for each beam independently. This was sufficient for most experiments, but introduced some limitations for the special case of IR2 when operating with separated beams. In 2011, it is considered to move the tertiary collimators with the beams. This might facilitate larger scan ranges, which would be an advantage for Van der Meer scans.

Optics measurements: Optics measurements were carried out on several occasions and revealed again the excellent quality of the machine. The experiments are interested in these measurements, in particular in the IR optics. The β^* values enter in the luminosity formula. When combined with emittance measurements, these data allow one to cross-check the luminosity numbers in a totally independent manner. They may also allow one to understand possible differences between the various IPs (in particular, IP1 and IP5). A systematic and formal publishing mechanism of these results is of interest to the experiments. In the future, with the decrease of β^* values, waist position measurements and hourglas effects will become important. In addition, forward experiments (such as TOTEM and ALFA) have stringent requirements on the measurements of the machine optics.

Injection: Towards the end of 2010, injection losses became large enough to provoke BCM-triggered dumps in LHCb. This was traced back to ejection of uncaptured beam from previous injections. This was temporarily circumvented by permanently increasing the fastest running sum threshold of the BCM system by a factor 3. For 2011, both ALICE and LHCb will implement a more sophisticated mechanism to mitigate the effect of injection losses. A kicker pre-pulse from the RF (point 4) will be used to reduce the thresholds during a short time. However, AL-

ICE and LHCb would like that ways to reduce the losses by cleaning in the LHC (and by shielding, in the long term ?) are pursued.

Handshake: Generally, handshake between the machine and experiments worked well. Minor issues with the exact timing of the procedures were discussed and revisited (e.g. removal of the "imminent" flag). Training of shift crews in the experiment control rooms will be further improved to avoid the occasional loss of time due to misunderstandings. It is important to remember that a handshake is only required when the machine is about to go from a safer state to a less safe state (as gauged by the experiments). Occasionally, a DUMP handshake was initiated while the machine was in ADJUST mode. This is not required (the DUMP mode is not considered less safe than the ADJUST mode for the detectors). The procedures and documentation are now being revisited for 2011 [7].

Data exchange: The principal mechanism for data exchange between the machine and experiments relies on DIP. The service worked relatively well in 2010. A few hiccups were observed. As an example, the LHC fill number was occasionally not correctly transmitted (or not changed at the source ?). On the experiments side, this generates book-keeping errors which need to be treated manually. A method to force the fill number change during the LHC cycle is being discussed. Mechanisms for automated restart of DIP servers and automated signalling of lost DIP services could and should be further developed.
The data published by the experiments were not always archived in the LHC Logging Database, for various reasons (lack of human resources on both sides, occasional service breakdown, insufficient data integrity, etc.). The LHC and the experiments could benefit from a better documentation (definition) of the data to be transmitted from the experiments to the LHC.
In order to alleviate the impact of the missing data, a separate (offline) path for data exchange was set up. Summary files provided by the experiments for physics fills were stored as text files in a dedicated storage space on AFS [8]. These files contain luminosity data and luminous region characterisation data (sizes and positions). Additionally, LHCb (and initially also CMS) provided individual beam sizes and positions from beam-gas imaging. Some experiments delivered data per bunch pair for some of the fills. An advantage of these data files is that the data can be regenerated by the experiments quite easily (for example, if new detector calibration data are available).
These data were used to analyse (specific) luminosities, also per colliding pair [9]. Unfortunately, the bunch-by-bunch data were not produced coherently by all experiments (incomplete data set).
In 2011, this independent data path will be maintained and possibly improved. The persistency of these data is an issue. The idea of allowing these offline data to be stored centrally in the LDB (or a new central database) should be considered.

Vacuum: Strong pressure rises in the neighborhood of the IPs have been observed toward the end of the 2010 proton run, when e-cloud effects became important. This has raised the question "how much pressure increase could the experiments tolerate during physics fills ?". A precise and definitive answer cannot be given. ATLAS has, for example, seen effects of the pressure rise on the jet rate (increase of the "fake" jet rate), although it is believed that means to reduce this effect could be implemented. In general, a pressure not exceeding 10^{-8} mbar seemed bearable. Nevertheless, the experience and impact of such vacuum degradations needs to be further investigated and monitored.

Ghost charge / satellite bunches: The amount of charge outside the nominal buckets ("ghost charge") was larger in certain fills. In some occasions, this was traced back to issues in the SPS (800 MHz cavities). However, the amount of ghost charge is also expected to increase with the reduction of bunch spacing (in bunch trains). The experiments were asked to re-assess their requirements on the amount of proton charge not contained in the nominal (colliding) RF buckets. As a starting point, it seems that a fraction of up to 5% ghost charge (relative to the total beam intensity) could be acceptable. However, as for vacuum pressure degradation, a definitive answer cannot be given. The effects should be further investigated and monitored. For the special case of luminosity calibration runs (typically with largely spaced bunches) the required limits on ghost charge are more stringent ($< 0.5\%$) and also depend on the ability to quantify the amount of ghost charge.

CONCLUSION

The LHC produced first pp physics collisions at $\sqrt{s} =$ 7 TeV in March 2010, starting with a luminosity of about $8 \cdot 10^{26}$ $\mathrm{Hz/cm^2}$ and finally reached $2 \cdot 10^{32}$ $\mathrm{Hz/cm^2}$ in October 2010, thus brilliantly surpassing the target.

The experiments took advantage of the gradual luminosity increase to step through (i) calibration of the detectors, (ii) "re-discovery" of particle physics (quarkonia, weak bosons, top quarks, ...), thus gauging the level of understanding of their detectors, and finally (iii) to actually produce physics results.

Cooperation between machine and experiments was again excellent and needs to be steadily continued, both for forthcoming operation and for offline data analysis. A detailed list of suggestions and points for possible improvements was presented. These now have to be followed up.

ACKNOWLEDGEMENTS

Above all, the experiments and myself would like to congratulate all our colleagues from the accelerator sector for the excellent work and for the truly impressive 2010 achievements.

My special thanks to Martin Aleksa, Federico Antinori, Nicola Bacchetta, Helmut Burkhardt, Tiziano Camporesi, Maria Chamizo, Mario Deile, Antonello Di Mauro, Chilo Garabatos, Benedetto Gorini, Richard Jacobsson, Daniela Macina, Anders Ryd, Andreas Schopper and Simon White for their feedback, for reading and correcting this paper.

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LHC OPERATIONAL EFFICIENCY IN 2010

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Abstract

An overlook on the beam and machine statistics in the 2010 run is given. We report on the machine availability and efficiency for physics and give a breakdown of the downtime according to the various technical systems. We revise the frequency and duration of the technical stops with respect to their impact on the machine availability. Finally the tools presently available for the collection of this kind of data are reviewed and needs for 2011 are defined.

INTRODUCTION

LHC beam operation in 2010 was mainly driven by commissioning activities, although a significant collision data set was eventually delivered to the experiments.

The time period considered in this paper spans from the 1st of March to November 30 (6600 hours). Machine statistics were collected by surveying the e-logbook and cross checking with minutes of various meetings and with logged data for the beam intensity. The machine states considered here are beam setup, stable beams, setup without beam (the joined time of these three being defined as the machine availability), technical stop and fault (machine not available due to some system fault). Time spent in supplementary hardware commissioning was included in technical stops.

MACHINE STATISTICS

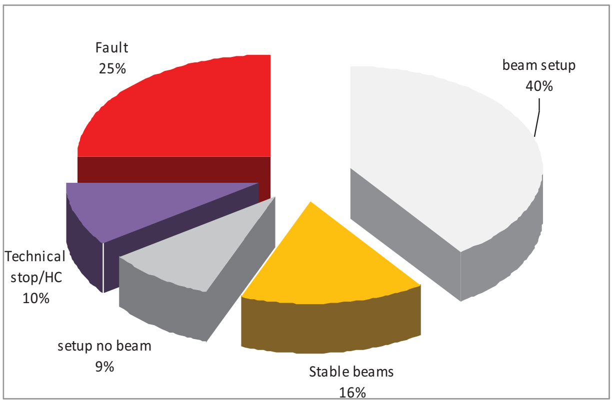

Fig. 1 Global 2010 machine statistics

Setup without beam

At the LHC, even with 100% availability, there would always be a physiological time without beam: the magnetic machine must be brought back to injection energy at the end of physics fills, and it needs to be pre cycled whenever the magnetic history deviates from the established standard, as for example after an access. In addition, the injectors have to prepare the required beam, which must be steered down the transfer lines and injected into the collider; a delicate operation in itself, which cannot always be carried out parasitically.

The time spent setting up the machine without beam was 9% of total. Cycling the machine as a consequence of faults was considered as downtime (machine not available) and attributed to the faulty system.

Beam setup

Under this category fall both the physiological phases with beam which are preliminary to collision data taking by the experiments (injection, adjustments at injection and at high energy, ramp, squeeze, steering of collisions); and all the machine commissioning and development with beam. These activities represent the highest fraction of total time (40%). Because of the way statistics were collected, this bin contains as well a good deal of inefficiencies, i.e. time when the beam was present but some problem was being handled (wrong settings, interpretation of doubtful measurements or unexpected events, struggles with the software, hesitation, panic, etc.), both during physics runs and during commissioning activities.

Stable beams

The time spent in stable beams was 16% of the total over the year. This rather low average was due to prevalence of the above mentioned commissioning periods. Figure 2 shows the evolution of this value along the run. In periods entirely devoted to physics we managed to have up to 29% of the time in stable beams. Noteworthy are the dips in June and in September, when the efforts were focused on commissioning the machine for higher intensities. Both were followed by an upward trend, which did not seem to reach saturation.

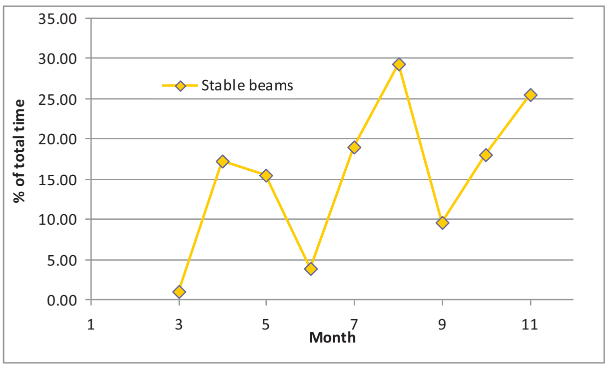

Fig. 2 Stable beams fraction along the run

Technical stops

There were six scheduled technical stops, with very little adjustments of the actual dates with respect to plans. The average duration of stops was 4 days, and the average spacing was 39 days. The main activities driving the frequency and the duration of technical stops were the maintenance of the cryogenics systems (de icing, replacement of malfunctioning valves), of the QPS (repair of quench heater power supplies, replacement of defective cards, etc), and replacement of power converter modules. In some cases hardware upgrades were carried out, for example to allow the QPS coping with higher current ramp rates in the main magnets. On these occasions some hardware commissioning had to follow the technical stop.

The time devoted to technical stops was 10% of total.

It is well known that maintenance activities, besides beneficial effects, can introduce new problems (as the say goes: as long as it works, do not touch it!). Trying to assess if the frequency of technical stops had been appropriate, I have considered the three days preceding and the three days following each technical stop and looked at the number of faults occurred in these two periods. Preventive maintenance reduces the number of faults after the technical stops, but on the other hand new problems appear. At the start of the run, the net result was that the number of faults after technical stop was (much) higher than before! However, in the course of the year, this phenomenon went decreasing and eventually it disappeared.

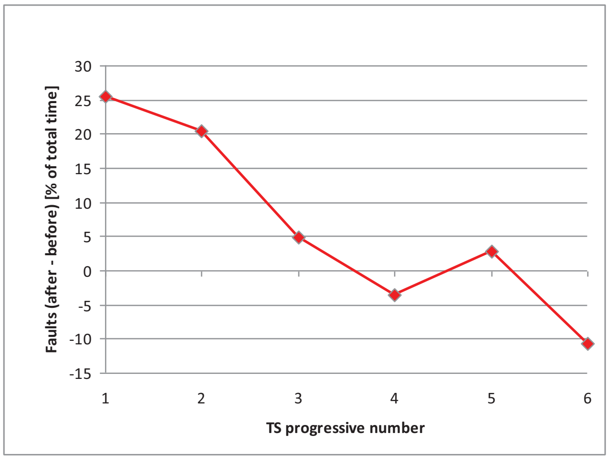

Fig. 3 Increment of faults after technical stop

Figure 3 shows the degradation (difference in downtime due to faults before and after technical stop), along the run.

Faults

The total downtime time due to faults (including the time needed to bring back the machine after the repair) was 25% of total. In many cases we had coupled faults, for example a QPS board would not come back after a trip due to a power converter fault, or a loss of cryogenics conditions or an electrical perturbation.

Faults statistics

The distribution of downtime according to the technical system is shown in figure 4.

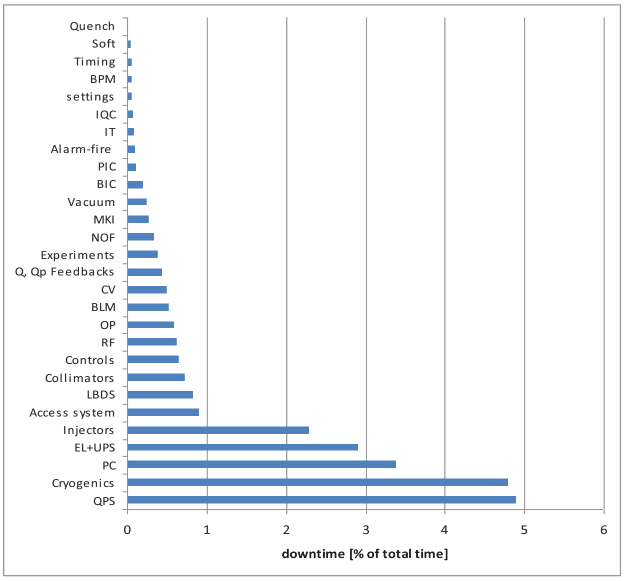

Fig. 4 histogram of LHC faults

Data are raw: no attempt was made to normalize the downtime to the complexity of the systems. Therefore it is no surprise that a hugely complex system such as the QPS it at the top of the score. Since the integral of the histogram equals 25%, numbers can be multiplied by four to get the fraction of downtime for a given system.

The faults statistics of such complex systems show that, although improvements are still possible, their reliability is already remarkable. As an example, Table 1 gives some details of the QPS "internal" statistics.

Equipment type	Faults	Quantity	Availability [%]	MTBF [hours]
Quench heater power supplies	26	6076	99.998	1145760
Quench detection systems	19	10438	99.999	3362135
DAQ caused by radiation (SEU)	12	1624	99.997	828240
DAQ other causes than radiation	8	2532	99.999	1936980
DAQ all faults combined	20	2532	99.997	774792
EE600	6	202	99.988	206040
EE13 kA	5	32	99.939	39168

Table 1 detailed QPS statistics (courtesy R. Denz)

Although less frequent, faults in the cryogenics systems, in particular cold compressor stops, have a big impact on the machine availability because of the long recovery times.

Power converters have the third position. Again, this is expected due to the large number of elements.

Electrical perturbations from the supply network are the fourth source of downtime; the immunity of the LHC to this kind of events is somewhat lower than that of the injectors. The cryogenics systems, present only in the LHC, were sensitive to electrical perturbations at the start of the run, but the cryogenics team managed to increase their immunity in the course of the year.

The injectors contributed to the downtime due to faults for a little more than 8%. This is not the downtime of the injectors, but the injector faults seen from the LHC, i.e. the cumulated time when the LHC was requiring beam and the injectors could not deliver it due to some internal fault.

These five systems alone account for 70% the downtime. The remaining 30% is shared among 23 other categories. It should be noted that "small" systems may have low MTBF without becoming "visible" in the statistics. Also, systems which give "small", i.e. easily recovered faults would create a "dust" of sub threshold incidents, which escape completely the present approach as they would not appear in the logs. Examples of this are small software bugs and many controls issues.

OPERATIONAL EFFICIENCY

For operational efficiency it is meant here the ability to use the available machine time in order to produce maximum integrated luminosity. It is the efficiency of the operations team running the machine in the control room. Once a refilling policy is given, there is a theoretical maximum fraction of the total time in which the machine can run in stable beams mode. In other words, operational efficiency is defined with respect to the minimum turnaround time.

It is useful to consider as well other definitions of efficiency: since after all the goal of the LHC is to produce integrated luminosity, then ultimately its efficiency is the fraction of runtime which is spent in stable beams. This is rather the efficiency of the collider, which considers downtime due to faults, technical stops, but also machine commissioning and development time as inefficiencies. Such a crude definition is certainly ungenerous, but not depleted of sense, from certain points of view. Other possible definitions would exclude some combination of machine commissioning, machine development time, and technical stops from the runtime. The so called Hubner factor was used at the time of LEP to relate the integrated luminosity to the peak luminosity and the scheduled time for physics [1]. In this case, operational inefficiency and hardware faults occurring during the scheduled physics time, but also the optimization of refilling, contribute to the final result.

As reported above, the LHC was producing luminosity in stable beams mode for 16% of the runtime in 2010.

Normalizing to the available time (i.e. not considering faults and technical stops) the resulting operational efficiency (for physics) would be 24% over the year. However that is not very meaningful as it includes commissioning and machine development in the operational inefficiencies.

During the last two weeks of August, when the only aim of the operation crews was to produce luminosity, the operational efficiency was 50%. This must be compared to the theoretical maximum, i.e. with minimum turnaround: in the period considered the operational efficiency could have been 83%, which indicates the margin for improvement from the side of operations. The analysis of operational inefficiencies is the subject of another contribution [2]

SUMMARY

The overall availability of the LHC during the first operation year was a remarkable 65% [Fig. 1], steadily increasing along the run.

The dominant activity was beam commissioning in a quest for higher intensities (first single bunch, then total), which eventually paid off with doubling of the luminosity goal for 2010 and delivery of ~50 pb^{-1} to the experiments.

Downtime due to faults amounted to 25% of the total; the top 5 systems were QPS, Cryogenics, EPC, EL-UPS, and the injectors. The hardware teams are working on identified weak points, although the reliability of the equipment is already very high.

Recovery from technical stops was initially troublesome, with a clearly visible degradation of the machine availability due to new faults after the stops. The detrimental effect of technical stops was steadily decreasing and disappeared at the end of the year.

Operational efficiency reached 50% (60% of the theoretical maximum) when running the machine in physics mode.

Finally, a word on tools: statistics are extremely important as they provide the input to understand and improve the exploitation of the LHC. Digging out the information from the logbook at the end of the year is time consuming and error prone. Automatic tools for data collection are missing, and needed for 2011.

ACKNOWLEDGEMENT

I like to thank R. Denz, S.Claudet, V. Montabonnet and M. Zerlauth for their help

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THE LHC RF: OPERATION 2010 AND PLANS FOR 2011

Reported by P. Baudrenghien, CERN, Geneva, Switzerland
for the LHC RF Team*

Abstract

We will first briefly present the intended RF operation, as of the original Design Report. We will then review the 2010 operation: from the first collisions of single bunch pilot to the emittance blow-up required for nominal single-bunch intensity. RF noise will be briefly mentioned and results of bunch lengthening during physics will be presented. The difficulties to fill the machine given the intolerance of the Beam Loss Monitors to radiation created by capture loss will be reminded. Ions operation will not be covered. There will be a brief summary of klystron and cavity faults. The second part will address 2011 operation. The planned improvements will be presented (tools to ease energy matching, longitudinal damper, klystron DC settings). Finally the cavity impedance issue will be revisited with emphasis on the stability with RF feedback and the scenario of a klystron trip will be studied.

HOW IT WAS INTENDED TO WORK

The LHC is a high-current collider (more than 0.5 A DC nominal) and this brings two challenges for the RF: the Cavity impedance must be reduced by orders of magnitude to keep the beam stable and to control transient beam loading, and the RF noise must be minimized to achieve a luminosity lifetime in excess of 20 hours. The design was optimized for those [1]: low R/Q (45 Ω) Superconducting Cavities are used for their low impedance for a given accelerating voltage. These cavities are single-cell, each with a private klystron. This brings much flexibility for improving performance using a strong RF feedback [2]. Movable couplers allow for high bandwidth when needed (damping of injection transients) and high voltage during physics. The loaded Q_L can be varied between 20k and more than 80k.

The LHC filling proceeds batch per batch in successive portions of the rings. To avoid phase errors while filling, the RF phase must be kept rigorously constant in the beam portion and in the no-beam portion, and this is achieved by the strong RF feedback. For a constant RF voltage, the transient beam loading will make the klystron demanded power different in the beam-on segment and in the no-beam segment, with the difference depending on the cavity tune. The "Half detuning" scheme was selected. It consists in detuning of cavity for half the beam current so that the power is identical during beam and no-beam portions, thereby minimizing the klystron peak power [3]

$$\frac{\Delta f}{f} = -\frac{1}{4} R/Q \frac{I_b}{V_{acc}} \tag{1}$$

where I_b is the RF component of the beam current and V_{acc} is the accelerating voltage per cavity. Once the half-detuning policy is enforced the klystron power is function of RF voltage, beam current and cavity loaded Q_L

$$P(x) = \frac{1}{8} \frac{V_{acc}^{\ 2}}{Q_L R/Q} + \frac{1}{2} Q_L R/Q \left[\frac{I_b}{4}\right]^2 \tag{2}$$

At injection a low Q_L is favourable for fast damping of momentum and phase errors. For 0.5 A DC (nominal current at the time), the original design proposed to use Q_L=20 k, 4.5 kHz detuning and 8 MV total (1 MV/cavity) at injection. The needed klystron power would be 167 kW. The 8 MV are well above matched capture voltage: in 2010 the SPS RF was set at 7.2 MV before transfer. The four-sigma bunch length was adjusted at 1.5 ns using longitudinal emittance blow-up. This results in 0.51 eVs. In the LHC the matched voltage would be 3.1 MV (0.51 eVs for a 1.5 ns bunch length). The Design Report was less optimistic on the SPS performances, specifying 0.7 eVs and 1.8 ns. This may indeed be the case with 25ns bunch spacing in the future. The margin in capture voltage may be needed with increasing intensity and emittance: there will be more bunch-to-bunch dispersion in the SPS bunch position (injection phase error) and length, and beam loading will be more severe. During physics the lifetime is limited by intra-beam scattering. The longitudinal emittance must be blown up to 2.5 eVs at 7 TeV. The intended RF settings for nominal intensity were 16 MV total with Q_L =60k and 2.25 kHz detuning at 7 TeV. The klystron power would have reached 270 kW for an RF saturation at 330 kW.

RF OPERATION 2010

Winter 2010. Single bunch towards nominal intensity

During the 2009-2010 shutdown, we had observed signs of overheating on the klystron collectors [4]. The supplier will modify the design but it will take several years before all sixteen klystrons are upgraded. Decision was taken to operate at reduced DC settings in 2010, thereby limiting the available RF power around 200 kW (instead of the nominal 330 kW). We first captured with 8 MV (Q_L =20k). At the end of the flat bottom the couplers were moved to Q_L =60k and the voltage raised to 12 MV before starting the ramp. Ramp and physics with a constant

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12 MV. Cogging worked very well: with the bunches injected to collide in the IPs at 450 GeV, the collision point does not drift during ramping. No need for rephasing at 3.5 TeV. The single-bunch cycle in the SPS produced low longitudinal emittances: around 0.25 eVs for the 5E9 p/bunch pilot and below 0.4 eVs for the 1.1E11 p/bunch nominal (SPS RF voltage 7.2 MV @ 200 MHz at transfer). The lifetime was very good. Bunch lengthening was as expected from adiabatic evolution in the ramp and nothing dramatic was observed when crossing the much feared 50 Hz synchrotron frequency. Figure 1 shows the four-sigma bunch length evolution measured by the Beam Quality Monitor (BQM), during one of the early ramps. The BQM is the LHC version of the system developed for the SPS [5]. It was not calibrated at the time. The bunch on the flat top is actually shorter than the indicated 700-750 ps. With single bunch pilots, the bunch lengthening was around 30 ps/hour at the 450 GeV injection energy (8 MV) and 6 ps/hour at 3.5 TeV (12 MV).

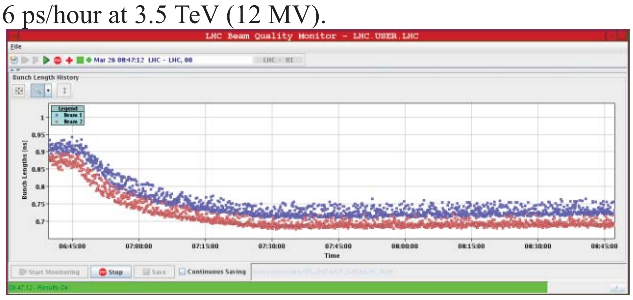

Figure 1: Four-sigma bunch length during the ramp. March 26. Single bunch pilot in both rings, ~ 0.2 eVs. 8 MV at injection (Ω_{s0} =65.3 Hz), increased to 12 MV before ramp (Ω_{s0} =80 Hz), constant 12 MV during acceleration ramp (Ω_{s0} =28.9 Hz @ 3.5 TeV).

Spring 2010. Ramping single bunch nominal intensity

At injection, the nominal intensity (1.1E11 p) single bunch was 1.2-1.3 ns long, with 0.3-0.4 eVs longitudinal emittance. The matched voltage is around 2.3- 3 MV and we decided to capture with 5 MV. We then raised the voltage to 8 MV before the start of the ramp. Ramping was done with a constant 8 MV. The bunch was violently unstable. During the ramp it shrank down below 500 ps resulting in loss of Landau damping (figure 2).

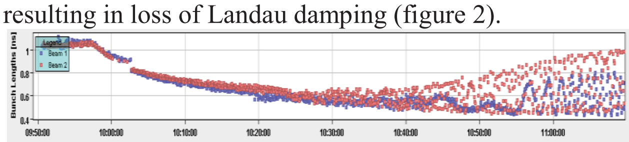

Figure 2: May 15th. First attempt to ramp nominal intensity single bunch. Bunch length during ramp. The longitudinal emittance is too low (< 0.4 eVs). The bunch becomes unstable when the length falls below 550 ps.

At the time longitudinal emittance blow-up was not available yet in the LHC but it was possible in the SPS [6]. So we decided to blow-up in the SPS to a length of 1.7 ns, maximum for injection in the LHC 400 MHz bucket. The longitudinal emittance became 0.6-0.7 eVs. We revised the voltage function in the LHC to better match the capture in order to preserve bunch length. After capture with 3.5 MV, the bunch would be 1.5-1.7 ns long. We raised the voltage linearly to 5.5 MV in the parabolic part of the momentum ramp, then kept it constant for the rest of the ramp and during physics. On May 28th a nominal intensity single bunch reached 3.5TeV, with a length of 0.8-0.9 ns providing Landau damping sufficient to preserve stability (figure3).

Figure 3: Single bunch nominal intensity. Fast BCT and four-sigma bunch length through the ramp. The bunch shrinks from 1.5-1.7 ns on the flat bottom to 0.8-0.9 ns at 3.5 TeV.

Summer 2010. Longitudinal emittance blow-up in the LHC ramp

Maximal blow-up in the SPS is not a lasting solution as it creates long bunches and results in capture loss at injection. Emittance blow-up in the LHC ramp is preferable. It is also needed for longitudinal stability at nominal intensity [7]. Blow-up in the LHC became operational on June 15th. The frequency of the synchrotron oscillation depends on the peak amplitude ϕ_{pk}

$$\Omega_s(\phi_{pk}) \approx \Omega_{s0}\left[1-\left(\frac{\phi_{pk}}{4}\right)^2\right] \tag{3}$$

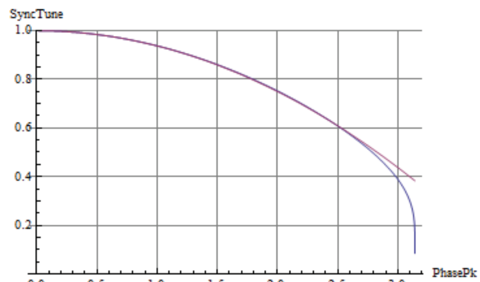

Figure 4: Ω_s/Ω_{s0} as a function of the maximum phase deviation in radian. Exact formula (bottom trace, blue) and approximation Equation (3). Non-accelerating bucket.

We modulate the RF with phase noise whose Power Spectral Density (PSD) covers only the synchrotron frequency band corresponding to the desired bunch length. For 1.2 ns four-sigma, we used

$$\frac{6}{7}\Omega_{s0} \le \Omega \le 1.1\Omega_{s0} \tag{4}$$

The upper frequency exceeds Ω_{s0} to be sure that we do not miss the core. Excitation is applied during the acceleration ramp. The spectrum of the phase noise tracks the changing Ω_{s0}. For a precise control of the bunch length we developed an algorithm that adjusts the amplitude of the excitation x_n from a measurement of the instantaneous bunch length (averaged over all bunches) L_n and comparison to the target L_0

$$\begin{aligned} &x_{n+1} = a.x_n + g.(L_0 - L_n) \\ &if \quad x_{n+1} \le 0 \quad then \quad 0 \rightarrow x_{n+1} \\ &if \quad x_{n+1} \ge 1 \quad then \quad 1 \rightarrow x_{n+1} \end{aligned} \tag{5}$$

The diffusion is fast at the beginning of the blow-up and tends to slow down with time. The parameters *a* and *g* are functions during the ramp, optimized for a precise and smooth blow-up. The target bunch length L_0 was originally set at 1.5 ns with 5 MV, and later reduced to 1.2 ns with 8 MV. After blow-up to 1.2 ns we obtain an emittance around 1.6 eVs at 3.5 TeV, with 8 MV. We could then reduce the SPS bunch length to 1.5 ns (~ 0.5 eVs) at transfer to the LHC.

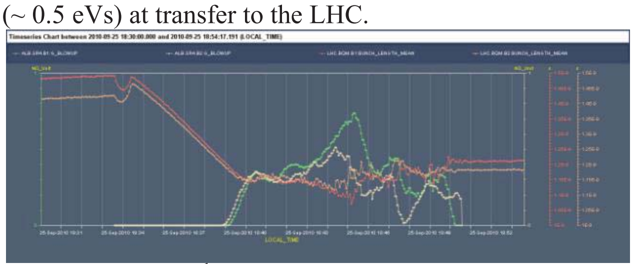

Figure 5: Sept 25th, fill 1372, 104 bunches/ring, 150 ns spacing. Bunch length and phase noise excitation level during ramping.

Another feature of the blow-up is the reduction of the dispersion in bunch length: at injection we would typically have ±200 ps variation between the various bunches. After blow-up in the LHC it would be reduced to ±40 ps. This favorable behavior, observed in the SPS also, is not very intuitive as the noise excitation is common to all the bunches of one ring.

Autumn 2010. Increasing the number of bunches, 150 ns and 50 ns spacing

Begin September we reconfigured the RF for higher intensity (batch of bunches with 150 ns spacing) and faster ramp: without active feedback a cavity presents a very large impedance to the beam and that can drive Coupled-Bunch instabilities. We therefore switched all klystrons on. So far we had observed no bunch lengthening in physics, beyond the 1.5 ns target bunch length. Suspicions came that some particles (the tails of the bunch) were lost out of the bucket. So it was decided to reduce the target bunch length to 1.2 ns and increase the voltage to 8 MV in order to keep 1.6 eVs emittance, sufficient to reduce the damaging effect of Intra-Beam Scattering. Capture voltage was set to 4 MV with a cavity Q_L=20k. To limit dissipation in the klystron collectors we set all cavities at 1 MV (~150 kW) and used ±60 degrees counter-phasing per pair. The counter-phasing was zeroed at the beginning of the ramp, then the voltage was increased linearly from 4 MV to 8 MV during the ramp. This resulted in a more gentle bunch length reduction than with the previous voltage rise in the parabolic part of the ramp only. The blow-up shown on figure 5 corresponds to these new RF settings.

The 150 ns bunch spacing did not cause any problem. However, with the increased number of injections, the injection dump would fire on occasion, triggered by radiation measured by the Beam Loss Monitors (BLM) and found above threshold. The problem was traced to a small amount of beam, un-captured at each injection, and slowly drifting in the machine. When the next bunch or batch is injected behind the previously injected one, the kicker deflects the un-bunched beam in the 8 μs long kicker window. This un-bunched beam then hits the TDI, causing radiation that propagates in the tunnel, hits the BLMs on the cold magnets downstream, and are wrongly considered as loss of circulating beam. The BLM system then triggers the dump. The situation worsens with the number of injections as the Beam Phase loop efficiency decreases. The sensitivity of the BLM towards capture loss was calibrated and we found the dump level to be at an un-bunched beam line density of 3.3E6 p/m or a maximum loss per injection of ~9E9 p (8 μs long kicker window). The above capture loss mechanism was studied in 2003 with the concern of un-bunched beam in the abort gap. The allowance was one hundred times larger than today's dump level [8]. The situation got even worse when trying 50 ns spacing in October: as the bunches are placed closer together and with more intensity in the SPS, we have more dispersion in bunch position and length along the batch resulting in more un-captured beam [9].

Transfer from the SPS 200 MHz bucket into the LHC 400 MHz bucket cannot be done without loss. Unavoidable tails in the SPS 1.5 ns long bunch will fall outside the LHC bucket. The RF team hopes to keep capture loss below 1% per injected batch. With 4x72 nominal intensity bunches per batch, the 1% results in 3.2E11 p loss/inj, a factor 35 above the present dump level. To operate reasonably at nominal intensity, the sensitivity of the BLM dump system to injection loss must therefore be decreased by 2 orders of magnitude.

If the injection goes OK, the LHC can tolerate capture loss. On Oct 27th, with 368 bunches injected, 4.3E13 p total per beam, Cav4B1 started generating significant RF noise resulting in severe debunching. It was decided to start ramping anyway and 3.5 % of the total intensity got lost (1.6E12 p) on the momentum collimators (figure 6). The fill proceeded to physics smoothly.

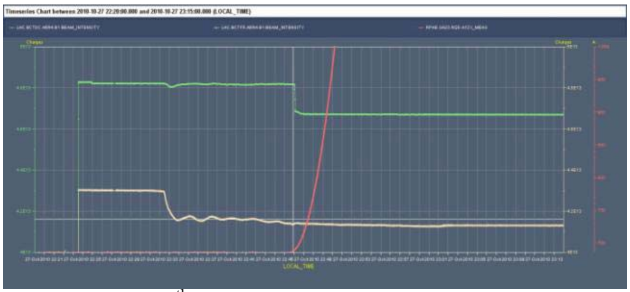

Figure 6: Oct 27th, fill 1450, 150 ns spacing, 368 bunches, 4.3E13 p total per beam. Beam 1 Fast BCT (beige), DC BCT (green) at beginning of ramp (red). The loss corresponds to 1.6E12 p.

Another interesting observation is the natural cleaning of the abort gap at 3.5 TeV. Later in fill 1450, the HV Power Supply feeding the first four klystrons of beam 1 tripped twice. Cav4B1 had been switched off-line following the noise problem mentioned above and the 8 MV re-distributed over the remaining seven cavities. When the power supply tripped, the voltage therefore dropped from 8 MV to 4.57 MV, resulting in small debunching and increase of bunch length (from 1.23 ns to 1.43 ns). The abort gap got populated at each trip. But the operation crew restarted the Power Supply and put the three cavities back on with barely any loss (figure 7).

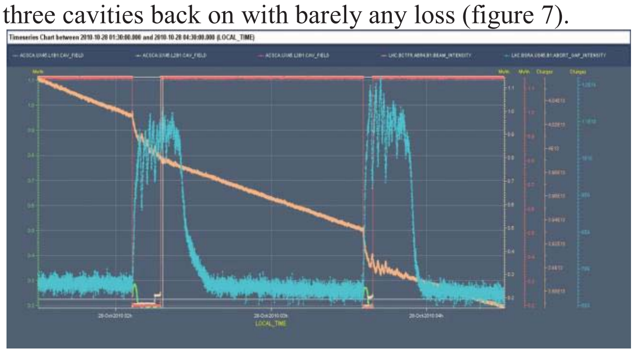

Figure 7: Fast BCT (orange) on a much enlarged scale, Abort Gap Population (blue) and Cav1B1, Cav2B1 and Cav3B1 field.

Notice that the cleaning of the abort gap does not depend on the time when the cavities are switched back on but takes place ~15 min after the cavities where switched off. That is the time for the debunched beam to move to the momentum collimator. The particles lost from the buckets loose energy through synchrotron radiation. The ones that were below the acceptance energy drift radially inwards till they hit the momentum collimator. The ones that had excess energy first surf on the buckets in phase space until they cross between buckets and move to the lower energy side. They then drift and hit the collimator.

The Cavity Controllers have a sequencer to handle this recovery after a trip. When a klystron or RF power converter trips, the LLRF loop settings (tuner position, klystron polar loop gain and phase) are frozen. When the veto condition is removed and OP sends the RF ON command, the voltage set-point gently returns to the demanded value and the loops are active again. Only the loss of cryogenic conditions on a module would make the RF fire the beam dump.

At 3.5 TeV the Synchrotron Radiation damping time is about two hundred hours. The target for longitudinal emittance blow-up growth time caused by RF noise was 13 hours minimum at 7 TeV (equal to the synchrotron radiation damping time at that energy). RF noise was a major concern during LHC design: klystrons convert HV ripples in phase modulation whose frequencies are harmonics of 50 Hz, extending to 600 Hz in the LHC. During acceleration the synchrotron frequency crosses the 50 Hz line and problems were expected. The LLRF was therefore designed to reduce noise sources and minimize their impact on the beam. Figure 8 shows the bunch length evolution during fill 1444. Observe the fast bunch lengthening during the first 60 min at 450 GeV (250 ps/hour), the reduction caused by the 15 minutes long accelerating ramp with controlled emittance blow-up, and the slow 15 ps/hour lengthening during physics.

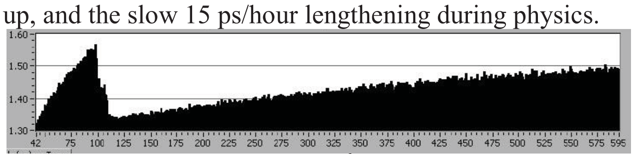

Figure 8: Fill 1444, Oct 26th, 150 ns spacing, 368 bunches. Horizontal axis in minutes. Vertical: bunch length in ns. The above data have not been corrected for the bandwidth of the measurement chain. The bunch length is over-estimated by 100-200 ps.

Figure 9 corresponds to the same fill. Shown are the profiles of bunch 1, beam 1 at various moments in the fill. RF noise was finally not a problem in 2010.

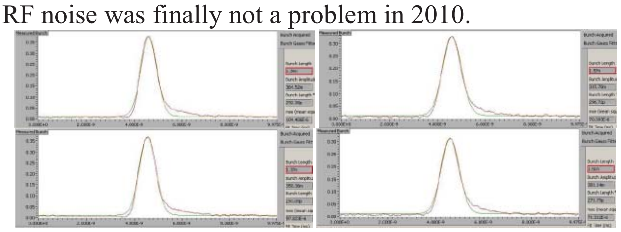

Figure 9: Fill 1444 as above. Longitudinal bunch profiles at different times, 3 GHz BW. Top left: injection, 1.34 ns long. Top right: start ramp, 1.57 ns long. Bottom left: end ramp, 1.37 ns long. Bottom right: end physics, 1.51 ns. The bunch length is over-estimated by 100-200 ps.

RF problems

The following problems were observed

- Waveguide arcing: the problem arose when increasing the beam current in fall. Arcing would happen close to the main coupler and was thought to be caused by radiation. It was solved by ANDing the detector signals by pair.
- Klystron vacuum: the fault affected K2B1 (klystron 2, beam 1) mainly. It was switched off-line for the remaining of the run and will be replaced during the shutdown.
- Main Coupler Blowers: false alarm from the air pressure detectors. The problem was solved by using

the air flow in/out temperature as redundant measurements for validating the fault.

- Oscillation in the filament heater circuitry in K2B1. There was a real problem with the Cathode Current tetrode. It has been replaced.
- Quenches: observed on all four modules but more frequent on M1B2 (module 1, beam 2). We have recorded one quench every two weeks on the average. These result in a beam dump triggered by the RF.
- Crowbar on the HV supply: there was a real problem with the thyratron for M2B1. It was replaced on week 42.
- Spurious in the klystron drive: we have observed three spurious lines at 340 kHz, 490 kHz and 670 kHz in the drive of all klystrons. It has no effect on the beam and is present without beam. It however requests a significant power from the klystrons. We will investigate it during re-commissioning.
- RF noise on Cav4B1: first observed towards the end of a physics fill on early morning Sept 26th. It was visible on the bunch length monitoring (the trace became a bit more noisy) but did not affect the luminosity. Later re-filling became impossible however as debunching was very fast at 450 GeV. The problem could be reproduced without beam but never lasted long. It died out as soon as voltage or frequency was changed. We have replaced all modules in the LLRF and tried to put the cavity back in service on Oct 27th. After ten hours of quiet operation, the problem came back (figure 6). Cav4B1 has not been operational since. The problem must be understood.
- Cav7B2 became noisy at high current levels (48 bunches per batch) during the 75 ns scrubbing run (Nov 18th-19th). There was a clear correlation between the injections and the cavity field ripples. No problem was observed with the 150 ns spacing or with the injection of 24 bunches batches at 75 ns spacing.

PLANS FOR 2011

The following new features will be developed and deployed through the year.

SPS-LHC Phase-Energy matching

Figure 10 shows the display used by the operation to monitor the SPS-LHC longitudinal injection transients in 2010.

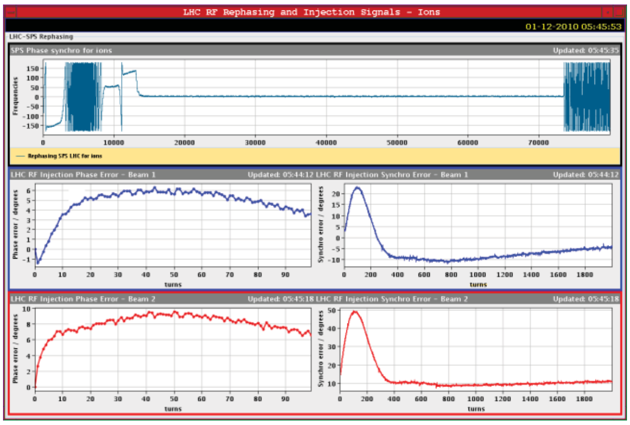

Figure 10: The top trace shows the LHC-SPS phase beat. It monitors the rephasing. The horizontal axis is labeled in SPS turn (23 μs/turn). The other four traces show: Phase Loop (left) and Synchro Loop (right) injection transients. Beam 1 (blue) and 2 (red). Horizontal axis in LHC turns (89 μs revolution period).

The OP crew would correct the injection phase error for each beam, estimate the energy (frequency) error from the Synchro Loop transients and trim the injection frequency to reach a best compromise between the two rings, while keeping the radial position of the circulating (captured) beam close to centre. An application will be developed to help the OP with these adjustments in 2011 (estimation of the errors and proposed corrections).

Longitudinal damper for injection errors

The LHC does not have a dedicated longitudinal kicker. Unlike in the transverse plane, Landau damping is sufficient to keep the nominal intensity beam stable in the longitudinal plane. But some damping of the longitudinal errors would be highly desirable at each batch injection to minimize capture loss. With the strong RF feedback, we can precisely control the field in the RF cavities. In the LHC, small-signal field change is possible in ~1 μs [2], which is the time separation between the successive batches at injection. By quickly modulating the phase of the cavity field between the batches, we can give momentum kicks to the incoming batch only, while keeping the field quiet for the circulating bunches. PEPII used a similar system that they nicknamed the Sub-Woofer as it would take care of the lower frequency part of the damping bandwidth. (The high frequency part was sent to a real longitudinal kicker).

In the absence of a real kicker, the LHC longitudinal damper will allow for the correction of the average phase and energy error at each batch injection. The bandwidth is not sufficient to correct for the bunch to bunch variations within a batch. The LLRF feedback loop can change the cavity field in 1 μs in the small-signal regime but, in order to give an effective momentum kick to the beam, we need klystron power to get the injection errors damped within a few synchrotron periods. Otherwise filamentation and loss will take place before sufficient damping effect. These considerations will be important for the optimization of the klystron DC settings in 2011 (see below). Dedicated Machine Development time will be needed.

Changing klystron DC settings between filling and ramping

In 2010 the klystron DC settings have been reduced to 50kV/8A to protect the collectors [4] resulting in a 400 kW DC power and a saturated RF power around 200 kW. We would like to operate with a used RF power between 100 kW and 150 kW because

- Below 100 kW RF, we dissipate more than 300 kW in the collector and that could lead to damage
- Above 150 kW RF the klystron gain drops as we get close to saturation. That makes the LLRF loops less efficient.

During physics in 2011, we plan to further increase the longitudinal emittance by raising the total voltage to 14 MV (1.75 MV/cavity). This is very close to the original design (16 MV). With Q_L=60k and 1.75 MV/cavity we need 142 kW per klystron with zero beam intensity and 155 kW at 1/3 nominal (0.193 A DC). These RF power levels are perfectly compatible with the present DC settings (50kV/8A). For the ions run in November we have operated reliably with 1.75 MV/cavity.

At injection, we will keep the voltage almost matched to the SPS emittance (4 MV total) and work with the lowest loaded Q (Q_L=20k). With 0.5 MV/cavity the needed RF power will be 35 kW with zero beam current and 39 kW with 1/3 nominal. That is not compatible with 400 kW DC power. It would result in too large a power dissipated in the collector (>360 kW). In 2010 we set all cavities at 1 MV and used ±60 degrees counter-phasing per pair to reduce the total voltage to 4 MV. But counter-phasing is not a solution with high beam intensity: the beam requires excess power from the klystron feeding the accelerating cavity and reduces the requested power in the decelerating cavity klystron. The solution is to operate with reduced klystron DC settings during filling. It will also increase klystron lifetime. As mentioned in the previous section, the actual needed peak power will depend on the longitudinal damper's needs. The scenario is

- Filling with 46kV/7.6A DC (350 kW DC) settings or somewhat below
- Change to 50kV/8A (400 kW DC) before ramp
- Ramp/physics with 50kV/8A

The variation of DC parameters with circulating beam and all LLRF loops operational has been tested on Oct 27th. The RF team needs time to commission it towards the end of the shutdown and with beam.

SURVIVING A KLYSTRON TRIP

This section is concerned with the longitudinal Coupled-Bunch Instability caused by the impedance of the RF cavity at the fundamental. The analysis is much simplified: we use formulas applicable to bunches short compared to the bucket width and consider dipole mode only. A more complete analysis will be presented at the Chamonix workshop. The growth rate and tune shift of coupled-bunch mode *l* (dipole only) can be computed from the cavity impedance

$$\sigma_l + j\Delta\omega_l = -\frac{\eta\, q\, I_0}{2\beta^2\,\Omega_s\, E\, T_{rev}} \sum_{p=-\infty}^{\infty} \omega Z(\omega) \qquad (6)$$

With

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} \qquad (7)$$

and

$$\omega = (p.h + l)\omega_{rev} + \Omega_s \qquad (8)$$

For a cavity at the fundamental, only two terms in the above infinite sum are not negligible: *p*=1 and *p*=-1. The impedance *Z(ω)* is modified much by the LLRF feedback. The above equation can be used to analyze different configurations. The exercise was done independently by the author (using a simple linear model for the RF feedback loop) and by the US-LARP collaboration (with a complex model including klystron non-linearity, finite bunch length and fine optimization of the LLRF loops). Both results will be listed, with the one from the simple model first and the prediction from the more complex model between brackets. Stability is preserved if the growth rate is significantly smaller than the tune spread [10]

$$\sigma_l < \frac{\Delta\Omega_s}{4} \qquad (9)$$

With tune spread function of the 4-sigma bunch length *L*

$$\Delta\Omega_s = \Omega_s \frac{\pi^2}{16}\left(\frac{hL}{2\pi R}\right)^2 \qquad (10)$$

3.5 TeV conditions

We consider the following longitudinal parameters: 14 MV, cavities at half detuning (3 kHz), 1.2 ns bunch length (4-sigma) and nominal beam current 0.58 A DC. The synchrotron frequency is 31 Hz. $\Delta\Omega_s/4 = 7s^{-1}$.

With RF feedback only, the maximum growth rate is $0.013s^{-1}$ per cavity ($0.005s^{-1}$ predicted with the more complex LLRF model) and the max tune shift 0.07 Hz/cavity while the tune spread is 4.4 Hz. The corresponding mode number is $l \approx -12$.

So the 8 cavities will give a total growth rate of $0.1s^{-1}$ ($0.04s^{-1}$), that is a good order of magnitude below the $7s^{-1}$ Landau damping. The growth rate is however very sensitive to the correct adjustment of the RF feedback Open-Loop phase. If that phase drifts by 10 degrees, the growth rate is multiplied by 10.

If a cavity trips during physics, it sits, without impedance reduction, at the 3 kHz detuning. Its contribution to the growth rate jumps to $1s^{-1}$ ($0.87s^{-1}$), with 1 Hz tune shift, still OK given the $7s^{-1}$ damping.

In 2010 we have survived a trip of 3 out of 7 cavities during physics at 12% nominal current (figure 7).

Conclusions for 3.5 TeV

- From the stability point of view we can survive a klystron trip during physics
- However when a klystron trips at nominal, the beam induced voltage in the idling cavity will much exceed 2 MV and the RF power dissipated in the load will exceed 300 kW [11]. Figure 7 shows a 200 kV beam induced voltage with 3.9E13 p and Q_L=30 k. Scaling it to nominal beam and Q_L=60 k, we get 3.3 MV that exceeds the maximum field at which the cavities are conditioned. **Above half nominal, the RF will trigger the beam dump when one klystron trips to protect the idling cavity and its circulator load**

450GeV conditions

We now consider the situation during filling: 4 MV RF, cavities at half detuning (10 kHz), 1.5 ns bunch length (4-sigma) and nominal beam current 0.58 A DC. The synchrotron frequency is 46 Hz. The Landau damping $\Delta\Omega_s/4=16s^{-1}$.

With RF feedback only, the maximum growth rate is $0.2s^{-1}$ ($0.19s^{-1}$) per cavity and the tune shift 0.3 Hz/cavity, to be compared to a 10 Hz tune spread. The corresponding mode number is $l \approx$-12. The large growth rate (compared to the 3.5 TeV situation) is due to the large detuning that is not strictly needed with only 4 MV. Deviating from a strict half-detuning policy, and with 5 kHz detuning only, the growth rate drops to $0.1s^{-1}$ ($0.135s^{-1}$) per cavity.

So the 8 cavities will give a total growth rate of $1.6s^{-1}$ ($1.53s^{-1}$) or $0.8s^{-1}$ ($1.08s^{-1}$) for 10 kHz and 5 kHz detuning respectively. That is still comfortably below the $16s^{-1}$ Landau damping. Notice however that the margin is reduced compared to the 3.5 TeV case. The 1-T feedback would help at injection.

If a cavity trips towards the end of the filling, its contribution to the growth rate and tune shift jumps to $15s^{-1}$ and 2.4 Hz (10 kHz detuning) or $8.5s^{-1}$ and 3 Hz (5 kHz detuning). With the larger detuning we probably loose the beam on mode l=-1, while it should remain stable with the smaller detuning.

Conclusions for 450 GeV

- **Cavity trip towards the end of filling is fatal at nominal intensity with half detuning. It could be survived at half nominal**
- To keep Landau damping at injection we should not reduce the SPS bunch length below the present 1.5 ns
- When approaching nominal intensity we should re-consider the detuning during filling.

Filling with one klystron off

If one klystron or cavity is off, we would "park" the cavity, that is detune it maximally (100 kHz detuning) and enter the coupler to reduce its Q_L to 20k. In the conditions considered above (4 MV total from the remaining seven cavities and nominal beam current 0.58 A DC) the growth rate caused by the un-damped cavity would be

- $20s^{-1}$ if its tune happens to be on a revolution frequency line
- $15s^{-1}$ ($7.45s^{-1}$) if its tune is just in between two revolution frequency lines

Conclusions

- Recalling the $16s^{-1}$ Landau damping at injection, **re-fill with one line off will not be possible much above half nominal**
- In 2010 we have operated comfortably with one line off at ~12% nominal

CONCLUSIONS

In 2010 the LHC has made physics with 12% nominal intensity: 368 bunches with 150 ns spacing. From the beginning of the intensity increase in September (batch injection with 150 ns spacing), the following longitudinal parameters have been used

- Filling: 1.5 ns long, 0.51 eVs bunches from the SPS (7.2 MV @ 200 MHz) captured with 4 MV RF (for a matched voltage between 2.3 and 3 MV)
- Ramping: linear voltage ramp from 4 MV to 8 MV. Longitudinal emittance blow-up to 1.2 ns length: as soon as the bunch length is reduced to 1.2 ns by the ramping, it is kept at this target value for the rest of the ramp
- Physics: 8 MV.

The bunch lengthening observed in physics was 15 ps/hour, probably mainly caused by IBS. There has been no visible effect of the RF noise. Neither did we find any problem related to the intensity increase.

The main difficulty in 2010 has been the very high sensitivity of the BLMs to capture loss. A series of improvements are being made in the BI and CO groups (shielding, injection gap cleaning, sunglasses at injection). The longitudinal damper will also help. Machine Development time will be needed for its commissioning.

RF reliability has been very good in 2010. The beam stability considerations presented above indicate that we can survive a klystron trip and operate with one klystron off, up to half nominal intensity. The RF should not be responsible for much down time in 2011 either.

We will start 2011 with the same longitudinal parameters as 2010, except for the RF voltage at 3.5 TeV that will be increased to 14 MV. We have used 1.7 MV/cavity during the ions run in November without problem.

On the RF hardware side the main operational difference with respect to 2010 will be the variation of the klystron DC settings (HV and Cathode current) between filling and start ramp. Time is required towards the end of the shutdown for measurement of the klystron characteristics at varying DC settings, plus some MD time for optimization with beam.

The only clouds in this very bright picture are the problems observed with Cav4B1 (intermittent RF noise observed with and without beam) and Cav7B2 (RF noise observed with the injection of 48 bunches at 75 ns spacing). These two cavities will be conditioned first as soon as the HV power supplies can be switched back on and we will concentrate on them in the last weeks of the shutdown.

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BEAM QUALITY AND AVAILABILITY FROM THE INJECTORS

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Abstract

The success of the first year of operation of the LHC would not have been possible without the hard work from the whole injector chain. Beams with different intensity, emittance and bunch spacing have been produced and tuned according to the often varying needs of the LHC. A review of the produced beam parameters is given, as for example transverse and longitudinal emittances, equality between bunches, presence of satellites. Additionally a critical view on how time could have been saved and which tools could be improved for the future is also given.

INTRODUCTION

This paper presents an overview of many aspects of the operation of the LHC injector chain as seen from the point of view of LHC operations. A list of the produced beam types is given, highlighting the flexibility of the injector chain. Some considerations on the transverse plain are presented, as the techniques used to perform emittance blow up, a short overview on the SPS scraper and on transverse size measurements. The subject of intensity measurements and bunch-to-bunch equality are treated next, followed by a short introduction on the SPS Beam Quality Monitor (BQMSPS) and lists of improvements foreseen for the SPS and PS RF. Some considerations on satellite bunches are also included. All along, possible improvements are highlighted when needed, as for example equipment which needs to become Pulse-to-Pulse Modulated (PPM).

BEAM PARAMETERS IN 2010

The progress of the LHC machine during the year 2010 has been impressive, and one of the factors that contributed to that is the flexibility of the injector chain in delivering different beam parameters according to the changing needs.

The PSB determines the transverse emittance of the beam and thus its intensity through the number of turns injected from Linac2 (multi-turn injection). At the PS the longitudinal structure of the beam is fixed as the RF splittings define the bunch spacing. Additionally transverse blow up can be performed. At the SPS more transverse blow up can be performed, longitudinal blow up is also available and PS batches are packed together so to minimize the number of injections at the LHC.

On March 30th 2010 the first stable beams at 3.5 TeV/c were declared, beams consisting of 2 pilot bunches per beam. Low intensity single bunches were injected until May, when the LHC started taking single nominal bunches. In July a campaign of injection studies allowed the first multi-bunch injections, with four bunches extracted from the SPS at a time. Time was allocated in September for bunch train setting up where the bunch spacing was 150 ns and 8-16-24-32 bunches were injected at a time. In November lead ions were injected at the LHC as single, then four and eigth bunches per injection, interleaved by a couple of short runs with both 75 and 50 ns proton beams. This meant that the LHC took 1 to 3 PSB rings, in 1 to 4 PS batches, different batch spacing at the SPS and different bunch spacing at the LHC (50, 75, 150, 500, 1000, 1250, 2500 ns). This while increasing the bunch intensity, decreasing the transverse emittance, and playing around with longitudinal emittance.

The possible multibunch types of beam are listed in Table 1 along with their intensities and transverse emittances [1]. The last two columns in the table indicate which beams were taken at the LHC in 2010 and which were used during Machine Developments (MDs) at the injectors up to the SPS.

Table 1: LHC multibunch beams characteristics in the injectors (◇ for single batch production, ○ for double batch production). The emittances are given at PSB extraction (1 σ normalized).

Type of beam	ppb@SPS [$\times 10^{11}$]	$\epsilon_x + \epsilon_y$ (μm)	to LHC	to SPS
150 ns (◇)	1.1$\times 10^{11}$	2.5	√	√
75 ns (◇)	1.1$\times 10^{11}$	3.5	√	√
50 ns (◇)	1.1$\times 10^{11}$	5	√	√
25 ns (○)	1.1$\times 10^{11}$	5		√
ultim. 50 ns (◇)	1.6$\times 10^{11}$	7		√
ultim. 25 ns (○)	1.7$\times 10^{11}$	8		√
50 ns (○)	1.1$\times 10^{11}$	3		

It has to be noted that the 75 ns and 150 ns beams are produced with emittances that are much smaller than nominal and require tranverse blow up at the downstream machines. The 50 ns beams are now operationally produced with single batch injections from the PSB; the double batch version that was operational until 2008 allows smaller transverse emittances. Ultimate intensity beams consist of 1.6/1.7$\times 10^{11}$ ppb and were first studied during MDs up to the SPS in 2010 in 25 ns and 50 ns configurations. To be noted that for these MDs the losses at the SPS were still significant and the emittances were not optimized.

TRANSVERSE SIZE

Transverse blow up

In the LHC Design Report the nominal values for the transverse emittances are 3.5 μm rad at the LHC injection, but many types of beams are produced with smaller values (see Table 1). While at the PSB controlled emittance blow up cannot be performed in a reproducible fashion, reliable techniques were found and used at both the PS and SPS.

At the PS [2] transverse blow up was performed by changing the tune and coupling the two planes. This method consists of one knob only, is inherently PPM and gives very reproducible results. Additional controlled blow up at the SPS was needed as the PS transverse blow up was not sufficient to reach nominal emittances.

Also other techniques were experimented at the PS, namely mis-steering of injection trajectories and injection optics, but in both cases the amount of obtained blow up was not sufficient. To be noted that the transverse damper in combination with powering the octupoles is used in the case of multi-turn extraction cycles, but could not be used for LHC-type beams as its controls are not PPM.

At the SPS the transverse damper is used to apply the excitation and perform the controlled blow up [3]. Powering the octupoles provides a large and defined tune spread that tends to minimize the creation of tails. The controls for this method are unfortunately not PPM and not integrated into the SPS control system, and this complicates the procedures the SPS shift crews have to follow in order to use the blow up.

An upgrade of the system is on the list of BE-RF-CS projects and is based on the use of a CVORG board (developed by BE-CO), also foreseen to be used for the longitudinal blow up. It has to be noted that the current verifications on orbit, tune and chromaticity will still be required after the hardware improvements as this technique will still need reproducible tunes, tune spread and chromaticity.

Scraping

In [4] it was foreseen to “clean the tails of the beam distribution down to 3-3.5σ by means of fast scrapers” at the SPS.

In 2010 only one scraper was available, installed in sextant 5 [5]. The main showstopper was that the cables which hold the counterweight broke four times over the run, requiring each time an access to fix them. In order to increase the mean time between failures, the scraper was later in the run turned on only when filling the LHC, effectively reducing the time it was on, but also delaying shortly the start of the filling process to allow the final and fine tune of beam parameters. Additionally the scraper rest position is too close to the beam and this often caused the scraping to happen already at injection rather than only at the flat top.

One additional scraper is planned to be installed in sextant 1 in 2011, followed later in the year by one spare. The fragile cables will be substituted with springs, and it is planned to move the scraper in as late as possible in the cycle in order to avoid scraping at injection. Beam Loss Monitors will also be added in the long term for scraper protection.

It has to be noted that throughout the year extra transverse blow up was needed due to the fact that the scraper often scraped 5% of the beam, rather than the tails only.

Transverse size measurement

Concerning transverse measurements, none of the injectors has a continuous, online, non-destructive measurement of transverse size during acceleration, nor bunch-by-bunch measurements are possible. The only measurement system consists of the wire scanners, which require a manual action (the operator decides to “fly the wire”).

Concerning the PSB wire scanners, measurements were carried out from operations and benchmarked against SEM grids. The result [6] is that they are now considered to work reliably and can be used more easily thanks to the new saturation detection algorithm. Concerning the PS wires, one outstanding issue which still remains is the mechanical fatigue of the bellows, which does not allow for repeated multiple measurements, impacting heavily on the acquisition of statistics.

Due to the small emittance and low intensity of the LHC beams, the linear wire scanners (517) are required at the SPS to get precise/accurate measurements. Unfortunately this system is currently unavailable. A full system upgrade is planned, which involves the use of LHC electronics and a software upgrade that includes the saturation detection algorithm from the PSB developments. It would be important to also include the correction for the known systematic errors between “in” and “out” measurements, which can be tackled by either the hardware or software side. A list of SPS wire scanner systems, with statuses and foreseen upgrades is shown in Table 2 [7].

Table 2: List of SPS wire scanner systems, status and foreseen upgrades.

Device	Scanner Type	Electr.	Status	2011 run
414 h	rot.long	90’s	motion card issue	
414 v	rot. long	90’s	OK	
416 h,v	rot.short	LHC	OK	sw upgrade 40 MHz test
517 h,v	linear	90’s	not avail.	hw+sw upgr. 40 MHz test
519 h,v	rot.long	90’s	OK	
521 h,v	linear	90’s	OK	

INTENSITY

In 2010 the LHC shift crew would decide which intensity they wanted, pass the request onto the SPS crew that then would ask the PSB to regulate the number of turns injected from LINAC2 such that, including the losses along the chain, the required value per bunch would be found at extraction from the SPS.

The workhorse for intensity measurements is the DC-BCT (Beam Current Transformer), for which the agreement between the SPS-ring and PS-ring intensity is very good. Minor flaw is that for now the threshold on DC noise level is only an expert setting and can be found to be not perfectly regulated, resulting in an offset in the BCT measurement which for example still gives a reading even after the beam has been dumped.

The intensity per bunch was manually derived from the total intensity at extraction by dividing by the number of bunches. That is because unfortunately the reading of the fast-BCT is often not well calibrated and cannot be trusted in absolute value, but only in relative terms for an indication of bunch to bunch equality.

Concerning the PS measurements, more sensitive electronics for low-intensity beams is to be commissioned, and a follow-up from BI was agreed on which implies removing the auto-calibration feature (which should improve cross calibration between ring and TT2 transformers).

BUNCH-TO-BUNCH EQUALITY

From [8], "fluctuations inside the bunch train in intensity, bunch length and transverse emittances are within 10%" for 25 ns spacing beams. The main reason for bunch-to-bunch differences is the transient beam loading at the PS splittings.

As already mentioned earlier in the section concerning transverse emittance measurement, nothing is available at the injectors that allows assessing bunch-to-bunch transverse emittance differences, so that possible discrepancies are found only with LHC measurements.

The bunch length is monitored before SPS extraction by the BQMSPS. Every bunch is measured and if any is too long, the beam is not extracted to the LHC. More concerning the BQMSPS is discussed later in the section on Longitudinal Parameters.

Intensity

As already quickly mentioned in the intensity section, the SPS fast-BCT is the measurement system that should allow bunch-by-bunch intensity measurements, but unfortunately is was so far used only in relative terms. Its absolute calibration with respect to the DC-BCT is not obvious as the sampling phase (at 40 MHz) needs to be scanned to make sure to integrate the whole signal from each bunch. A calibration of the 40 MHz phase was suggested with bucket 1 as reference as any LHC beam will be injected from bucket 1 on with a 25 ns (or multiples) spacing.

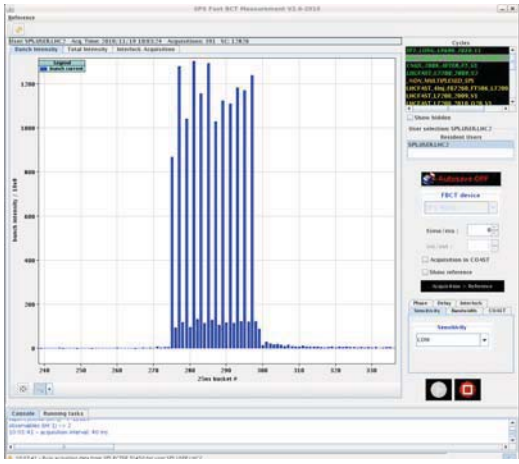

Figure 1: Example of bunch-by-bunch intensity acquisition with the SPS fast-BCT, 12 50 ns spaced bunches in the machine. The tails after the last bunch are clearly visible and are not due to real charge captured in the following buckets.

Additionally there are long tails for each bunch signal which can be up to 10% of the main bunch and are present up to two 25 ns slots. These tails are due to a lack of bandwidth, possibly from the long cables that bring the signal to the surface, but make it impossible to use the fast-BCT for satellite bunch detection. An example acquisition for the fast-BCT is shown in Figure 1.

An interlock signal derived from fast-BCT data has been developed as part of the LHC Software Interlock System (SIS) tree, but has not been made operational yet due to the above mentioned problems. When intensity fluctuations happened repeatedly due to some known temporary problem at the injectors, a "human" interlock was used, that is manually flipping the LHC injection inhibit (OP switch) in case of need for the ongoing SPS cycle.

The possibility of adding further checks in the BQMSPS will be investigated during the shutdown: limits on the calculated standard deviation on measured bunch lengths or peak values will be rather straightforward, while reasonable values for interlocking thresholds will be dictated by operational experience.

LONGITUDINAL PARAMETERS

SPS Beam Quality Monitor

The BQMSPS is a tool that performs an automated analysis of the longitudinal beam profile at the SPS with the aim of avoiding injection at the LHC of beams which are measured not to be good. It is based on an acquisition of a Wall Current Monitor (WCM) profile. This is digitized by an Acquiris DC211 ADC controlled by a FESA class and synchronized to the SPS RF and revolution frequencies by VME Trigger Units (VTUs). The analysis routines are written in C++ and are part of the same FESA class: they perform various checks on beam parameters. If these beam parameters are found not to be compliant with the expected values, then the result of the analysis is negative and the beam is dumped already at the SPS in order to avoid stressing Machine Portection components at the LHC and in order to save time (as losing one SPS supercyle is much shorter than dumping a fill at the LHC).

The BQMSPS performs three sets of acquisitions. The first acquisition is performed at each injection to verify the injected beam parameters from the PS: it calculates the bunch lengths and verifies that the first bunch is injected into the SPS bucket 1. The second acquisition is performed during the ramp and verifies the presence of satellite bunches and that the bunch pattern corresponds to what is requested by the LHC. The third acquisition is performed just before extraction and verifies the beam stability, the bunch lengths and re-checks the first bunch position. As the flat top acquisition is synchronized to the LHC-SPS fiducial frequency, the bunch position verification is equivalent to checking whether the LHC-SPS rephasing has performed correctly. The thresholds that determine acceptance or rejection are set through the Graphical User Interface (GUI) so that a certain degree of freedom is allowed for daily operation.

During the 2010 run, the BQMSPS blocked extraction for many different causes, among which: very bad injection phase or bad PS splittings, fully debunched beam, missing PS LHC-cavities, not enough or too much SPS longitudinal blow up, injections in the wrong bucket, missing injections.

Statistics concerning the 2010 run were acquired from the logging database and analysed, extracting information for the LHC beam modes Injection Probe and Injection Physics Beam, for most fills between 1000 and 1535. Notably about 20% of the LHC beams were dumped at the SPS due to the BQMSPS and a breakdown of the causes is shown in Figure 2. The main cause for dumps is a failure of the LHC-SPS rephasing, which was particularly painful in the case of overinjection. The missing extraction due to the BQMSPS in fact does not prevent the LHC Injection Kicker (LHC MKI) to fire, and this resulted in the pilot being kicked out while no new beam was injected, effectively emptying the machine and obliging the shift crew to start over with the filling process. It can also be noted that the presence of satellite bunches was not a limiting factor, and the fill pattern check prevented quite often the injection of beams that did not match the request.

SPS RF improvements

A number of improvements are needed and foreseen in the SPS RF systems [9].

Concerning the BQMSPS, the system so far required dull maintenance that consisted in filling in by hand a text file containing all possible SPS beam patterns in the form of a Look-Up-Table (LUT). In 2011 there will be no need for a LUT as the patterns will be set directly through the LHC Injection Sequencer (or the SPS GUI in case of SPS mastership). The hardware currently in use imposes the satellite sensitivity to be limited to about 2-3%, while more

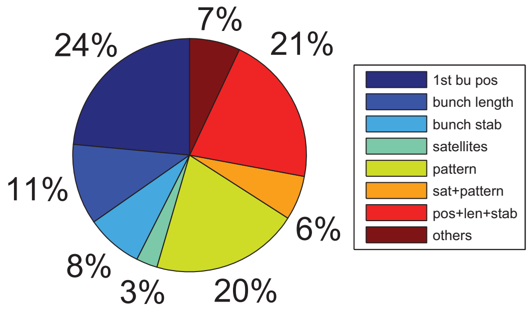

Figure 2: BQMSPS 2010 statistics: main reasons that prevented extraction.

recent hardware is being ordered or installed (fibre optic link, new front end CPU) and should allow better results to be reached after a full campaign of studies.

Concerning the LHC-SPS rephasing, for 2011 it is foreseen to use the same settings for the "training" of ring 1 and 2, as the LHC RF frequencies for beam 1 and 2 are foreseen to stay locked. This could not be done in 2010 and requires a small software upgrade. Additionally, in order to reduce the number of pilots kicked out at overinjection, two options are available. First and most simple, fill patterns that leave the pilot in can be designed (this can be used until the pattern is not too packed, e.g. not for the nominal 2808 bunch scheme). Second, the idea of a "late" pilot injection, which consists of using a pilot injected, rather than in bucket 1, later in the LHC, somewhere where it is not affected by a MKI pulse targeted for bucket 1, and where it is fully kicked out with a later MKI pulse.

The SPS longitudinal blow up was thoroughly tested in many SPS Machine Developments in the past years and became operational in 2010. Still many software improvements are needed to ease the job of the shift crews, as for the moment it is not Pulse-to-Pulse Modulated (PPM), hardware settings are not readable, the interface is non standard. A FESA version was being tested towards the end of the 2010 ion run and is foreseen to become operational sometime in 2011. It will communicate with LSA to retrieve settings as the synchrotron frequency, the noise amplitude, the spectrum shape. It will also allow the development, and later use, of a standard Java GUI.

The 800 MHz RF system currently presents the difficulty of not allowing any diagnostics directly from the CCC. In fact it requires an expert intervention e.g. to verify whether it is locked on the wrong harmonic frequency, or whether it is not locked at all. An alarm is foreseen for 2010 to inform the shift crews if the free running frequency is too far from the target, with measurements at the flat bottom and at the flat top. For sometime in the future the amplifiers are foreseen to be upgraded also, and this will come with a full low level upgrade also.

Finally in the list of improvements, the SPS frequency program playback is planned to be made PPM (to be tested later in 2011).

PS RF improvements

Concerning the PS RF system, the 80 MHz cavities were the most noticeable weak point seen from LHC operation point of view. Presently there are three cavities, two of which are operational and one a spare. The spare had to be re-tuned to a different frequency for ion operation, and this is a problem during parallel operation with ions and protons in case that one cavity has problems: this year it meant a one-hour stop between ion and proton fills. For 2011, the mechanical tuner control is foreseen to become automatic, and this will compensate for pressure and temperature changes. Two streams of thought were encountered by the author while discussing about this subject with various PS colleagues: some thought one extra 80 MHz cavity would not be bad, while others believed it to be better to improve reliability of the existing system, while not increasing the impedance in the machine.

Additionally, ideas for a "PS Beam Quality Monitor" are starting to circulate, as means to have an online monitoring of longitudinal beam parameters. Some of the information could even be fedforward to the LHC SIS to prevent injection in the LHC in case of bad cycles.

Satellite bunches

In the LHC nominal pattern, at most one 2.5 ns bucket is filled every ten, corresponding to one bunch every 25 ns. In early filling schemes, the bunch density is even lower, e.g. 150 ns and 50 ns spacings were used for physics in 2010. If any non-negligible quantity of beam is present in the buckets which are designed to be empty, these bunches are called "ghost" or "satellite" bunches. They can be created for example from not well tuned bunch splittings at the PS or by not well corrected injection phase at any of the transfers between machines.

An agreement between machine and experiments was found at the LEADE meeting [10] indicating a limit of a "few percent" as acceptable for the satellite bunches. Down to the level of 2-3% they are checked with the BQM-SPS with two different algorithms, one based on the mid-bucket bunch height and one based on signal intregration per bucket. It has to be pointed out how more precise measurements will be possible only after the BQMSPS hardware upgrade, which includes the use of a fibre optic link for the WCM signal, and a recent CPU for allowing more computation capability in the same amount of time.

Measurements of satellite bunch population were performed at the LHC by J.J. Gras (BE/BI) with the LHC Longitudinal Density Monitor [11]. For the LHC lead ion fill 1515, a beam 2 measurement integrated over 50 min during stable beams revealed that many 2.5 ns buckets had been populated due to the newly introduced RF gymnastics at the flat bottom (total voltage dip at every injection). Some of the satellites though were noticeably higher than the neighbouring ones, indicating that they were already present on the injected beam, rather than created at the LHC. Additionally, they showed a 5 ns structure which is another clear indication that they came from the injectors. The intensity of these ghost bunches was a few per mille of the main bunches.

Additional measurements came from the experiments for Van der Meer scan fills, and were presented in [12]. Measurements from the ATLAS and Alice Collaborations gave indications of contributions of about 1 per mille to 1 per cent of the main bunch peaks, with longitudinal spacing pointing to the injectors as sources of the satellites.

OTHERS

A number of various other possible improvements was foreseen. Something which was highly desired by the LHC Performance Coordinator is the automatization of the selection of the number of Booster rings in use. This would allow an increased flexibility in the creation of LHC fill patterns, but would also allow the filling to be faster in case of enforced reduced number of bunches for the first high intensity injection (limited to 8 or 12 bunches). The main issue is the PS RF settings which require a very fine tuning (mostly for 50 and 75 ns spaced beams), so that the automation of the number of Booster rings boils down to either storing the settings in different users, or to make use of "double" or even "triple" PPM settings.

At the SPS, the batch spacing cannot be remotely programmed, but requires a setting through the Man-Machine Interface (MMI) software. An improvement of this has long been promised, and is foreseen for sometime in the future.

It has also to be noted that the SPS supercycle composition and the supercycle change affect the LHC efficiency. Concerning supercycle changes, e.g. for pilot and nominal intensity users, it was noticed that the change was faster when the sequences were ready. But this would be most optimized for standard sequences, that is in the absence of MDs, which highlights a tradeoff between LHC efficiency and injectors schedule flexibility.

Last but not least, it has to be noted how in 2010 the injectors never went into dedicated LHC filling, which by the way led to greater than expected performance for non-LHC beams, like CERN Neutrinos to Gran Sasso and Fixed Target beams. This is due to the fact that anyway the LHC could not have taken beams from contiguous SPS cycles as extra time was needed for the Injection Quality Check analysis and to send the next request down the injector chain. For example, in order to request beam on the LHCION2 user (ion cycle, up to 4 PS injections), a padding with 12 extra basic periods would allow LHC injection every SPS supercycle; while 10 extra basic periods would not be sufficient. This delay could be avoided if the request handling was "per ring" in the injection sequencer, rather than purely serial as it is at the moment (a verification for ring 1 is awaited before sending a request for beam2, and viceversa). An upgrade of the LHC Injection Sequencer in this direction is foreseen for the 2011 run.

Communication

A few words have to be spent for noting how the whole CCC learnt along the first year of LHC operation how to handle LHC requests. At the shift crew level, the shift crews learnt the tricks: for example, back in the beginning of the run many first injections failed simply because the PS shift crew was not informed to turn on their cavities, which were still off when the LHC was requesting beam. Or for example when first trying the overinjections, many pilots were kicked out simply because the SPS extraction kickers were forgotten disabled.

At the level of coordination between the different machines, often it was noted from the injectors how not enough time was allowed for them to set up the users and beams properly. But also this improved as time passed by and steps will be taken from 2011 to try and improve the communication even further.

STATISTICS AND CONCLUSIONS

In the 2010 statistics presented in these proceedings [13], it is shown how 2.3% of the LHC downtime is due to the beam not being available at the injectors. A further breakdown per machine, according to the LHC logbook, points to the PSB for 14.5% of the time, to the PS for 17.5% and to the SPS for the remaining 68%. It is not clear whether the SPS was really the major cause, or whether the faults were not fairly assigned from the shift crews.

Anyway, regardless which of the injectors caused most faults, the injector chain provided a very high availability over the run and made 2010 a remarkable year. It has to be remembered also how this was helped by the fact that plenty of problems were kept in the shade, as for example fixes were held until the next LHC access or until filling was finished. One example for all, when the vacuum at the SPS was a problem, then the LHC had the record fill length of about 30 hours.

Despite the great success, this paper provided a list of improvements and upgrades which will make operations even easier and the performance even better in the future.

ACKNOWLEDGEMENTS

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50 AND 75 NS OPERATION

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Abstract

Two machine development sessions have been performed in order to understand potential limitations for the operation of the machine with 50 and 75 ns beam spacing. The main results of the studies and a possible outlook for 2011 will be presented. The overview will focus on the electron-cloud related issues while beam-beam aspects will be discussed elsewhere [1].

INTRODUCTION

At the end of the proton run 2010 a series of Machine Development sessions, from Friday 29/10 to Thursday 4/11 were dedicated to the setting-up of the LHC with bunch trains with a spacing of 50 ns and the study of the beam dynamics at injection, ramp and high energy, including collisions. These sessions were interleaved with physics runs (TOTEM run, ALICE length scale calibration, longitudinal luminosity scan) and other machine development subjects (abort gap filling characterization and quench tests with a wire scan).

The main aim of the studies with 50 ns beams [2] was the investigation of potential problems for 2011 operation, e.g.:

- potential vacuum issues at number of bunches comparable with those achieved with 150 ns,
- long range beam-beam effects,
- electron cloud effects,
- RF and longitudinal aspects and issues related to the higher total intensity in the LHC and injectors (e.g. capture efficiency),
- background and luminosity/beam lifetimes in collision.

The setting-up and the studies with 50 ns beams spanned a period of 126 hours of which approximately 78 hours could be effectively used. The setting-up period took approximately 2.5 shifts (beam time) as initially expected [2].

After an initial physics fill with 108 nominal bunches (9x12 bunches) important dynamic pressure rises were observed at injection when filling with trains consisting of 24 bunches each. The first attempt led to the closure of the vacuum valves in point 7 (VVGSH.774.6L7.R) after the injection of 108 nominal bunches per beam as the vacuum interlock level of 10^{-7} mbar was reached on two vacuum gauges. The evolution of the vacuum pressure on the penning gauge VGPB.773.6L7.R on the (uncoated) cold-warm transition of Q6L7.B2 (warm-cold transition with NEG coating only on the warm side of the transition) is shown in Fig. 1.

In that area the two beams circulate in different vacuum chambers. It must be noted that pressure rises had been observed with 150 ns spacing beams only in common vacuum chambers.

After this observation emphasis for the machine studies has been given to the characterization of the electron cloud build-up and its effects and possible cures as well as to the comparative study of the behaviour of the 75 ns beam which took place in another dedicated machine study period from Wednesday 17/11 to Saturday 20/11 for a duration of 74 hours of which 65 hours could be used for the setting-up of the injection and capture of the 75 ns beam and for the studies with 75 and 50 ns beams.

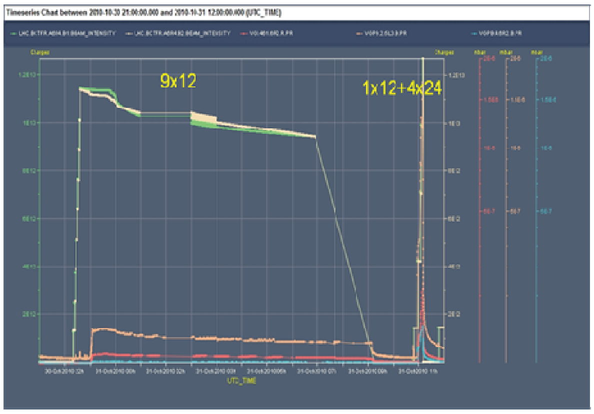

Fig. 1: Pressures and total intensity for the first two fills with 50 ns spacing.

The electron cloud build-up with 50 and 75 ns spacing beams has been studied by means of vacuum pressure measurements in the straight sections and by cryogenic measurements for the arcs.

EFFECTS ON VACUUM (STRAIGHT SECTIONS)

50 ns beam at 450 GeV

The dynamic pressure rises have been measured at all the available vacuum gauges as a function of the bunch population for a given filling pattern. The evolution of the vacuum pressure (logarithmic scale) for three vacuum gauges VGPB.2.5L3.B (where the highest pressure rise was observed), VGI.461.6R2.R, VGPB.4.6R2.B is shown in Fig. 2. The filling pattern consisted of two trains of 12 and 36 bunches spaced by 35.7 microseconds.

The threshold for the onset of the build-up for the considered pattern is between 0.6 and 0.8x10^{11} p/bunch. The dependence of the dynamic pressure rise as a function of the number of bunches in the train has been studied by injecting 12+12 bunches, 12+24 bunches and 12+36 bunches. The distance between the two trains of 12 bunches and nx12 bunches (n=1,...,3) was 35.7 microseconds. The pressure rise in the vacuum gauges previously considered is plotted in fig 3 (logarithmic scale) together with the total beam intensity. The electron cloud build-up occurs after the first 12 bunches as no visible pressure rise is observed for 12+12 bunches.

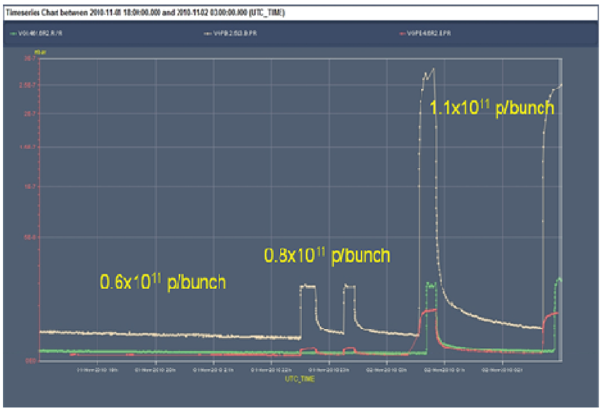

Fig. 2: Vacuum pressures at VGPB.2.5L3.B VGI.461.6R2.R, VGPB.4.6R2.B for different bunch populations for a constant filling pattern (12+36 bunches)

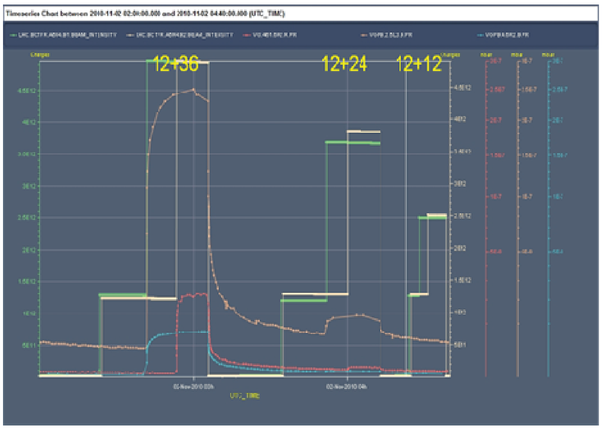

Fig. 3: Vacuum pressures at VGPB.2.5L3.B, VGI.461.6R2.R, VGPB.4.6R2.B vs. number of bunches in the train for nominal bunch population.

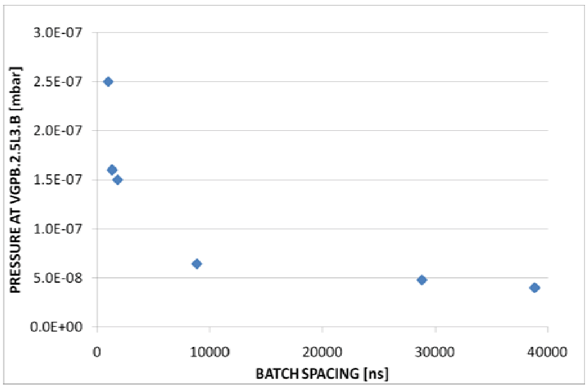

Fig. 4: Dynamic vacuum pressure rise at VGPB.2.5L3.B vs. spacing between two trains of 24 bunches with nominal bunch intensity.

The dependence of the dynamic pressure rise on the separation between two consecutive trains of 24 bunches for the vacuum gauge VGPB.2.5L3.B is shown in Fig. 4. The survival time of the electron cloud after the batch passage can be as long as 8 to 9 microseconds.

75 ns beam at 450 GeV

The studies with 75 ns beam where conducted by injecting trains consisting of 48 bunches obtained by injecting two trains of 24 bunches in the SPS spaced by 225 ns.

Fig. 5 shows the dependence of the dynamic pressure increase for the 75 ns beam measured at VGPB.2.5L3.B as a function of the beam total current. In comparison with the 50 ns beam the threshold for the onset of the electron cloud build-up with a train of 24 bunches is located between 0.9×10^{11} p/bunch and 1.1×10^{11} p/bunch.

As for the 50 ns beams pressure rise is observed in vacuum chambers where only a single beam is passing differently from what was observed with the 150 ns beam.

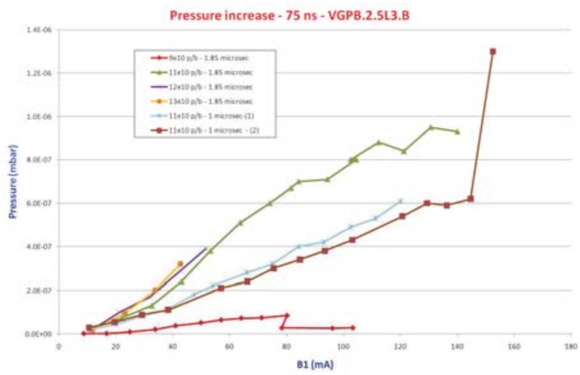

Fig. 5: Dynamic vacuum pressure rise at VGPB.2.5L3.B vs. beam current for different bunch populations at injection (Courtesy V. Baglin)

The reduction observed in the pressure rise for the fill with bunch population of 0.9×10^{11} p/bunch (red curve) can be explained by the time elapsed between the 10^{th} and 11^{th} injections and could be a result of the emittance blow-up occurred at injection or even the sign of a reduction of the desorption yield and secondary electron yield. The same argument could explain the observed reduction of the rate of dynamic pressure increase for the nominal bunch population at injection when reducing the bunch train spacing from 1.85 µs to 1.005 µs, taking into account the non-nominal operation of the transverse feedback for this train spacing (which is not a multiple of 25 ns) and the temporal order of the fills (the initial bunch train spacing was 1.85 µs and only later it was reduced to 1.005 µs). The large deviation observed for the point correspondent to the largest current is due to the high losses recorded at the injection of the last batch and should be discarded. From the above graph we can also safely assume that the maximum increase in dynamic pressure rise to be expected when going from 1.1×10^{11} p/bunch to 1.3×10^{11} p/bunch is smaller than a factor 3.

The linear dependence observed for the vacuum pressure rise after the second or third injections indicates that the electron saturation density is achieved after a constant number of bunches after two to three trains of 48 bunches.

The pressure rise observed for the 50 ns beam is a factor 2 to 3 higher than that observed for the 75 ns beam for the same beam current and bunch population (see Fig. 6).

Although the observed pressure rise for the 75 ns beam is lower than that observed for the 50 ns beam it must be noted that without scrubbing it would not be possible to ramp a large number of bunches with 75 ns spacing taken into account the additional pressure rise observed during the ramp for energies larger than 1.5 to 2 TeV.

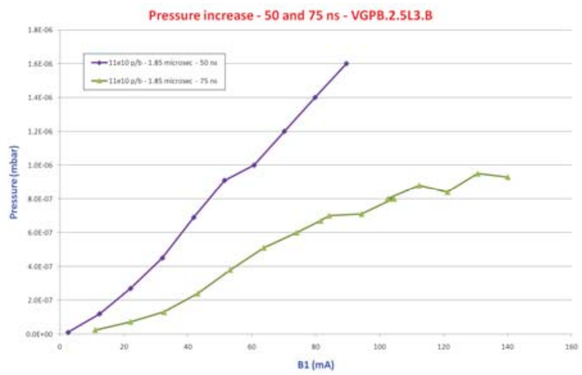

Fig. 6: Dynamic vacuum pressure rise at VGPB.2.5L3.B vs. beam current for 75 and 50 ns spacing and nominal bunch population at injection (Courtesy V. Baglin) [3].

Effects of the "scrubbing" run on the dynamic vacuum pressure rise.

Electron bombardment of the vacuum chamber (respectively beam screen for the arcs) wall surfaces reduces the desorption yield as well as the secondary electron yield of the surfaces. A reduction by a factor seven of the dynamic pressure increase induced by the injection of a train of 12+36 bunches has been observed after approximately 16 hours of operation with 50 ns beams with configurations leading to pressure rises larger than 10^{-7} mbar. The measurements conducted at the beginning and at the end of the scrubbing period with 50 ns are shown in Fig. 7. Assuming an exponential decay of the pressure rise as a function of the beam time this would correspond to a time constant of approximately 8 hours.

Shorter time constants, of the order of 3.5 hours, have been measured from other pressure evolution data as shown in Fig. 8 corresponding at the initial phase of the scrubbing run. It must be noted that during the period considered in Fig. 8 a slight reduction of the bunch intensity has been observed (smaller than 10 %).

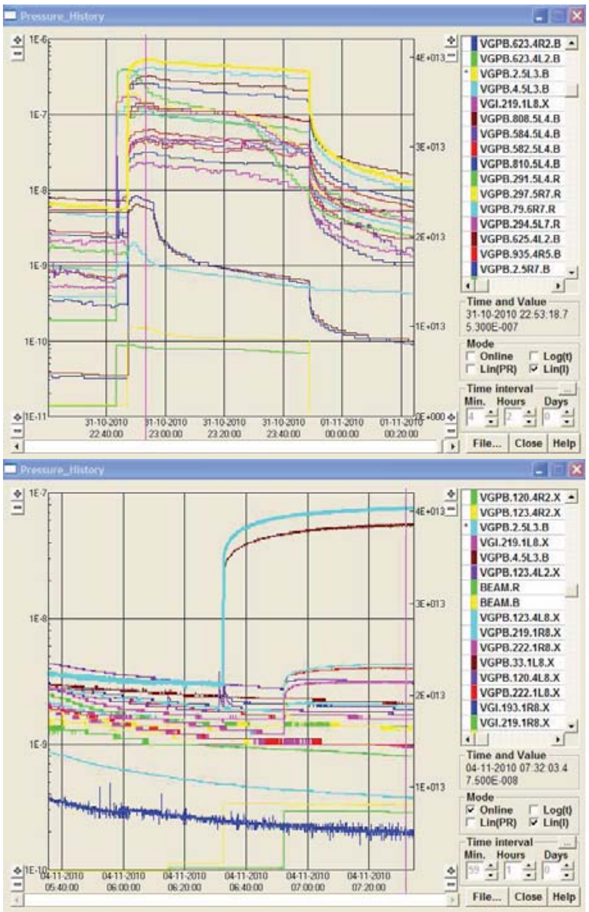

Fig. 7: Dynamic vacuum pressure rise for the injection for a train of 12+36 bunches with 50 ns spacing before the scrubbing period (top) and at the end of the scrubbing period (bottom). (Courtesy V. Baglin, G. Bregliozzi, G. Lanza).

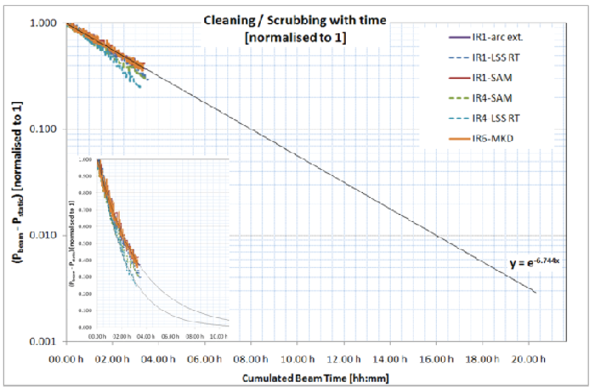

Fig. 8: Dynamic vacuum pressure rise evolution versus time with beam – 12+24 bunches with 50 ns spacing and nominal bunch population (Courtesy J-M Jimenez).

Effect of the fringe fields of the experimental solenoids

Although solenoidal fields are very effective in suppressing multipacting (see [4]) scrubbing does not occur at those positions, this is for example the case of the experimental regions of ALICE, ATLAS and CMS and in their vicinity (i.e. in the areas where solenoidal stray fields are present). Fig. 9 shows the evolution of the pressure rise measured in different gauges located close to experimental region in point 2, affected by the stray field of the ALICE solenoid, as a function of the excitation current of the ALICE solenoid and of the injected beam current. This implies that any scrubbing run should be conducted with experimental solenoids OFF.

Fig. 9: Dynamic vacuum pressure rise close to the point 2 experimental area vs. injected beam current and ALICE solenoid current.

EFFECTS ON CRYOGENICS (ARCS AND TRIPLET-D1)

Electron bombardment of the beam screen walls in cold magnets is a source of heat load for the cryogenics. The amount of heat load can be determined by measuring the Helium temperature at the outlet of each beam screen cooling circuit if the flow of Helium is kept constant. Measurements of the heat load have been performed both with 50 and 75 ns beams and they are presented in Fig. 10. The expected contribution to the heat load due to synchrotron light and image currents is also shown.

While the heat load measured with the 75 ns beam is compatible with the contributions from image currents and synchrotron light, that measured with 50 ns beam exceeds the estimations by approximately 40 mW/m/beam and it is therefore expected to come from electron cloud. The expected resolution of the measurement is 5 to 10 mW/m/beam.

A significant temperature increase on the Helium outlet temperature at the beam screen circuits has been measured in the triplet-D1 circuits in point 2 and point 8 as shown in Fig. 11. The fast decrease in the temperature occurred at around 15:00 is due to the activation of the regulation of the cryo-valve opening to control the temperature of the beam screens. The observed difference between point 2 and 8 on one side and point 1 and 5 on the other might be due to the heat load deposition in the cold D1 magnets. The D1 magnets in point 1 and 5 are warm magnets and they have NEG coated vacuum chambers.

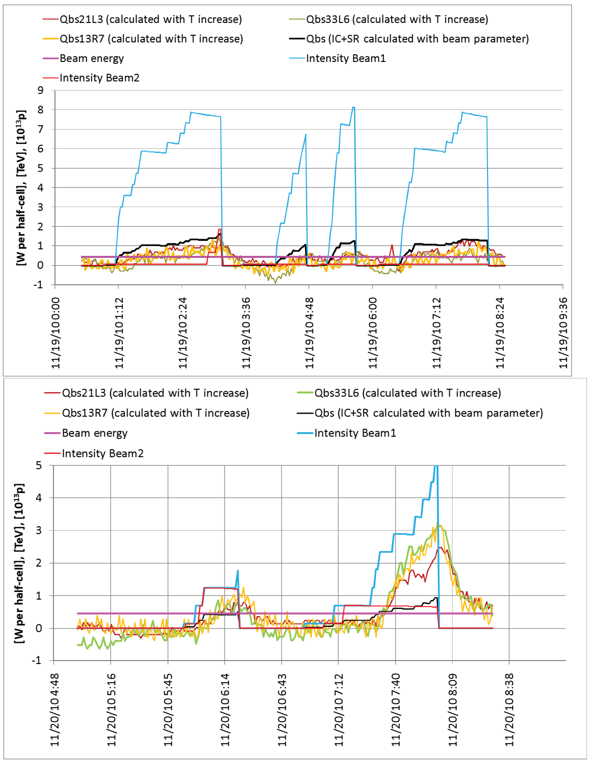

Fig. 10: Heat load as measured in the arcs with up to 824 bunches spaced by 75 ns (top) and with up to 444 bunches spaced by 50 ns (bottom). The total beam current for beam 1 and beam 2 and the beam energy (kept constant at 450 GeV/c) are shown. The above data refer to cell 33L6 considered to be representative of the situation in the arcs (courtesy L. Tavian).

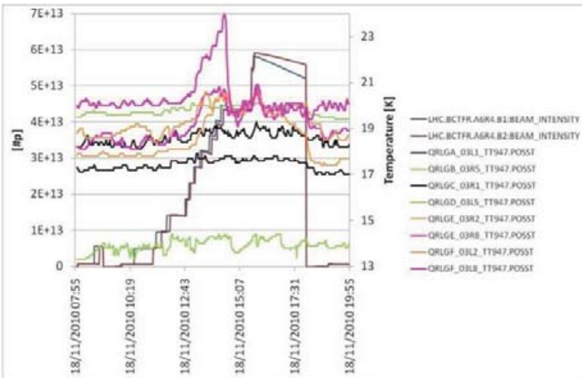

Fig. 11: Time evolution of the temperature of the Helium at the output of the beam screens for the D1-triplets in point 2 and 8 and for the triplets in point 1 and 5. The total intensity of the 75 ns beam during that time is also shown (courtesy L. Tavian).

While the heat load measured with the 75 ns beam is compatible with the contributions from image currents and synchrotron light, that measured with 50 ns beam exceeds the estimations by approximately 40 mW/m/beam and it is therefore expected to come from electron cloud. The expected resolution of the measurement is 5 to 10 mW/m/beam.

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Effect of the "scrubbing" run

The effectiveness of the scrubbing run conducted at 450 GeV/c with a 50 ns beam in reducing the electron cloud build-up and the heat load in the arc dipoles at injection and at 3.5 TeV has been proven by comparing the heat load in the beam screen of the reference cell 33L6 before and after the scrubbing run for beams consisting of 108 bunches with the same filling pattern and bunch population. The results are presented in Fig. 12.

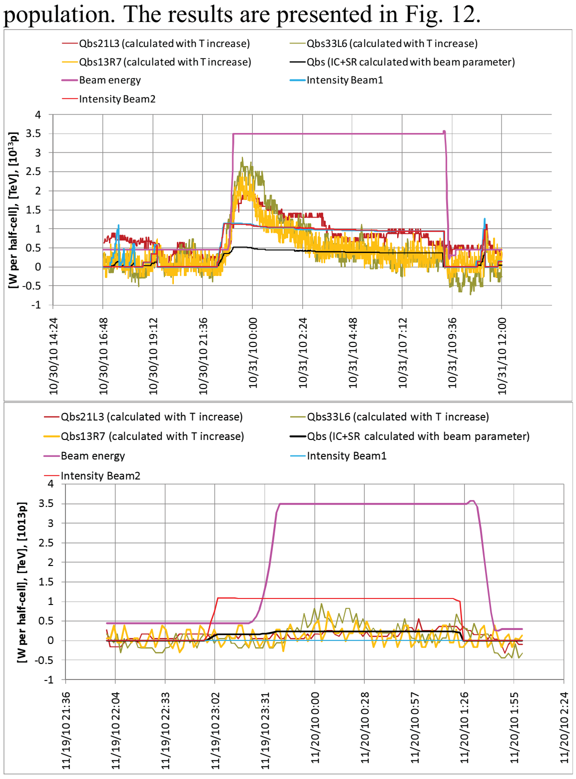

Fig. 12: Heat load measured in the beam screen of the cell 33L6 during injection and ramp of 108 bunches before (top) and after (bottom) the scrubbing run (courtesy L. Tavian).

After the scrubbing run only a single beam (Beam 2) could be injected due to a problem with the beam dump system for Beam 1. A reduction of the heat load from ~20 mW/m/beam to less than 5 mW/m/beam (which is also the resolution of the measurement) has been observed. This corresponds to a reduction of the heat load by a factor 4 after a scrubbing period of 16 hours.

EFFECTS ON BEAM

The electron cloud building-up along the bunch train interacts with the proton bunches and can couple the motion of consecutive bunches or even the motion of different longitudinal slices of a bunch as a result of the pinching of the electron cloud during the bunch passage. For that reason electron clouds can be responsible of single and coupled-bunch instabilities in the horizontal and vertical planes.

In a dipole field region electrons spiral around the magnetic field lines and their motion in the plane perpendicular to these lines is essentially frozen already at injection (magnetic field strength is 0.535 T). Therefore no pinching occurs in the plane perpendicular to the field lines and no horizontal single bunch instability is expected to originate from electron cloud in dipole field regions [5][6][7][8].

The single bunch instability occurs when electron cloud densities -before the bunch passage- exceed a certain threshold (typically in the range of 10^{11} electrons/m^3). Below this threshold density, blow-up is observed due to incoherent effects deriving from the highly non-linear fields generating during the bunch passage. As a result of these phenomena blow-up is observed along the bunch trains in correlation with the build-up of the electron cloud along the bunch train.

50 ns beam at injection

The transverse emittances measured along a bunch train of 36 bunches with 50 ns spacing (injected after a train of 12 bunches with a spacing of 35.7 microseconds) are shown in Fig. 13. A blow-up of the emittance is visible starting in the second half of the train. This is consistent with the observations on the dependence of the pressure rise as a function of the bunch train length presented in Fig. 3. These measurements were taken with typical machine settings at injection (damper gains close to maximum, 4 units of chromaticity in both planes).

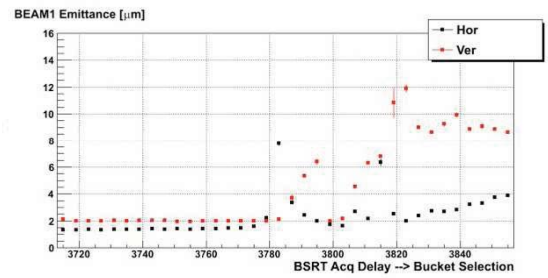

Fig. 13 Transverse emittance along a bunch train of 36 bunches for Beam 1. (Courtesy F. Roncarolo).

The rise-time of the transverse instability observed at 450 GeV/c was ~1 s horizontally and a few tenths of a second vertically as shown in Fig. 14.

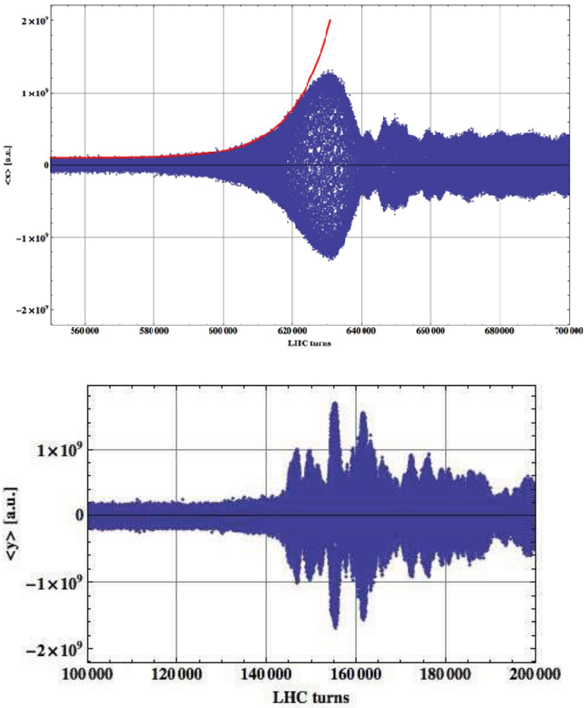

Fig. 14. Time evolution of the horizontal (top) and vertical (bottom) beam position as measured by the BBQ after the injection of a train of 36 bunches in addition to 12 bunches circulating in the machine (Courtesy E. Métral).

The transverse emittances measured along 4 consecutive trains of 24 bunches spaced by 1.85 µs (injected after a train of 12 bunches with a spacing of 35.7 µs) are shown in Fig. 15. The vertical blow-up is mostly affecting the last two trains.

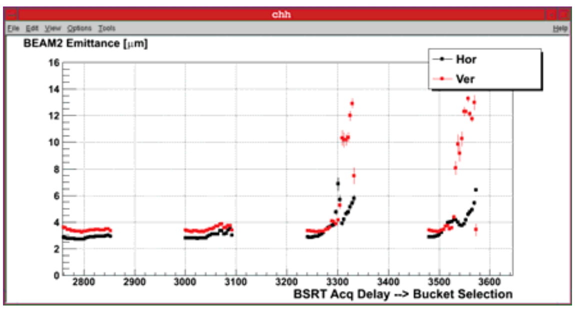

Fig. 15. Transverse emittance along 4 trains (spaced by 1.85 µs) of 24 bunches. (Courtesy F. Roncarolo).

This is a consequence of the fact that decay time of the electron cloud after a bunch train passage is larger than the batch spacing (in this case 1.85 µs) as shown in Fig. 4. These measurements were taken with typical machine settings at injection (damper gains close to maximum, 4 units of chromaticity in both planes).

The smaller vertical emittance of the last bunch of the last two trains is the result of the losses mostly affecting those bunches.

Large chromaticity and large injected emittance have proven to have a stabilizing effect on the single bunch instability induced by electron-cloud both in simulations and experiments in other machines and in particular in the SPS [5][9]. The effectiveness of these cures has been demonstrated also in the LHC and they could be used to increase the number of bunches during scrubbing while minimizing beam instabilities and losses.

The transverse emittances measured along 7 consecutive trains, each consisting of 24 bunches, spaced by 1.85 µs (injected after a train of 12 bunches with a spacing of 35.7 µs) after having increased the horizontal and vertical chromaticities to 14 units in both planes are shown in Fig. 16. The measured emittance blow-up is reduced by more than a factor two also for the trailing bunch trains. The blow-up is further reduced after having increased the chromaticity to 18 units and after increasing the transverse emittance of the beam delivered by the injectors from 2-2.5 µm to 3-3.5 µm (see Fig. 17).

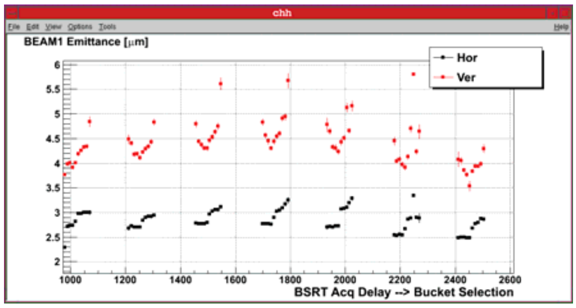

Fig. 16. Transverse emittance along 7 trains (spaced by 1.85 µs) of 24 bunches. (Courtesy F. Roncarolo). Chromaticity was set to 14 units in both planes.

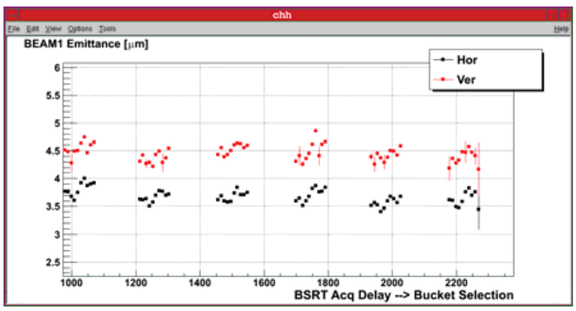

Fig. 17. Transverse emittance along 6 trains (spaced by 1.85 µs) of 24 bunches. (Courtesy F. Roncarolo). Chromaticity was set to 18 units in both planes and transverse emittance blow-up was applied in the injectors.

In spite of that some blow-up is still observed that could be related to the above mentioned incoherent effects of the electron cloud pinching.

50 ns beam at 3.5 TeV

At injection operation with large chromaticity seems to be required even for large gains of the transverse feedback pointing to single bunch instabilities at frequencies outside the bandwidth of the feedback as observed in the SPS [7].

At 3.5 TeV the instabilities have been observed, when the transverse feedback is switched OFF, with beams consisting of trains of 24 bunches (12+4x24) instead of trains of 12 bunches (9x12) for the same total number of bunches (108) and with the same settings (tune, chromaticity, octupole strengths). The rise time of the instability in the horizontal plane was few tenths of a second in the horizontal plane and 1 to 2 seconds in the vertical plane as shown in Fig. 18.

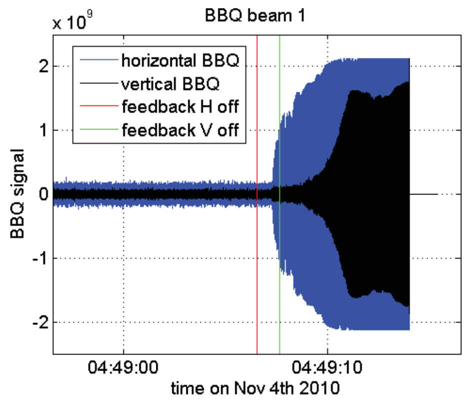

Fig. 18: Time evolution of the horizontal (blue) and vertical (black) beam position as measured by the BBQ at 3.5 TeV when the transverse feedback is switched OFF The accuracy of the logged timing of the transverse feedback switch OFF is approximately 1 second (Courtesy of H. Bartosik and B. Salvant).

75 ns beam at injection

Coupled-bunch oscillations at low frequency (~1-2 MHz) were observed also for the 75 ns beam at injection (see Fig. 19), mostly in the horizontal plane, although it is not clear whether they are induced by the electron cloud. In the vertical plane blow-up was observed even when operating the machine to high chromaticity (Fig. 20). This is compatible with instabilities and incoherent effects generated by the electron cloud close to threshold electron density.

SUMMARY AND RECOMMENDATIONS

Electron cloud effects (vacuum pressure rise in the straight sections, heat load in the arcs, instabilities and transverse emittance blow-up) have been observed for 50 ns beams. Although a reduced vacuum activity has been measured with 75 ns beams, acceleration of nominal trains of 936 bunches would lead to vacuum pressures larger than 2×10^{-7} mbar (interlock level). No significant heat load due to electron cloud in the beam screens has been measured for the 75 ns beam while a clear increase of the temperature of the beam screen of the triplet-D1 magnets in point 2 and in point 8 has been observed and in particular on the left side of point 8.

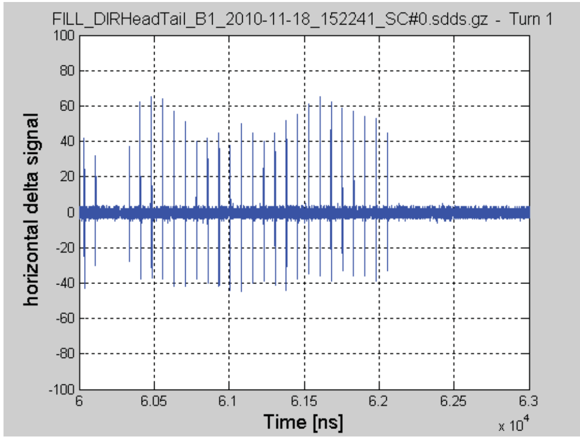

Fig. 19. Snapshot of the delta signal (product of the horizontal displacement and of the bunch profile) provided by the Head-Tail monitor for a train of 24 bunches at injection. (Courtesy B. Salvant).

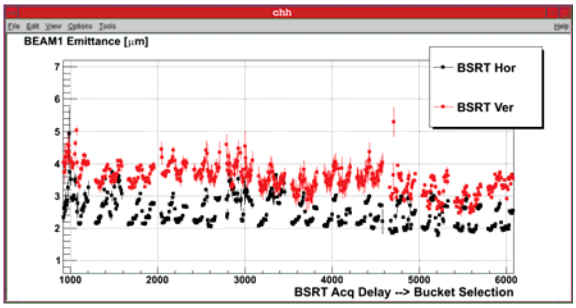

Fig. 20. Transverse emittance along 14 trains (spaced by 1.005 μs) of 48 bunches (Courtesy F. Roncarolo). Chromaticity was set to 20 units in both planes.

The typical signatures of electron cloud instabilities have been observed with 50 ns beams. For the 75 ns beam vertical blow-up correlated to coherent and incoherent effects typical of electron cloud densities close to threshold have been evidenced. For both beams these effects translate into low beam lifetime and losses.

The comparison of the dynamic pressure rise in the uncoated portion of the straight sections and the heat load in the beam screens of the arcs for a 50 ns beam at injection, during the ramp and at 3.5 TeV before and after scrubbing at 450 GeV clearly shows a reduction of both phenomena with a reduction by more than a factor 7 in the dynamic pressure rise and by a factor 4 in the heat load after 16 h of scrubbing with beam.

Experience in the SPS (see Fig. 21) shows that scrubbing with 25 ns beams allows operation with 50 and 75 ns beams with no significant electron cloud build-up.

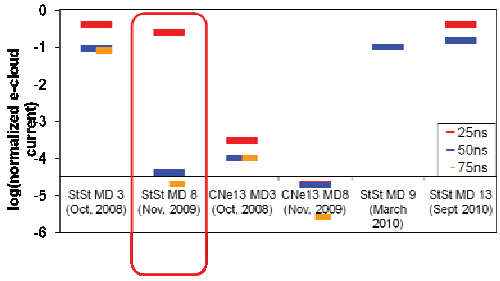

Fig. 21. Electron cloud signal measured for beams with different bunch spacing. A reduction by more than 3 orders of magnitude has been measured with 50 and 75 ns beams after scrubbing with the 25 ns beam in the SPS (see highlighted column - courtesy M. Taborelli).

Operation with 75 ns beams requires a scrubbing run with a 50 ns beam which would allow scrubbing the arcs as well. The extrapolation of the experimental data collected so far and the SPS experience indicate that a dedicated period of 1 week for scrubbing with 50 ns beams with ~1.3-1.5x10^{11} p/bunch should allow running with 1.3x10^{11} p/bunch (maximum possible in the PS at present) with 75 ns beams for physics. This would also allow studying the behaviour of 50 ns beams during machine studies to prepare a run with 50 ns beams later in the run.

The following prerequisites must be present before the start of the scrubbing run:

- injection of at least 4 trains of 24 (possibly 36) bunches (50 ns spacing) per SPS extraction up to nominal transverse emittance should be set-up;
- machine protection should be set-up for high intensity at 450 GeV/c;
- RF should be conditioned for operation at high intensity;
- solenoids (experimental and anti e-cloud) should be OFF in order to condition all the machine;
- vacuum interlock levels should be temporarily set to 2x10^{-6} mbar when and where pressure rises limit the progression of the scrubbing and compatibly with machine and experiment protection.

ACKNOWLEDGEMENTS

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INTENSITY RAMP-UP

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Abstract

In 2010 the LHC operated with destructive stored beam energies. The main phases of operations and the intensity ramp up strategy are recalled along with a look at the outcome of machine protection and operations reviews that took place during the year. With the experience gained in 2010 in mind a possible strategy for progress in 2011 is presented.

PREAMBLE

LHC is pushing into dangerous territory. The LHC represents a huge capital investment for CERN and the consequences of getting it wrong with beam are enormous. The maximum stored beam energy in 2010 was around 28 MJ, this is enough energy to cause serious damage. It is planned to at least double this figure in 2011. Damage to a superconducting magnet and leak of helium into the beam vacuum would require a stop of several months and cause severe delay to the physics program.

2010 - OVERVIEW

The main milestones of the 2010 commissioning are outlined in table 1.

Table 1: main commissioning milestones 2010

Date	Milestone
March	Initial commissioning leading to first collisions
April	Squeeze commissioning
May	Physics 13 on 13 with 2e10 ppb
June	Commissioning of nominal bunch intensity
July	Physics 25 on 25 with 9e10 ppb
August	3 weeks running at 1 – 2 MJ
September	Bunch train commissioning
Oct - Nov	Phased increase in total beam intensity

The intensity ramp-up following the bunch train commissioning in August is shown in table 2.

Table 2: intensity ramp-up and associated performance

Date	Bunches	Colliding pairs	Luminosity
29th August	50	35	1×10^{31}
1 – 22nd Sept.	Bunch train commissioning		
22nd Sept.	24	16	4.5×10^{30}
23rd Sept.	56	47	2×10^{31}
25th Sept.	104	93	3.5×10^{31}
29th Sept.	152	140	5×10^{31}
4th Oct.	204	186	7×10^{31}
8th Oct.	248	233	8.8×10^{31}
14th Oct.	248	233	1×10^{32}
16th Oct.	312	295	1.35×10^{32}
25th Oct.	368	348	2.07×10^{32}
4th Nov.	Switch to heavy ions		
9th Nov.	17	16	3.5×10^{24}
15th Nov.	121	114	2.88×10^{25}

REVIEWS

Operations review

An operations review was held in June 2010. It asked the question: are operations ready to deal with the destructive potential of 0.5 to 1 MJ stored beam energy?

Issues were identified with: preparation for beam and operational procedures; injection; collimator settings control; reliability of feedbacks; the sequencer; controls; software and settings management; the post operational checks of the beam dump system (XPOC); post mortem; and orbit stability and control through the nominal cycle.

The answer to the question posed above was a simple "no". At the time of the review it was clear that operations was not yet ready to deal with fully unsafe beams. The machine protection systems were working well but the potential to put the machine into an unsafe state was still possible and had been demonstrated on occasions. There was still a lot of room for human error.

Following the workshop a lot of effort went into resolving the issues identified and reducing the number of manual actions required when driving the machine through the nominal cycle. Improvements to the sequencer and sequences were rigorously pursued.

Internal Machine Protection Review

An internal machine protection review took place on the 17th and 18th June 2010 [1]. The following systems were considered and again a number of issues were identified.

- Beam Interlock System
- Safe machine parameters
- PIC, WIC and FMCM
- LBDS
- Collimation
- Transfer and injection
- Dump protection
- BPM system
- Orbit feedback
- RF frequency and power interlocks
- BLM system
- Software interlock
- Post Mortem system

Some of the issues raised are listed in table 3 []. They are listed more to illustrated the nature of the problems rather than highlight the problems themselves. It can be seen that, among other things, they concern intervention tracking, redundancy of signals, reliability of beam instrumentation, control issues etc.

Table 3: some issues arising from internal MPS review

System	Issue
BIS	Automated connection tests with users required.
BIS	Beginning of the ramp – operations – Safe Beam Flag to FALSE and unmask all inputs (sequencer)
SMP	Energy distribution must be checked, since there is no redundancy
SMP	Intensity for SBF – no redundant readings
SMP	SBF limit – MPS commissioning/availability
SBF	Now uses the FBCT - too complex for providing a safe system
PIC	After technical stops and interventions the traceability of changes and required testing must be documented. Sloppy if compared to HWC.
PIC	PIC configuration: automated tests of configuration and BIC connection to be performed more regularly.
XPOC	Reliability of some beam instrumentation data not good enough
LDBS	Technical stop modifications not properly tracked.
LBDS	Interlocked beam position monitors - safety – threshold and algorithms needs to be addressed
COL	Machine stability important, some worries
COL	Steady state losses are different from failure transients – careful with extrapolations
BPM	BPM sensitivity settings: automated and reliable sensitivity switching required
Dump protection	Abort gap monitoring and cleaning not operational
BPM	BPM readings dependence on intensity. Need a long-term approach for critical location (IR3, IR7, TCT-IR regions).
BPM	Orbit correction strategy not clear
BLM	Threshold management – critical. Must be managed properly.
BLM	Data from “direct dump” BLM
SIS	Most conditions are maskable (independent of SBF)

EXTERNAL REVIEW

An external machine protection review took place 6th to 8th September 2010. The review panel came to the following conclusions.

Clear criteria should be established by which steps and under which conditions the beam intensity will be increased. This includes, among other points:

- *establishing the necessary operational discipline associated with the potential risks in the new regime of stored energy which to a large extent was promoted during the LHC engineering and construction phase,e*
- *the understanding of the mechanisms populating the abort gap and their scaling as a function of beam intensity,*
- *consolidation of the beam position monitoring system,*
- *the improvement of a detailed and comprehensive post-mortem analysis, and*
- *establishing a robust and rigid set of operating procedures and sequences.*

In summary, the Committee felt that the LHC was ready to go beyond 3 MJ. It saw no objection to a relatively fast but successive increase in stored energy. This conclusion was based on what was presented on the machine protection system and its performance. It assumes

- *that the improvements are implemented which have been presented by the LHC project team themselves, including the priorities made by the Committee in addition to further recommendations,*
- *that the machine performance is all the time understood as the stored energy increases and that confidence is gained in all the operational phases,*
- *and that it is verified that there is no onset of new phenomena affecting the reliability of the machine protection system.*

PUSH TO 1-2 MJ

There was a halting push through nominal intensity commissioning to a total stored beam energy of around 1-2 MJ. The LHC was held at or around this range for around 3 weeks. There was much discussion about the need for the hiatus, which saw the LHC running with 25 bunches per beam (1.6 MJ) until 17th August and 48 bunches until 1st September (3.1 MJ).

The question of whether or not we could we have gone to 1 to 2 MJ earlier was naturally enough asked many times. The answer from an operational and machine protection standpoint was a categorical “no”. One must read between the lines of the above summaries of the reviews and realize that the LHC was still very much in a commissioning phase during these months. It simply was not in a state to accept the risks and the consequences of getting it wrong with a multi-mega Joule beams.

BUNCH TRAIN COMMISSIONING

The period of steady running at in August was followed by a timeout for bunch train commissioning that lasted around 3 weeks. The importance of this period should be stressed. Besides getting the machine ready for bunch trains this commissioning period saw a lot of ramps and squeezes for the required loss maps. These provided an opportunity to consolidate and really marked: the transition to a more rigorous, dependable sequence; the reduction of manual actions in the nominal sequence; and some sense that routine operation was under control. Operations had eventually nailed down the sequence, procedures, orbit, and settings to a state that pushing high stored energy beams through the cycle could be more or less be done with some confidence that the safety of the machine would not be compromised.

Interestingly enough, once the procedures had been established at the start of the intensity ramp-up, very little was changed thereafter. There was a clear reluctance to fiddle with a proven modus operandi. It was only when the switch to lead was made that significant modifications were made.

MOVING ABOVE 2 MJ

The key features of the procedure use to control the steps up in intensity follow.

- Maximum step size: 50 nominal bunches (~ 3.2 MJ)
- 3 physics fills required at each step
- 20 hours of stable beams required at each step. There was always some debate. The critical phases are those before stable beams and it was argued that even if the fill was lost a short time after going into physics (e.g. UFO) the necessary tick had been made. Some latitude was asked for and some given.
- Dump BPM test had to be performed for each new bunch configuration.
- The checklist had to be signed off before moving up in intensity (see below).
- A meeting of rMPP took place where practicable. Lively debate was common.
- Some step-ups took place at night, and at weekends. Essentially the operations crew were given the go ahead to increase the number of bunches and were then responsible of pushing the increased intensity into physics.

Criteria for passage – the checklist

The criteria in the intensity increase checklist are tabulated below. See discussion below.

Magnet powering
No unexplained IPOC failure in Post Mortem for FMCM and PIC
No magnet quench after beam dump in RQ4.R/L6
No unexplained quench of a magnet
No unexplained abort of the 3 previous fills by magnet powering system
No problems with loss of QPS_OK for main circuits following injection process
Beam interlocks
No unexplained IPOC failure in Post Mortem for BIC
No unexplained false beam dump from beam interlock system
No failure of BIS pre-operational check
BLM
Internal test (sanity checks) results must be true
Rise time (10 to 90%) of fast losses must be larger then 200 us
No unexplained BLM check failures
Expected losses for the to be injected beam must be 30 % below threshold level
BLM system modification (ECRs) have to be agreed on, EDMS: notified persons signature is needed
No nonconformities in the energy transmission to the BLM crates
Collimation
Betatron loss map
Off-momentum loss map
No observed violation of cleaning hierarchy
Post-mortem
Loss leakage to TCTs below 0.5% during beam dump
UFO occurrences
No unexplained PM event above 450 GeV
Orbit
Global orbit in tolerance in stable beams (< 0.2 mm rms)
Orbit IR3/IR7 collimators within ± 0.2 mm in stable beams
Check that orbit is correctly measured
BPM IP6 (interlock BPM) test at start of first beam with higher intensity and different bunch pattern
Orbit at TCTs in tolerance in stable beams (≤ 1 sigma)
Feedbacks & operation
OFB operational status / no anomalies
QFB operational status / no anomalies
Beam dump
Asynchronous dumps understood? Protection worked correctly?
Parasitic asynchronous dump data show no loss of protection
No positioning errors on TCSG/TCDQ
No settings or thresholds mistakes/wrong sequences/unexplained faults on TCSG/TCDQ
No unexplained MKD, MKB kicker, TSU or BETS faults
No potentially dangerous XPOC or IPOC failure on MKD or MKB
No unexplained synchronization problem with TSU
Pressure and temperature rise in TDE block within tolerances
Requalification passed OK at 450 GeV and 3.5 TeV with pilot in case of any important component exchange
Injection
Injection oscillations within tolerance for all injections
No unexplained large beam loss on TCDIs
No issues in injection procedure, settings or tolerances
Orbit in injection region in tolerance wrt reference (tolerance <0.5 mm)
Resetting of TL trajectories and TCDIs done when needed
No increased rate of MKI flashovers
No increased rate of MKI switch erratics or missings
No unexplained MKI vacuum or temperature activity
No machine-protection related injection system failures

Could we have gone faster?

Could we have gone faster? There are really two questions here: could we have started the ramp-up in intensity sooner; and could be have performed the ramp up faster. The answer to the first question is given above.

The ramp-up was already very fast: ~6 MJ per week. As Ralph Assmann notes, we passed beyond Tevatron and HERA record stored energy in as little as 6 months. We added 3 record Tevatron or HERA beams every week. It was safely done with not even a single quench. (Although we should be careful not to confuse safety with luck.)

The collective awareness of the dangers and the collective experience of operating the LHC provided a natural brake on over exuberance. The length of time spent on the intensity increase seems appropriate, if not pushing the limits of haste.

Discussion and observations

- **Checklist** The circulation to the rMPP seems appropriate. There was good representation of concerned parties in the membership, although it might be noted that there was a limited number of initials against the items. There was fast turnover that sometimes took place at nights and at weekends. This might lead one to question the rigor with which full and comprehensive sign-off was pursued. What was probably happening that there was a perceived sense among the community that things were OK, and only a nod was made towards to the checklist.

- **MPS coverage**. Is it assured? The checklist should certainly be reviewed. If we agree that it is a useful device then it must be taken seriously.
- No special considerations were invoked when coming out of **technical stops**. (Although test dumps are routinely performed.)
- **Operational non-conformities** were observed during the ramp-up. These included tune feedback not working in ramp and squeeze. Others affected the orbit (particularly experiments' IRs). These did not prevent increases in intensity. The acknowledged assumption was that the beam interlock system would catch problems arising. Whether this is the right attitude is a debatable point. It wasn't all plain sailing and we indeed topped out at 368 bunches because of unexplained issues with 424 bunches.

The strategy was useful in providing a framework for a phased intensity increase. It thus prevented the need for protracted wrangling at each step.

It provided a braking mechanism and gave us the chance to address issues that did arise with increasing intensity. The eventual result would seem perfectly acceptable. This should be remembered when considering 2011.

2011

Re-commissioning in 2011 foresees:

- 3 to 4 weeks re-commissioning with a virgin set-up, new ramp, new squeeze, new beta*s, orbit, modified parameter space… it will be different.
- Full collimator set-up and full validation (loss maps, asynchronous dumps etc.)
- One would foresee a ramp backup to around 200 bunches in 50 bunch steps (with 75 ns. bunch spacing). In 2010 it took around 4 days (minimum) per 50 bunch step with most time lost to machine availability and lost fills (UFOs…). Thus it is reasonable to anticipate around 2 weeks to get back to 200 bunches
- After a 10 day scrubbing run, larger steps of 100 bunches is foreseen driving through from 200 to a maximum of 900 bunches (for 75 ns.). This should take around 3 to 4 weeks.

It is important that a revised checklist and regular meetings of the rMPP are used to sign off each step up intensity. Regular beam-based checks should also be performed.

Open Issues

- Do we need another review?
- Does the procedure need to be modified or extended? Does it need to be more formal?
- Should there be more extended MPS unit testing? This might be particularly applicable when coming back from extended stops.
- Checks should be made that all issues arising from the reviews outlined above have been satisfactorily resolved.

REFERENCES

[1] Internal review of the LHC Machine Protection System, http://indico.cern.ch/conferenceDisplay.py?confId=97349

[2] External review of the LHC Machine Protection System, https://lhc-mp-review.web.cern.ch/lhc-mp-review

HOW TO IMPROVE THE TURNAROUND

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Abstract

After one year of operation in the multi-MJ stored energy regime, important operational experience has been gained on various aspects, with stable machine configurations (with fixed reference orbit, optics, collimator settings, etc.). In this paper, the analysis of operational efficiency in the standard operation cycle for physics fills is addressed and possible paths to optimize the LHC turn-around time are presented. The analysis is based on a critical look at the 2010 operational, aimed at identifying the bottlenecks of the present operational mode. Proposed improvements take into account the optimization of the machine cycle while respecting the appropriate boundaries from machine protection constraints and the operational flexibility required during commissioning. Specific aspects related to ramp and squeeze, with pro's and con's of alternatives of the run configurations tested so far, are also discussed.

INTRODUCTION

The 2010 LHC operation was an important success for the first physics goals but also for gaining operational experience. All the critical and complex operational phases were well under control to the extent that stable running conditions with highly automated sequences were achieved in the last months of run. Clearly, in this first operation year the focus was put on machine safety rather then on the optimization of performance aspects like the turnaround. On the other hand, the experience gained provides already an opportunity to look critically at aspects the can be improved for the 2011 operation. In this paper, after a brief introduction of the 2010 run configuration, the nominal LHC cycle is presented and all the relevant operational phases are described. An analysis of the time durations of the various phases during stable operation for proton and ion physics is carried out to identify the major bottlenecks for the turnaround optimization and possible improvements are proposed to optimize the 2011 operation. Before drawing concluding remarks, the possibility of combining ramp and squeeze is also addressed.

RUN CONFIGURATIONS AND APPROACH FOR DATA ANALYSIS

Run configurations in 2010

Figure 1 shows the integrated luminosity delivered in 2010 to ATLAS and CMS as a function of the LHC fill number during the proton operation. Three running periods can be identified [1, 2]:

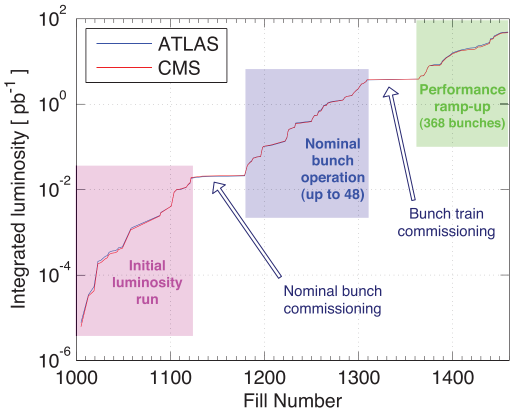

Figure 1: Integrated luminosity in ATLAS and CMS as a function of the fill number during the 2010 run. Courtesy of M. Ferro-Luzzi.

1. Initial luminosity run with reduced bunch intensities (up to 13 single bunch of a few 10^{10} protons);
2. Nominal bunch operation with single bunch injection (up to 48 bunches);
3. Nominal bunch operation with bunch trains (up to 368 bunches for physics fills).

The proton run was followed by a 4 week period of ion physics when the machine was operated in the same mode as period (3), with difference in the settings of crossing and separation in the interaction points (IPs) that are not relevant for the scope of the turnaround studies..

The transition between different periods was made possible through dedicated commissioning phases of the various systems, notably of the machine protection-related systems [1]. These transitions correspond to the flat lines in the delivered integrated luminosity plot of Fig. 1, which are all followed by a rapid increase of the luminosity.

Assumptions for turnaround analysis

The analysis of the turnaround statistics is focused on the proton run period (3) that led to the record performance of 25 MJ stored energy, with peak luminosities above $2 \times 10^{32}\mathrm{cm}^2\mathrm{s}^{-1}$ and on the ion run. This configuration is the most representative of the 2011 operation in terms of machine configurations (bunch train injections,

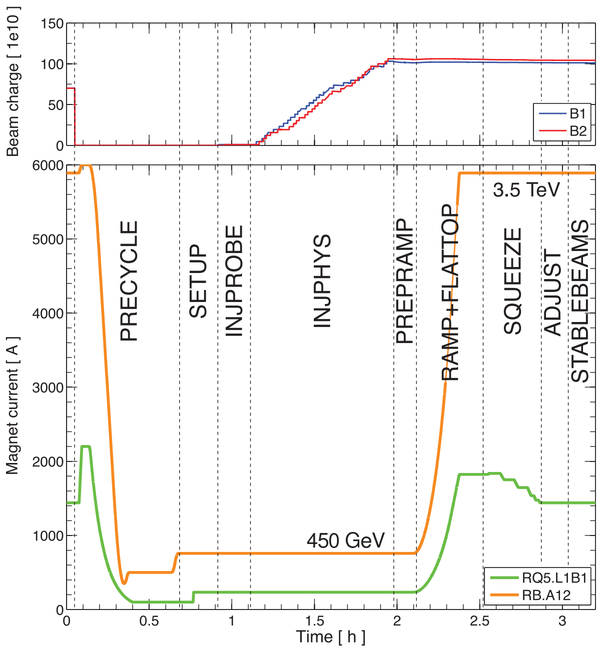

Figure 2: LHC turnaround cycle. Beam charge (top) and current of the main dipoles (orange) and of a matching quadrupole (green) are given as a function of time.

crossing angles, etc.), hardware parameters (nominal ramp rate for the main dipoles of 10 A/s) and beam parameters (single-bunch intensity, emittances, collimator settings, etc.). In addition, throughout the period (3) the parameters were kept constant with essentially no changes except the number of bunch trains injected, which makes a statistical treatment meaningful. The operational sequence had converged to a stable version with minimum manual action that will be used as a solid base for the 2011 sequence.

In the results presented here, only physics fills that successfully made it to physics are considered. The times spent in the various machine phases are calculated from the logged times of the beam mode [3] changes. This information is stored in the LHC logging database. This calculation is only precise to within tens of seconds to minutes, depending on the modes. This uncertainty occurs because some mode changes are not all done in an automated way but still rely on manual executions of sequences. This small error is not relevant for the total turnaround time estimate.

Note that the analysis of system faults and of machine availability is not treated here (see [4]). Additional aspect related to specific improvement for 2011, also affecting the machine turnaround, are discussed in [5].

LHC OPERATIONAL CYCLE

The different phases of the LHC operational cycle, from a top-energy dump to the next "stable beams", is illustrated in Fig. 2. The "stable beams" mode is declared for experiment data taking after the beams are put in collision and does not require further manipulation other than the fine optimization of the collision point. In Fig. 2, the beam intensity (top) and the current of main dipoles and a matching quadrupole, which shows when the squeeze takes place, are given as a function of time. The vertical dashed lines show illustratively when the mode change took place during the cycle. Here, the list of machine phases considered differ slightly from the official mode definition [3].

Table 1: Minimum times for the machine phases with the 2010 parameters.

Machine phase	Time [s]
Pre-cycle	2100+300$^{\#}$
Inject probe	300
Inject physics	1900 (=50×38)$^{+}$
Prepare Ramp	120
Ramp	1400
Flat top	60
Squeeze	1041
Prepare collisions	108
TOTAL	2h00

$^{\#}$ An additional time of 300 s must be taken into for a discrete current trim that brings the circuits to the maximum current. Also note that, if a standard precycle starting from zero current has to be performed instead than the recovery precycle from top energy, the total precycle time becomes 3100 s.
$^{+}$ Approximate figure for the maximum number of injections used in the 2010 (38) and for a 50 s long SPS cycle.

The minimum time for each mode, calculated with the 2010 parameters, are listed in Tab. 1. Note that the theoretical minimum are in some cases smaller than the ones that were possible in 2010. For example, longer than nominal SPS cycles are required to perform injection quality checks and therefore a ≈50 s long cycle was used instead than the minimum of ≈18 s (see [6] for possible improvements). In this paper, the parameters of 2010 are taken as a working assumption.

ANALYSIS OF 2010 STATISTICS AND POSSIBLE IMPROVEMENTS

Overall turnaround performance

In Fig. 3 the distribution of time intervals between beam dump at top energy and following stable beams is given. Blue and red bars correspond to the different ramp rates used in the running period (1) and (2), i.e. 2 A/s, and (3), i.e. 10 A/s. Only the proton fills are considered. The best turnaround times are 3h40 and 2h45, respectively. Even in the best cases, this is at least 45 minutes above the theoretical minimum achievable with the 2010 parameters (Tab. 1). In Tab. 2 the average time duration of the key phases of the LHC cycle is given for the proton run period (3) and for the ion run. The data are given also in the bar chart of Fig. 4. Error bars are large is some cases but the average values give a good indication of where time was lost.

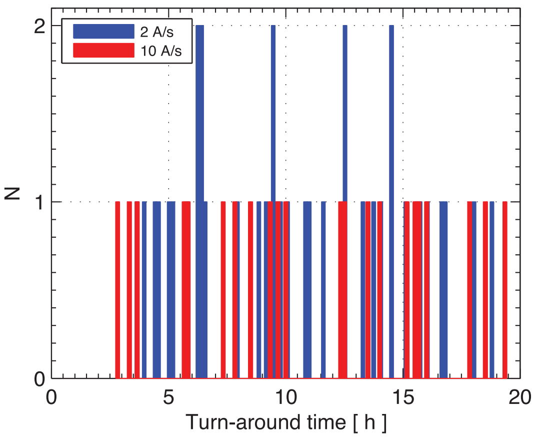

Figure 3: Distribution of turnaround times for proton physics fills, calculated as difference between time of the “stable beams” start and time of the previous beam dump at high energy. The fastest times to re-establish stable beams were 2h45 for the 10 A/s ramp rate and 3h40 for 2 A/s.

Table 2: Average times spent in the different operational phases (physics fills only). One standard deviation of the time distributions is given as error estimate.

Machine phase	Proton run (3) Time [h]	Ions Time [h]
Injection	3.0 ± 2.8	2.6 ± 2.4
Prepare Ramp	0.14 ± 0.09	0.10 ± 0.05
Ramp	0.43 ± 0.08	0.43 ± 0.03
Flat top	0.13 ± 0.18	0.05 ± 0.04
Squeeze	0.56 ± 0.18	0.43 ± 0.05
Prepare collisions #	0.22 ± 0.12	0.25 ± 0.08

For ions, the functions to collapse separation and set the collision crossing angles were 180 s long instead than 108 s for protons to allow larger angles in ALICE.

In the following sections, the different machines phases are analysed separately to understand the address the different sources of efficiency reduction. It is worth noticing that the overall performance is actually a good achievement for the first year of operation of a machine of the complexity of the LHC.

Precycle and setup without beam

After a beam dump at top energy, the LHC magnets are precycled. If there are no errors that required resetting the converters, the previous ramp is used as a part of the precycle and the magnets are brought to the injection values in an appropriate and controlled way [7]. This is the case for the example of Fig. 2. In case of errors, a precycle that starts from the minimum power converter current has to be used, which takes 3100 s instead than 2100 s. For both cases, additional ≈ 300 s must be taken into account to bring the converters to the first point of the functions.

The precycle length is by far sufficient to prepare the machine for the next injection, which includes verification of settings, conditioning of injection kickers, driving collimators to injection settings, performing the injection handshake, RF synchronization, etc. No improvement of the setup time is therefore easily possible unless the hardware parameters of the superconducting circuits are changed, which is not addressed in this paper. The nominal sequence is being improved in order to ensure that actions that can be run in parallel are done by the LHC sequencer in order to minimize the risk of human error while remaining in the shade of the magnet precycle.

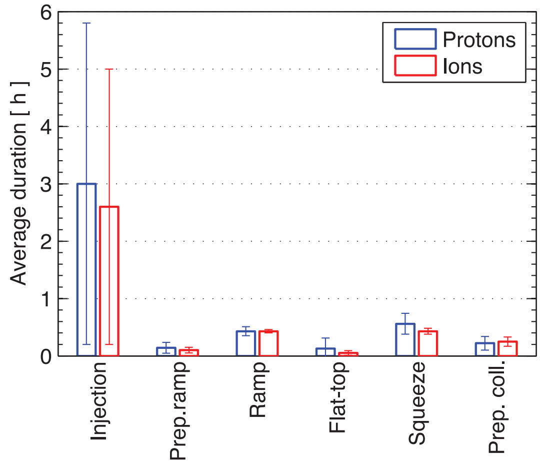

Figure 4: Bar chart of the data of Tab. 2.

Injection

The distribution of times required for injecting physics fills, calculated as the sum of setup time with pilot beams and of physics beam injections, is shown in Fig. 5. The minimum time (dashed red line) is calculated for the case with the largest number of bunches (368) and hence it is a pessimistic estimate. Nevertheless, the achieved values are well above this minimum value, with an average of 3 hours (with a large spread). Even if one excluded cases above 5 hours that might indicate specific and severe problems, the typical injection times range between 1 and 4 hours. There is obviously room for improvement so it is necessary to review the reasons that caused loss of time.

Without going into the details of the problems encountered, which are treated extensively in other papers of this workshop [8, 9, 6], the main sources of problems are listed below with possible paths for improvements:

- *Problem*: Injection losses (1) on the collimators at the end of the lines seen by the LHC BLMs and (2) on the superconducting triplet and on the tertiary collimators caused by uncaptured particles kicked by the injection kickers.
  Possible improvements: addressed in detail in [8, 9]. Ideally, one should be able to mask the beam loss signals at injection to avoid interlocks (*sunglasses*).

- *Problem*: Long setup times of the LHC beams in the

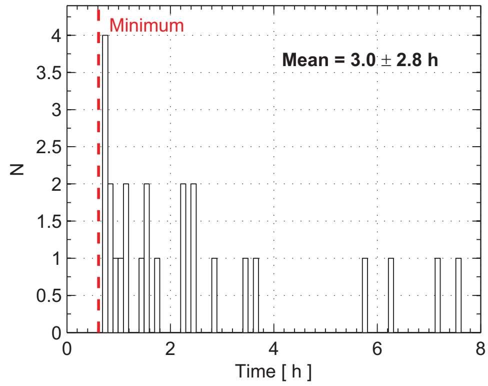

Figure 5: Distribution of times spent for injecting fills for physics, calculated as the sum of the times required for setup with pilot beams and of the physics beam injections. The red dashed line represent the minimum injection time calculated for fills of 368 bunches.

injector, primarily caused by the complexity of the many parameters to optimize (transverse and longitudinal blow-up, bunch intensity, tails scraping, etc.) [10].
Possible improvements: Procedures should be established to make sure that the beam setup in the injectors is completed timely during the recovery after a beam dump. Ideally, if agreed by the physics coordinators, one could consider to check the beam availability/quality before dumping the LHC beams in order to exclude major faults in the injector chain. A more efficient communication with the operation crews of the injectors is needed. The setup time would also profit from shorter SPS cycles (see next item).

- *Problem*: Long reaction times of the Injection Quality Checks (IQC) that stops the injection requests for both beams if either beams has errors, with subsequent loss of 1 to several SPS cycles.
Possible improvements: the injection request for one beam should be separated from the IQC results of the other beam (as it is for the software interlocks already) to allow continuing alternates injection while the IQC of the other beam is reset.
IQC thresholds should be adjusted to reflect real problems, e.g. requiring the expert intervention. In 2010, often the injection were blocked by conditions detected as problems that could simply to be ignored to continue the operation.
In addition, the time for the IQC analysis should be reduced as much as possible because in 2010 this was the reason to use long SPS cycles.

- *Problem*: Failing over-injections implying loss of the pilot beam, which the require restarting the injection procedure with several change of users for the injectors.
Possible improvements: The causes of this problem are several and cannot be fully excluded. It is recommended to leave a slot for witness pilot beams in the physics beams or to over-inject onto the pilot at the second injection such that a failing injection of the first high-intensity beam will not affect the circulating pilot. One should also consider the possibility to have an SPS cycle with pilot and physics beams to avoid frequent changes [6].

- *Problem*: Lengthy setup times with pilot beams before establishing reference orbit, tune and chromaticity.
Possible improvements: Tune and chromaticity reproducibility would profit from preventive trims that take into account the multiple decay as a function of the time spent at injection current [11]. These types of trims have be done manually in 2010 and should now be incorporated in the LHC sequence.

- *Problem*: Poor quality of the injected beams, e.g. missing or excessive scraping, unequal bunch intensities or emittances, etc., which occasionally required to dump and re-start injection in the LHC.
Possible improvements: The SPS BQM [10] detect efficiently longitudinal problems and prevents injections of poor quality beams. One should consider similar checks for the transverse parameters. For the moment, checks can only be done manually by disabling the SPS extraction with the hardware button, which is clearly not efficient nor error prone.

- *Problem*: Several iterations required to converge with the RF loops. Time was lost for the setup of the synchro loop also because the energy of the injected beams was mismatched from the reference orbit energy.
Possible improvements: The operation crew must be provided with sensitivity tables for the energy trims needed to correct synchro loop errors and with detailed procedures and tolerances that clarify when corrections are needed (this was often left to the choice of the shift crew). Ideally, the reference orbit should have the same energy as the injected beams. Differences should be corrected with the orbit correctors instead of with frequency trims (implementation is ongoing [12]).

In addition, if the need for frequent entries of snapshots remain actual for the 2011 operation, it is suggested to make available tools for automated entry of images into the operational logbook because this cause losses of time.

Preparation of the ramp

The distribution of times spent preparing the ramp is given in Fig. 6: the average time is slightly above 8 minutes, with several cases above 15 minutes. Special care in this phase is justified because mistakes leading to a beam dump after the start of the ramp functions would cause a

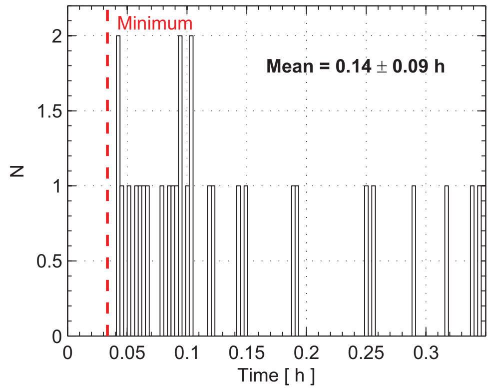

Figure 6: Distribution of times spent for preparing the energy ramp.

loss of several hours. On the other hand, improvements are possible.

In order to prepare the energy ramp, the operation crew has to verify orbit, tune and chromaticity, switch ON orbit and tune feedback, incorporate the injection trims into the ramp functions, secure the injection kickers (MKIs) and then open injection collimators, close the injection handshake and load ramp functions for power converters, RF and collimators. A number of checks are also performed before triggering the ramp. Strictly speaking, only the movement of injection protection, the preparation for the MKIs and the load of ramp functions must wait until the end of the injection.

It is recommended to start the orbit and tune feedbacks during injection: this would allow the OP crew to keep the parameters constant without need of further trims and thus to anticipate the setting incorporation. Some care must be taken in switching ON the radial feedback only at the end of injection because it has to be kept OFF during injection in case of energy differences between injected beam and reference orbit for the ramp.

Energy ramp

The energy ramp is performed with functions of well-defined length and there is no way to improve the ramp time without changing the hardware parameters of the main dipole circuits or to change the setting generation [13]. As the maximum ramp rate of 10 A/s is only obtained for about 20 % of the ramp time after a gentle start with parabolic and exponential shape, work is ongoing to speed-up the initial part of the ramp functions [14].

After the energy ramp to 3.5 TeV (1020 s), a flat branch of 380 s is used to compensate the decay of orbit, tune and chromaticity: feedbacks are left ON while the fields decay after having reached the energy and a feedforward correction of the chromaticity is applied. The length of this branch was determined empirically and it will be reviewed with the new ramp functions in order to see if some time can be gained there.

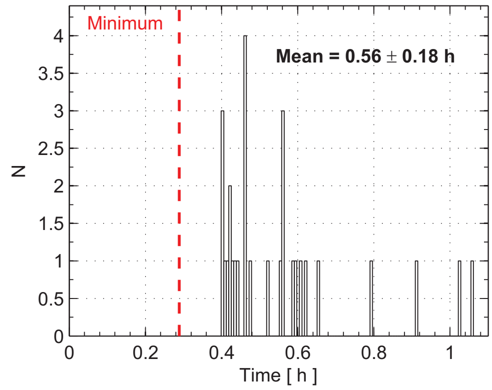

Figure 7: Distribution of times spent for betatron squeeze.

Flat top

After the end of the ramp function execution, a flat top setup is dedicated to the preparation for the squeeze: orbit, tunes and chromaticities are checked, the reference for the feedbacks are updated if necessary and the end-of-ramp settings are incorporated into the squeeze functions. This phase took 8 minutes with a couple isolated cases above 30 minutes. Theoretically, all this preparation could be done during the ramp: the experience with the operation in stable machine configuration showed as good reproducibility at top energy so no trims are usually required.

Changes of the orbit reference were still needed due to a change of crossing angle settings performed during the first part of the squeeze. Minor differences between orbit at injection and at top energy were also often seen because of the reference used for different collimator setups. For the 2011 operation, focus should be put in establishing one common reference to be kept throughout ramp and squeeze.

Squeeze

The execution of the betatron squeeze is done like the energy ramp by executing functions of a well-defined time length. Stops in two points were needed at intermediate β^* values in order to (1) change the orbit feedback reference for a reduced crossing angle configuration and to (2) close the tertiary collimators to their protection settings (one step movement done at $\beta^* = 7$ m). These stops at intermediate points were done by loading parts (“segments”) of the functions [15]. This mechanism was fully implemented in dedicated sequences. As shown in Fig. 7, the total time for the squeeze took in average twice the theoretical minimum of 1041 s that one would get by running continuously the functions without stopping. The squeeze required longer time than the energy ramp (Tab. 2).

It is interesting to note that the time lost at the stop points has been reduced as the operational experience improved (see Fig. 8). This performance improved further during the ion operation (Tab. 2) thanks also to an improvement of the sequences and to the confidence gained by the operation

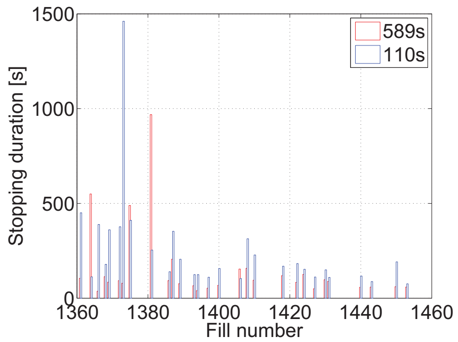

Figure 8: Time lost at the squeeze stop points as a function of the fill number. Courtesy of X. Buffat, EPFL.

crew.

Even if the time lost due to stop points is moderate compared to other phases of the operation, this mode of operation of the squeeze was often source of human errors, in particular for the feedback setting change. The manual manipulations combined with some issues with the implementation of the set of feedback reference caused several mistakes that led to beam dumps. An important goal for the 2011 operation will be to run the squeeze functions through without interruption. This can only be achieved if the feedbacks will be modified to to accept time-functions as reference, both for orbit and tune values (first implementation tested already in 2010).

The squeeze performance was also improved by feedforward corrections of the tune and by regular coupling compensation [16]. Coupling is particular important for the operation of the tune feedback because it can compromise its performance if not controlled better than 3 % of the tune split of 0.01. Feedforward correction are important to reduce the dependence on the feedbacks and should therefore be applied regularly in 2011.

Work is ongoing to improve the time length of the squeeze functions by optimizing the number of intermediate matched points that presently are being stepped trhough. Preliminary results indicated that at least 5 minutes could be gained while keeping the relevant beam parameters under control. Final results will be available by the end of January 2011.

Preparation of collisions

In this phase, the parallel separation of the counter-rotating beams is collapsed to establish collisions and at the same time the knobs for the optimization of the collision point are ramped to the values of the previous fill. At the same time, the tertiary collimators in all IPs follow the local orbit to maintain optimum settings all the time. This is achieved in mode "ADJUST" and the minimum time for the function execution was 108 s (180 s for ion with larger crossing angle change), limited by the ramp rate of the orbit correctors in the IPs. On average, this phase took took 13 minutes.

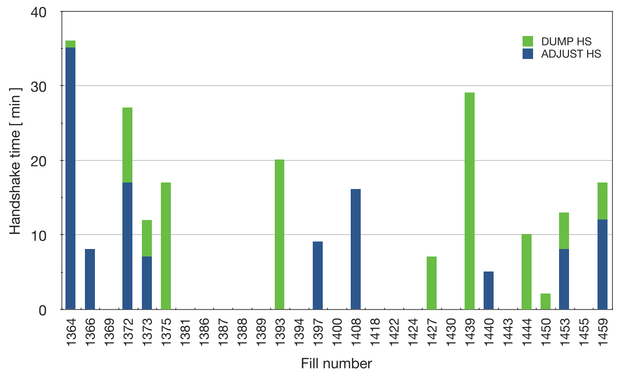

Figure 9: Duration of the dump and adjust handshakes as a function of the fill number for the physics fills of the proton running period (3). Fills with no data were ended by emergency dumps. The durations given here are calculated from the automatic handshake entries in the LHC OP logbook.

A way to improve this phase will be to reduce the parallel beam separation during the energy ramp. For beam-beam constraints, the separation at the IP's could be reduced proportionally to the square root of the beam energy, which would yield a 700 μm separation at 3.5 TeV for the nominal separation of 2 mm at 450 GeV. A linear variation of the separation versus time during the ramp will be implemented in the orbit feedback for the 2011 operation.

Closure of the dump handshake

The dump handshake [17] is a protocol used to communicate to the experiments an upcoming *programmed* beam dump request. According to the present procedure, a dump can only be made after all the experiments have successfully responded to the handshake. On the other hand, safety conditions are fulfilled all the time because unforeseen emergency dumps can occur anytime. Indeed, a significant fraction of the physics fills was ended by dumps triggered by the machine protection system [18], with no problems so far. An adjust handshake is used to exit from the stable beams mode while keeping the beams in the machine, typically for end-of-fill studies.

The times required for the dump and adjust handshakes of the fills under consideration are given in Fig. 9. Fills with no data represent cases of emergency beam dumps without handshake. Blue and green bars are added in case both adjust and dump handshakes took place for the same fill, for example if an end-of-fill study that required the adjust mode took place. Typically, the dump handshake takes less time if done after the adjust handshake. Up to 30 minutes could be lost due to punctual problems with some of the experiments. For 2011, the need for dump handshake has been questioned. The argument is that the experiments might loose precious time of data taking if they respond promptly to the handshake request and switch OFF sensitive equipment while other experiments have problems that block the handshake closure and hence delay the beam dump. The possibility to skip or revise the procedure for the dump handshake is being addressed.

Miscellaneous

It is recommended to establish clear procedures for the beam measurements at top energy: a homogeneous approach should be agreed upon about the need of chromaticity measurements (after the ramp and before bringing the beams in collision) and about the set values. Measurements can be time-consuming at top energy and are not completely risk-less so the choice should not be left to the people on shift.

It appeared clear that the tools to address operational statistics are not adequate (see also [4]). This problem should be addressed consistently. More automated changes of the beam modes are also to be envisaged because in some cases they are still not done homogeneously by the different shift crews.

It is noted that the fill number is changed during the machine setup before the injection. This complicates significantly the analysis of the fill statistics because the setup time belongs to the previous fill. It is therefore proposed to change the fill number immediately after the beam dump.

A LOOK AT ION OPERATION

The 4 weeks of ion operation that followed the proton run provided a good playground to test some of the improvements that were identified for protons. Magnetically, the machine behaved essentially in the same way as for protons and the proton sequence could be used with minor changes. The improvements can be summarized as:

- The filling scheme did not require over-injection nor change of the SPS cycle as the pilot used for injection setup was part of the physics scheme (same intensity). This improved as expected the problem with the missing extraction from that SPS that often kicked out the pilot for protons. The other issues related to the injection remained (except for the intensity related ones).

- The sequence improved further the automatization of some manipulations, like the change of tune feedback reference (only checks were available for the proton run).

- The learning curve for the squeeze continued and the time lost at the stop points was reduced by more than 20 % with respect to the proton run (Tab. 2).

- Improvement of the nominal sequence to execute in parallel the tasks that can be done without beam during the precycle.

Other than these improvements, the issues and limitations discussed for protons remained similar and the conclusions of the ballpark figure are the same.

COMBINING RAMP AND SQUEEZE

Ideally, one could optimize the LHC cycle length and virtually reduce to zero operational mistakes by driving the machine through one continuous function for ramp, squeeze and collisions. The time gain would be of about 0.5 h if the average figures of Tab. 2 are considered. From the beam physics point of view, the 2010 experience indicates that this could be achievable considering the machine reproducibility and the performance of the relevant systems (rarely trims were required in standard operation with feedback operational). On the other hand, this approach would also require more pilot fills to optimize the machine, as all the systems will be fully frozen in the standard operation while playing one long function. Essentially, much of the present operational flexibility would be lost. A very efficient method to stop when desired must be put in place (most likely, with different sequences than the nominal one). The total gain in time must therefore be evaluated and is not given for granted. New software implementation would also be required (1) for the generation of settings for combined functions and (2) for breaking in segments critical limit functions for the collimators. This implementation cannot be started timely for the 2011 because more urgent actions were identified.

For similar arguments, the possibility to perform (part of) the squeeze during the energy ramp is also considered a pre-mature option, in particular taking into account the fact that the most critical squeeze steps at low β^* can only occur at top energy due to aperture consideration. The price for a limited gain in time will be a loss of flexibilty that we still plan to profit from in 2011.

Having said that, it is clear that these two options (continuous functions for ramp, squeeze and collisions and combined ramp and squeeze) remain very promising and will be pursued. The implementations required will be followed up during 2011 with the aim of testing the new schemes in dedicated MDs to address their feasibility and the potential gains.

CONCLUSIONS

The analysis of the different LHC cycle phases during stable operational periods of the 2010 operation has been used to identify bottlenecks of the machine turnaround and possible improvements for 2011. Even if the 2011 performance is outstanding for the first year of operation of a machine of the complexity of the LHC, it is clear that there is a lot of room for improvement. The turnaround time is often dominated by the injection process, which can be improved in many respects. The gain from other machine phases can realistically sum up to 0.5-0.8 h, driven by a further improvement of the actions that for the moment are still relying heavily on manual operations. Paths for improvements have been drawn for all the phases.

Even if additional improvements could be achieved with more aggressive approaches, such as continuous and/or combined functions for ramp, squeeze and collision, these solutions seem still premature at this stage of the LHC commissioning and will be addressed after having improved the turnaround in the present mode of operation. The benefits do not seem yet to compensate the reduction of flexibility that will be imposed. These solutions are nevertheless being followed up for MD studies.

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SOFTWARE AND CONTROL ISSUES

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Abstract

The software applications and fixed displays in the control room are the unique windows to the LHC, the interface used to give it orders, diagnose its state of health and control its behavior. The better tools we have to communicate, the more efficient is the operation team to detect and cure problems, and also run the accelerator in an efficient way. Despite the impressive number of well working applications available in CCC, there is still room for improvement. This paper describes the main difficulties and issues encountered during 2010 LHC run that could be solved by improving the existing software applications, or by creating new ones.

INTRODUCTION

2010 has been a year of debugging for software in all domains of the accelerator and at each layer of the control system, from the PLCs to the user applications. The debugging and solutions of the diverse issues has been done with an amazing reactivity from the equipments control experts and high level application developers. They had to be very flexible to cope with the fast evolution of the LHC and to accept new requirements that came up. At the end of 2010 run, we can be proud of the impressive number of well working applications that are available in the CCC. At the same time, a full year of experience with the machine operation also leaves us with a big list of things that should be improved to make LHC operations easier and safer. A not exhaustive list of the mains requirements is presented hereafter.

EQUIPEMENT CONTROL

In general, the equipment software is well under control now. Still, some requirements to strengthen or improve the software are expressed.

TCDQ software

During 2010 run, several control problems for the TCDQ have been encountered. The origin of the main problem is the FESA class that does not handle properly the TCDQ statuses. The PLCs, low level control of the TCDQ is designed with the standard BT interface for SPS girders (MST, MSE and ZS), whereas the FESA class has to provide an LHC collimator like interface. In some cases, the mixing of status handling between low level and FESA led to the following problems:

- TCDQ stays armed when it is already at the requested position, then it does not accept other command until manually disarmed.
- TQDQ reports an idle state, but in reality stays armed and then moves unexpectedly at the first collimator timing event.

These problems appeared in the middle of the run in case of some combinations of expert commands, whereas it was not seen for standard operation.

As a solution, Etienne Carlier's team has already developed a new version of the PLC software that will handle by itself all the statuses and provide an LHC collimator like interface. The FESA class will be simplified, and will only publish the low-level statuses. This has been tested already in the test bench and will be deployed during the shutdown.

In addition, Etienne Carlier recommends creating separate sequences for the TCDQs that can be better adapted to its particularity.

RF

The control room applications for RF systems cover the needs to control and drive the RF cavities and ADT.

Nevertheless, RF diagnostics tools are still missing, like a detailed panel of the hardware interlocks for the RF lines, and a better display of the RF signals (e.g. mountain range) in the CCC.

Power converter PIC and QPS

In the control room there is currently no efficient way to restart individual power converters after a trip. Global sequences to prepare or drive the power converters by sector are available, but if we need to control only a sub-set of them, not less than 4 applications are needed:

- The equip state application to reset and drive to the operational value
- The PIC application to reset and give permit
- The Circuit synoptic application in case QPS switches need to be closed
- The generation application to set resident the necessary beam processes.

We have to switch from one application to the other to perform resets, open switches, give permits, reset again and drive to the right settings. In addition, the PIC and circuit synoptic application requires a special password as these systems are not protected by RBAC. This procedure needs to be simplified, for example with a dedicated sequence.

SOFTWARE FOR INJECTION

As shown in the presentation given by Stefano Redaelli about the LHC turn over [1], the injection process is very time consuming compared with the other phases of operation. As opposed of the pre-cycle or ramp phase, whose duration is driven by the magnet functions, it is possible to reduce the time spent at injection with some software modifications. At the same time, the process to prepare the injection scheme can be more efficient and the risk of getting a wrong circulating bunch configuration can be reduced.

Injection Sequencer and IQC efficiency

As the injection sequencer is designed, the B1 and B2 injections are done one after the other. This implies that to start requesting injection for one beam, the IQC analysis of the other beam has to be finished. As the IQC analysis takes time, the supercycle length of the SPS has to be adapted to achieve one injection every supercycle, but this is difficult because the analysis time of the IQC is not constant. Therefore, the injection sequencer should be modified to make B2 injection possible as soon as B1 is injected, i.e. without waiting for the IQC analysis. This would allow for shorter SPS supercycles with always optimal length. This change is limited to the injection sequencer GUI: no change has to be done at the IQC, SIS or CBCM level.

The other time consuming factor is the many IQC latches. The IQC is there to give a qualitative result of the injection, and the chosen design was to stop the injection process if the quality of the injection is not optimum. The problem is that several iterations were needed to estimate the correct thresholds (MKI pulse or BLM thresholds) needed to fairly qualify an injection as “good” or “bad”. In addition an IQC latch didn’t lead to any special corrective action, the OP team was instructed to unlatch and continue. One possibility to improve the situation would be to relax the threshold so that the IQC doesn’t latch too often, but then we would miss the valuable information that the quality of the injection wasn’t optimal. An other idea to consider is that “good” or “bad” is not enough, and an intermediate level could be added meaning that the process do not stop when the quality is not optimal, but the status is given as an information to the operation team. The level “bad” has to be reserved when an injection is so dirty that an immediate action has to be taken.

Also to be improved is the IQC playback application that should allow analysing the injections quality offline. For example, it misses filters by injection result.

Circulating bunch configuration

The circulating bunch configuration for each beam is an array with all the RF buckets that are filled with a bunch. This important information is distributed to the experiments via DIP and to certain equipment and software via a FESA class. It is also used by the injection sequencer to prevent unwanted over-injections. It is then very important to get it always right.

The circulating bunch configuration is updated by the injection sequencer according to the IQC analysis, which is responsible to publish the injection result. The decision of the IQC that beam has been injected or not relies on 2 BCTs measurement in the extraction line and the kicker pulse. Whereas it worked well with protons, with ions the BCT started to give false data to the IQC, which then reported an incorrect status of the injection (beam in when no injection has actually been done, or no beam even if the injection was successful). This implied that the circulating bunch configuration wasn’t updated properly, with the consequence that the beam couldn’t be injected anymore because the requested bucket was seen as filled, or we had a risk of over-injection because the injection sequencer repeated the request on the same bucket thinking it was empty. When it happened, the only possibility to go on with injection is to update the circulating bunch configuration table directly in the database, with the implied danger of database manual updates.

To reduce the risk of over-injection, soon a check has been added in the injection sequencer: before each injection the circulating bunch configuration is compared with the measurement given by the BQM, and a warning is given if this is inconsistent. The database is then corrected if needed.

In addition, the IQC should cross check the transfer line measurement with a ring measurement like a ring BCT or the LHC BQM.

It is already foreseen to add functionality in the LHC BQM to update the circulating bunch configuration directly from the filled bucket measurement, so no more manual update of the database would be needed in case of problem.

Filling schemes

For the 2010 run, almost 100 filling scheme have been created. The existing software to insert this filling scheme in the database is not flexible and efficient enough.

The bunch patterns, which are the SPS beam description that is then used to get the right bunch configuration in the LHC, couldn’t be created with an application but needed a direct update of the database by an SQL script. As a consequence, it is not possible to create new pattern without the knowledge of the database design and the connection right to the LSA database, and this has showed to be too restrictive especially during

MDs. A panel will be added to the injection scheme editor to create new bunch patterns.

The filling scheme had to be created manually, first creating the injection requests then assemble them. The source information to create a given filling scheme is a text file given by the machine coordinator containing description of all the necessary injection. The injection scheme editor application should be improved with the functionality to create the complete scheme directly from the text file. In addition of being much more efficient, this would also reduce the risk of errors.

LHC SEQUENCER GUI, SEQUENCER EDITOR

LHC sequencer GUI

The LHC sequencer is the key application in the control room, it has to be intuitive, easy to use, clear and above all, very safe.[2]

The first GUI that was developed by OP was not satisfactory. Users lost trust in it after experiencing some dangerous issues like the "run through" bug (the sequencer continuing to execute the following tasks even if the user pressed "step" to execute one task only). This GUI also had some layout problems. Therefore, it was decided to replace it by a new GUI developed by CO/AP section. The sequencer server was not changed. The good things of the previous GUI, like the quick launch panel, have been kept, and all the other OP requirements implemented. Still some improvements of the check list panel are needed. The sequencer GUI could also improve its flexibility by set the tasks parameters for certain tasks. (It would be useful if we get a sequence to restart a given power converter).

Sequencer Editor

During the 2010 run, an impressive number of tasks, sub-sequences and sequences were created. The existing software, the sequence editor, should be reviewed to include the listed requirements:

- A subsequence should be independent of a sequence, now a lot of sequences have been created with the only aim to contain the sub-sequences.
- The GUI should allow to copy, cut and past tasks, sequences and sub-sequences, possibly using drag-and-drop interactions.
- A clear tasks and sequence catalogue should be available.
- Change history should be made available for tasks, sequences or sub-sequences to show who changed what and why. A rollback possibility would be appreciated as well.

A new database schema is being implemented which covers part of the requirements listed above. A new sequences editor will be developed in 2011 to include all the new requirements and implement the new database schema.

LHC nominal sequence

The nominal sequence contains all sub-sequences and tasks needed to drive the LHC from ramp down to collisions. It has changed a lot during the run, following the fast evolution of the LHC: tasks have been added to replace manual actions, or to solve some issues. Others have been discarded or replaced. However, the overall structure of the sequence, especially the sub-sequences to prepare the LHC for injection, should be restructured to allow for more parallelism. For example, creating parallel sub-sequences that act in a single type of equipment would make this phase much more efficient.

The maintenance of the nominal sequence is a collective effort of several members of the operational team, who have to agree on a common way to operate the LHC. Better procedures and tools have to be put in place to prepare changes, to keep track of them and to distribute information about them to all the concerned persons.

STATE MACHINE

A state machine representing the functional states of the accelerator has been defined, together with a list of checks to be executed on each of the transitions. These checks verify for instance that certain actions have been carried out or that all the necessary equipments are ready for the next state. The checks are implemented as tasks in short "check list" sequences.

The state change is driven by the LHC sequencer

- A task in the nominal sequence request a change of state
- The state machine executes the check list sequence
- If all the tests are successful, the change of state is done.

A GUI application displays the state machine diagram and monitors the actual state. Another application shows which of the tests failed or were successful. The two applications will be combined into a single one soon.

The status of the state machine is well advanced; the mechanism for state transition has already been used at the end of the run and will be really operational next start-up. Still, the check lists have to be reviewed and some check tasks added.

In the future, the operational state will be distributed to other software and equipments to enable them to constrain their behaviour depending on the state, with the goal to increase safety of operations. For example, the sequencer will play certain tasks only in the appropriate operational state, and LSA will load certain beam process only in the corresponding operational state.

LSA AND SETTINGS MANAGEMENT

Problems with some hardware functions

Some of the hardware functions generated with LSA have a lot of constraints and end up being quite complicated, a good example being the tune-trim system and the RQTD and RQTF functions.

- Lots of source parameters and associated makerules
- Fast optic change during the squeeze
- Function has to be smooth and continue along the hypercycle (incorporation rules).

The so generated functions may have 2 kinds of problems

- The function doesn't load because rejected by the FGC. The FGC can raise an "Invalid time" exception in case some points of the function are too closed to each other, or a "di/dt out of limits" exception in case the function has at least 2 points with a di/dt over the FGC limit. The invalid time problem has already been solved by adding filters in the makerules. For the di/dt problem, a check of the max di/dt of the function will be added at the makerule, incorporation rule or value generator level. The advantage will be that if the function is not valid, it will be detected immediately and the trim (including regeneration and incorporation trims) will be rejected, whereas actually the problem is seen only at the moment we load the function (and the setting expert potentially long gone home).
- The function is loaded without problem to the FGC, but it trips the power converter as soon as played because the acceleration rate is too high and seen as a quench by the QPS. Implementing a check of the acceleration rate is not obvious, because it is a very difficult parameter to estimate for a function. The current evolution between 2 points has to be interpolated, but it hardly reflects the reality and can lead to reject functions that wouldn't cause real problems. Greg Kruk is working on a suitable solution. At the same time, work has to be done on a better smoothing of the function to avoid spikes. The idea is to add an intermediate parameters called Ksmooth that would handle the multiple sources for RQTF and RQTD, and apply a smoothing already at this level.

Other issues to be addressed

Incorporation

The incorporation has been one of the trickiest settings manipulations this year. This mechanism is quite complicated and difficult to understand for non expert, and this has sometime lead to errors. It has also some limitations that should be addressed:

- The possibility to define many incorporation ranges per beam process is already there, but should be improved with the possibility that a rule defined for a given range can modify the whole beam process.
- The GUI should help the user with the definition of ranges and in and out parameters. (Predefined parameters like start/end of beam-process for example).
- More sophisticated makerules should be created, to deal for example with the snapback or dynamic correction of B3 at injection.

LSA team will review, complete and simplify the incorporation mechanism and clarify the associated GUI .

Traceability, settings rollback and setting check

It would be very useful to have a way of logging every driven parameter and each beam process that is made resident. The trim history that we have is good when you know the parameters that have been trimmed, but if you want to know what parameter has changed it doesn't really help. At the same time, a rollback application (settings recovery at a given time), that would handle compound trims (e.g. orbit trims), is mandatory.

To guaranty the sanity of the settings, especially after MDs, we should be able to compare them with a reference beam process, which the details of implementation are still to be discussed. In a more general way, we should be able to easily compare settings of any beam processes.

MCS (critical settings)

The problem with MCS is that the re-generation of actual beam processes (that is done after ramp and during squeeze) does not work for critical settings as for the other parameters: with the present implementation, one can obtain usable settings only with expert signature (given by RBAC roles). If the expert is not there, in principle, the actual settings for critical parameters can't be regenerated. As this couldn't work in daily operation, complicated work around has been put in place: extra users linked to archived beam process for which the signature was manually generated. This makes the system more complicated and more difficult to maintain.

A solution for this problem is being implemented and will be in place next start-up.

An other issue with MCS is that it is not possible to load a segment of the function, as it is done for example for the squeeze function. As the possibility to have a combined ramp-squeeze-collide beam process is now seriously considered, this problem has to be addressed urgently.

OTHER SYSTEMS

Alarms

The alarm is now a robust and reliable system that could be used in a more efficient way for the LHC:

The LHC alarm screen is permanently filled with red alarms, even when the machine is working perfectly, the effect being that an important alarm can easily be ignored.

- OP and the equipment responsible should review the alarm configuration: what alarms are really needed by OP, and for each of the alarms carefully review the level.
- It would also help a lot if the alarm system where able to handle the machine modes properly, because, for example, an alarm can be very important at injection but completely ignored for other machine modes.

Diamon

When a problem occurs on a given application, it is often difficult for OP team to find the basic information like: what is the associated front end? Which software layer (e.g. middle-tier server, JMS broker, etc) causes the problem? Can the server be restarted without affecting the beam? Etc… Clear information of the dependencies between software processes and layers should be displayed in Damon.

In addition, Diamon does not always display the correct server status: some processes are permanently red whereas some others stay green even in case of problems.

This should be solved to make Diamon really useful for operations

Front-ends and Proxies

Front-ends and proxies still crash too often. This has often annoying effects, like data missing in the logging database, impossibility to perform measurements, loss of communication with experiments etc… And it can sometime have a big impact on the LHC efficiency if front ends of critical systems are affected.

Orbit and tune feedbacks

If most of the problem and issues of 2010 have been solved, there is still some improvement left to be done.

A reference change as a function of time is needed both for tune and orbit feedback (useful for tune change in squeeze, change of crossing angle, separation bump closure during ramp…).

The quality of the measurement should be estimated more precisely before the system decides to use it as input for trim.

2010 run has seen lots of discussions about the impact of the damper on the tune feedback measurement quality and how to reduce its effects. This has to be sorted out.

Fixed displays

There is a large amount of fixed displays permanently sitting on the LHC island screens. Apart from an obvious space problem, it is also more confusing for the team on shift that is given too much information. It would be very useful to define sets of fixed displays by machine mode, that the console manager could show and hide according to the LHC beam mode.

Injection interlocks

For the injection process, many interlocks systems are involved:

In SPS: the software interlocks system, the ring BIC, the extraction BIC and the BQM

In LHC: software interlocks system, ring BIC and Injection BIC with the experiments vetoes.

A simple fixed display with a status o all these involved interlocks would help OP team to diagnose faster the origin of the problem when beam has not been injected.

Software release

It never hurts to repeat that the releases of the operational software have to be well tested (proper test environment should be available). Also, the backward compatibility with previous version should always be checked to avoid unwanted side effects. Of course, the Friday evening releases have to be avoided, and the important changes coming with the release have to be communicated to the relevant persons.

Documentation

For most of the applications available in the control room, there is no associated documentation, or not in an easily accessible place. Although the OP team is familiar with “normal” use of most applications, they often need to ask experts for help for more advanced functions. This could be avoided if appropriate user manuals existed. They would also help for the training of new operators or EICs who have trouble finding sources of information.

CONCLUSION

A long list of requested improvement for many systems is presented in this document. Some of them are very important to reduce the turn around, like the injection software improvement. Some issues also need to be solved to minimize the downtime, like the TCDQ problem and the LSA settings management issues.

Efficiency could also be improved with an optimized nominal sequence. And the risk of error and mistake can be minimized thanks to the state machine and settings checks.

Some minor requests have also been expressed because they can help to diagnose problems more efficiently before calling the expert (RF interlock, diamond improvement), help to detect problems faster (alarms) and improve the ergonomics (dynamic fixed displays).

This represents a big amount of work for developers of controls, OP and equipment group. It will request also a dedicated testing time before LHC is back in operation.

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CAN WE IMPROVE THE MAGNETIC CYCLE/MODEL AND THEIR EFFECTS?

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Abstract

We first recall the precycling strategy defined for operation and we give an overview of how it has been applied in the 2010 run: in how many cases the previous physics run has been used as a precycle, in how many cases we precycled the magnets, and how we did it w.r.t. specifications. We then analyse the reproducibility of tune and chromaticity, giving an estimate of the present precision of the magnetic model and discussing if it is possible to improve it. We review how the hysteresis is presently treated in the field model, and its drawbacks on the beta beating corrections during the squeeze. Possible strategies to solve the hysteresis issue are presented.

INTRODUCTION

The LHC operation in 2010 has been very successful [1]. One of the key ingredients has been the good knowledge of the relation magnetic fields versus magnet currents, and its dependence on the cycles [2]. A beta-beating close to targets for the bare machine, without corrections, both at 450 GeV and at 3.5 TeV, is the best sign of the precision of the magnetic model. Taking into account that we are in the first year of commissioning (excluding the short but nevertheless intense experience of 2008), and with some settings far from the nominal operation, the achieved reproducibility has been remarkable. In this paper we summarize the main open issues of the magnetic model and we outline the highest priority topics that have been identified to ease operation in 2011.

The precycle strategy followed in 2010, which is the main ingredient of the reproducibility, is summarized. Then, we discuss the tune decay on the injection plateau The control of chromaticity at injection and during the ramp is then analysed. Finally, we summarize the hysteresis issues, which have been considered for a long time as a critical point of the magnetic model.

PRECYCLE

The precycle of the magnets is a key element to ensure the reproducibility of the accelerator [3]. During the 2010 run at 3.5 TeV, four different combinations of precycles, ramp rates and currents have been used (see Table 1). The initial phase at 1.18 TeV is not considered here. The ramp rate has been initially limited to 2 A/s, i.e., five times slower than nominal, to cope with issues related to magnet protection. For similar reasons the flattop current has been initially lowered to 2 kA - 4 kA. The nominal condition of the main dipole operation has been recovered in the last period, with the exception of the limitation to half nominal current (6 kA) corresponding to a top energy of 3.5 TeV.

Table 1: Features of precycles and ramps in 2010.

Period	Pre-cycle			Ramp with beam		
	Flattop (A)	Ramp up (A/s)	Ramp down (A/s)	Flattop (A)	Ramp up (A/s)	Ramp down (A/s)
19.03 to 16.05	2000	2	2	6000	2	2
17.05 to 22.07	4000	2	2	6000	2	2
23.07 to 29.08	6000	10	10	6000	2	10
3.09 to 31.10	6000	10	10	6000	10	10

The precycle strategy outlined in [3], based on several studies and measurements done before and during the production [4-6], aims at ensuring identical magnetic conditions for the accelerator after a physics run and after a precycle. This allows avoiding the precycle without beam if the physics run is normally terminated, with a considerable saving in the turn-around time.

Already in this very early phase of operation, 54% of the ramps used the previous physics cycle as a precycle. Notwithstanding several difficulties which jeopardized the initial phase of the commissioning, the precycle procedure has been strictly followed: only 3% of the ramps had an anomalous precycle.

The precycle time takes about 90 minutes, and is dominated by the interaction region quadrupoles MQM and MQY, which have unipolar power converter. In future one could envisage reducing the time for these circuits through hardware changes. For the moment this is not considered as a priority since the turn-around time is not dominated by these factors.

TUNE

The LHC tune decays during injection. The order of magnitude is 0.01, i.e., enough to need a correction (see Fig. 1). Time constants are rather long, i.e., a considerable decay is observed after one hour. The fit with the double exponential [4,5] gives time constants of the order of 1000 s. The operation can be bothered by this decay: since the last trims are included in the next run, the large trims used in a previous run with long injection time can push the tune on the resonances if the successive injection occurs much faster. Then the beam is lost and one has to inject again, losing precious time.

The other critical point is that for long injection times one has to monitor the tune continuously and to trim; if the damper is on this can be difficult to measure. An easy solution for the first problem is to reset the tune trims at each injection; indeed, one can do better and implement the full correction according to measurements. This is foreseen for 2011.

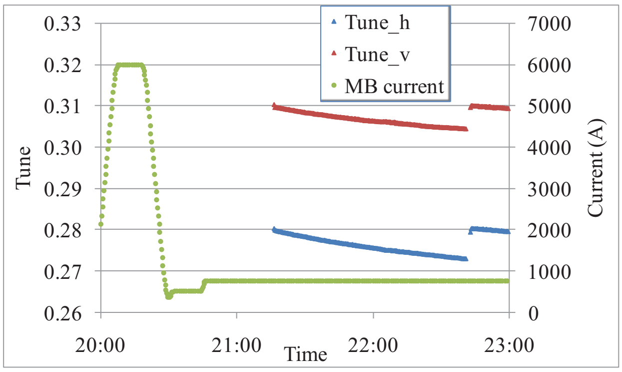

Figure 1: Measured decay of horizontal and vertical tune in different injection plateau.

CHROMATICITY

Decay at injection

In 2010 the magnets stayed at injection energy 1-2 hours [7] (see Fig. 2). We define this time from the point of view of the magnets, i.e., the time covering the span from dipoles reaching injection current to the beginning of the energy ramp. The minimal time has been 30 minutes, and the average time, including all ramps, of 5 h. During the injection plateau, the sextupolar component (b_3) in the dipole decays. The experience gathered through the magnetic measurements is that 80-90% of the decay takes place during the first 30 minutes (see Fig. 3). Since during the first year of operation we did not expect to inject in the first 30 minutes, the correction of the b_3 decay implemented in the control system has not been activated [8].

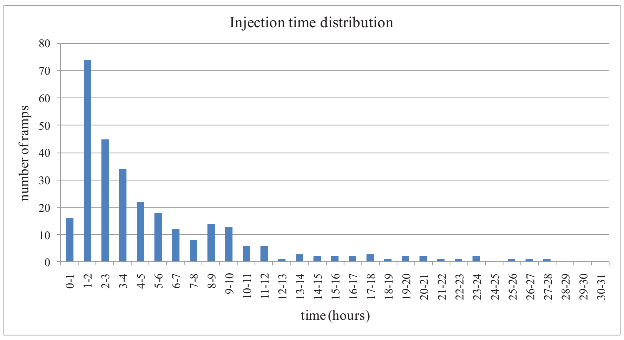

Figure 2: Time spent on the injection plateau by the main dipoles in 2010.

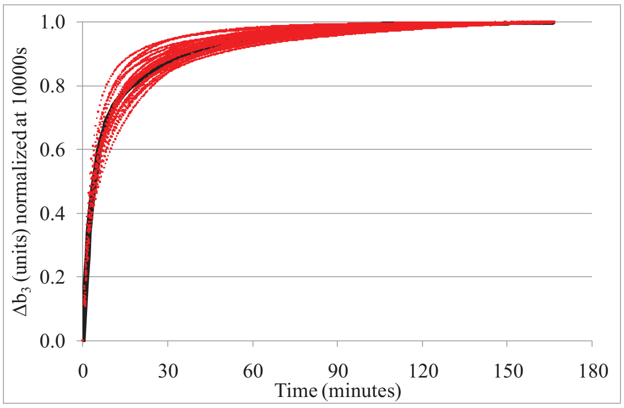

Figure 3: Measured decay in the main dipoles, normalized after 10000 s, versus time. Precycle at 50 A/s, flattop at 11.85 kA.

The expected amplitude of the decay with a 6 kA operation is 0.5 units, corresponding to 20 units of chromaticity [2]. The experience gathered during 2010 operation confirms this order of magnitude (see Figs. 4-5), even though a direct estimate is imprecise since no measurements are available from the time zero, where the decay is very steep. Indeed, the constant time is much longer, and 10 units of chromatic decay are observed from 2 to 10 h. A fit of the double exponential used for modeling the decay gives time constants of the order of 2000-4000 s, i.e., at least 10 times larger than what measured on the dipoles [5,6].

The large chromatic decay forced the operators to trim chromaticity before the injection, trying to guess the correct values and to avoid negative chromaticity based on personal experience and look-up tables. The implementation of the decay based on beam measurements is recommended for the 2011 run. From the point of view of the magnet builder, more investigation is needed to understand the discrepancy between the measurements of individual dipoles and the behaviour of the accelerator.

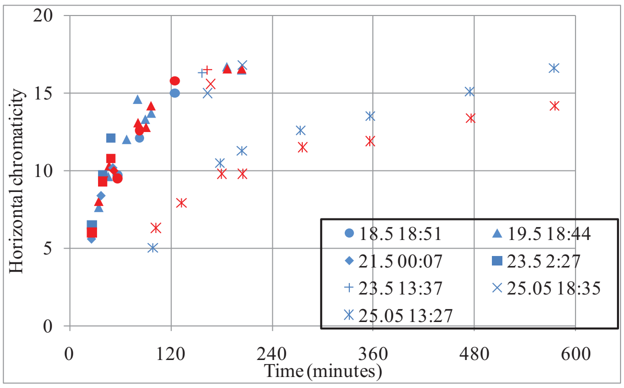

Figure 4: Measured decay of horizontal chromaticity in seven different injection plateaus [9].

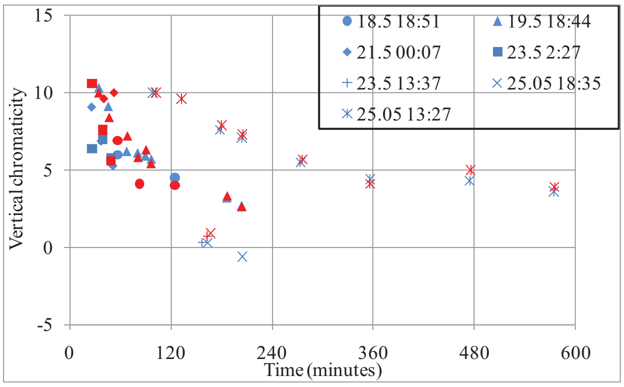

Figure 5: Measured decay of vertical chromaticity in seven different injection plateaus [9].

Behaviour during ramp

If the chromaticity decay is 20 units, as expected from magnetic measurements, during the snapback the model manages to keep track of two third of it, leaving about ±7 uncorrected units (see Fig. 6). This 30% error in the tracking precision has to be compared to the expected 20% error [10]: we are not yet there, but not so far.

The first possible source of error is the time constant of the snapback, which is given by the model and is related to the decay amplitude: a larger decay would imply a larger time constant [11], thus creating the pyramidal shape shown in the first 200 s of Fig. 6. Another source is the removal of the trims, which linearly decrease with time in 120 s: this could be too fast. We believe that there is space for improvement in 2011.

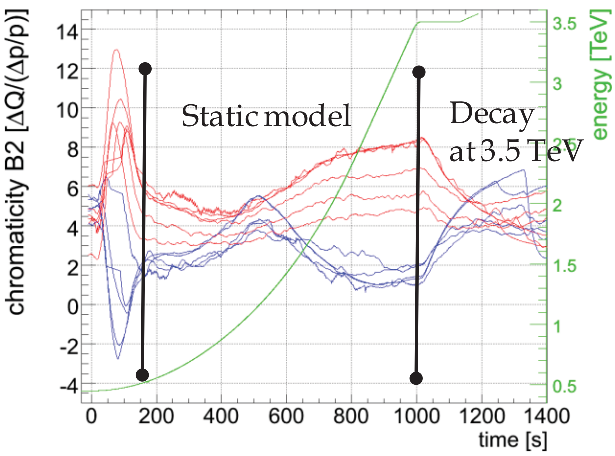

Figure 6: Chromaticity measurements [12] during the ramp in five different runs (red: horizontal, blue: vertical).

During the ramp, the model (with trims) tracks the chromaticity within ±3 units. The total change of b_3 in the dipoles from 450 GeV to 3.5 TeV is ~7 units, corresponding to about 300 units of chromaticity: this means that we manage to track chromaticity during ramp with an astonishing 1% error. Honestly, it looks difficult to make it better.

Surprise: the decay at 3.5 TeV is clearly visible (see Fig. 6) and corresponds to 5-10 units. For the moment, the strategy is to reach 3.5 TeV with a positive horizontal chromaticity of about 10 units to avoid ending up in the negative range when the squeeze is started. Moreover, a waiting time of a few minutes has been implemented to avoid setting the machine during the decay. This has not been shown to be critical for operation.

The good side of the story is that one could use the 3.5 TeV decay, measured with very good precision and not affected by the issue of the 'zero time', to guess the decay at 450 GeV. The higher the energy, the lower the decay: we will not see this at 7 TeV! But there are still a few years to go...

THE HYSTERESIS ISSUE

Hysteresis is a ghost that has periodically hunted the nights of the magnet modeller. Some years ago the hysteresis of the MQT, used for the tune trim, was considered to be too large, endangering the capability of setting the trim. Indeed, operation showed that this is not the case and that we have a full capability of controlling the tune. The same concern was expressed for orbit correctors, which today are not an issue for operation. More recently, a problem with the matching sections and dispersion suppressor quadrupoles has been identified: during squeeze, some magnets have decreasing current and reach very low values, where the persistent current component is large. Since the current is descending, the magnet is walking on the other branch of the hysteresis. Since the model considers only the upper branch, an error of several tens of units can be done on some cases [13].

The implemented strategy has been to change branch in the magnetic model, i.e., to change the sign of the persistent current component, when *dI/dt* changes sign. Unfortunately, this has shown some drawbacks [14]: during squeeze, some magnets have to perform small changes of currents, both positive and negative, and the current jumps on the other branch of the hysteresis, whilst the magnet stays close to the original branch (see Fig. 7). The same unwanted effect appears when trims are done to correct beta-beating during the squeeze. This reduces the efficiency of trimming.

The proposed solution is to remove the change of the hysteresis branch. This is inducing an error in some quadrupoles only for small β^* (below 1 m). These are deterministic, well-known errors that can be cured by a separate additional trim without jeopardizing the correction strategies. So for 2011 the change of hysteresis branch will not be in the model. A more refined approach would imply the complete modelling of hysteresis, i.e., including the path between the two branches. This is not considered to be a priority for the moment and could be treated after the first long shutdown.

CONCLUSIONS

Operation in 2010 started with conditions pretty far from the nominal ones, i.e. slower ramp and reduced energy. At the end of 2010, the nominal ramp rate has been reached. Notwithstanding these conditions, the precycling strategy has been strictly followed and has ensured remarkable machine reproducibility. More than half of the runs used the previous physics run as a precycle, reducing the turn-around time.

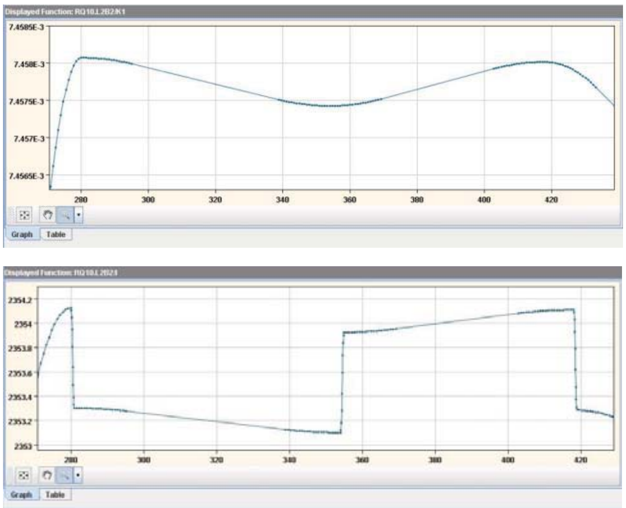

Figure 7: Quadrupole gradient during squeeze required by optics (upper part) and related current with the change of hysteresis branch.

Chromaticity control during ramp is done within 1%, i.e., a few units of b_3: this amazingly good result will be difficult to improve. On the other hand, some more work is needed to understand decay over times which are much longer than expected. At the beginning of the ramp, the snapback has proved not to be a major source of beam losses. Nevertheless, the model works with a 30% error, and additional work should be done to reach the 20% target that has been established many years ago.

The inclusion of the change of the hysteresis branch has shown to cause more problems (reduce the trimming capability) than what it had to solve. Since this change is only needed for a few magnets and for β^* below 1 m, we propose to remove it and to treat these magnets separately with ad hoc trims.

The magnetic model in the next years will be constantly improved through beam and magnetic measurements to ease operation and increase the integrated luminosity. The copious data coming from beam commissioning are also a fundamental tool to better understand the magnet behaviour, and to improve our knowledge needed for the future upgrades.

ACKNOWLEDGEMENTS

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What do we need to understand and optimize the LHC

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Abstract

The second year of LHC operation aims at a performance maximization of the operation at 3.5 TeV and will push the bunch intensities and the number of bunches to the maximum acceptable values. This paper addresses the potential challenges and limitations of this performance push and discusses desirable diagnostics and operation tools for achieving the best performance in 2011 and running the the LHC efficiently at its performance limit.

POTENTIAL PERFORMANCE LIMITATIONS IN 2011

The operation in 2010 identified the following potential challenges for pushing the performance in the LHC for the 2011 operation at 3.5 TeV:

- Electron cloud effects;
- Beam losses due to UFOs;
- Beam-beam effects;
- Overal accelerator efficiency and machine availability.

The following sections will discuss each point separately by giving first a summary of the operation observations in 2010, a short outlook at the potential performance reach for each point and a discussion of the desirable diagnostics and operation tools for operating the LHC at these performance limitations.

ELECTRON CLOUD EFECTS

The operation with more than 100 bunches per beam and 150ns bunch spacing showed a clear indication of electron cloud triggered vacuum pressure increases in the common beam pipes where the two LHC beams cross each other resulting in effectively shorter bunch spacings when considering only the interval of passing bunches at a given location. Figure 1 shows the vacuum pressure in the warm part of the common beam pipes near the experiments for operation with injection of trains of 8 bunches with 150ns separation as a function of time. The solid red curve shows the beam energy, the green and yellow curves shows the currents of the two LHC beams and the orange and blue lines show the vacuum pressure at Pt1 during the injection and ramp process. One clearly recognizes how the vacuum pressure increases once the two beams start the ramp and then slowly recovers once the beam reached the top energy of 3.5 TeV. Figure 2 shows a similar plot for the attempt of injecting and accelerating 152 bunches. One clearly observes a much stronger increase in the beam vacuum for the last two fills which featured the injection of 152 bunches as compared to the first three fills on the left which were prepared for 104 bunches. The explanation of the observed vacuum increase by electron cloud activity was later confirmed by applying additional solenoid field in the region of the vacuum gauges and observing that even small solenoid field can successfully suppress the observed effects in the field free regions of the LHC vacuum system.

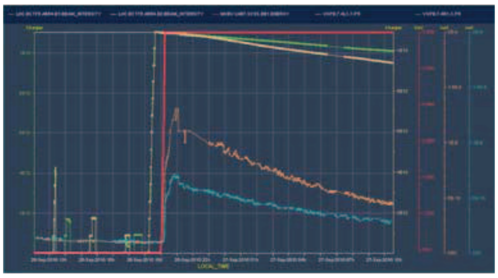

Figure 1: The vacuum pressure in the warm part of the common beam pipes near the experiments for fill 1373 with injection of trains of 8 bunches with 150ns separation as a function of time. The solid red curve shows the beam energy, the green and yellow curves shows the currents of the two LHC beams and the orange and blue lines show the vacuum pressure at Pt1 during the injection and ramp process. (Source: TIMBER).

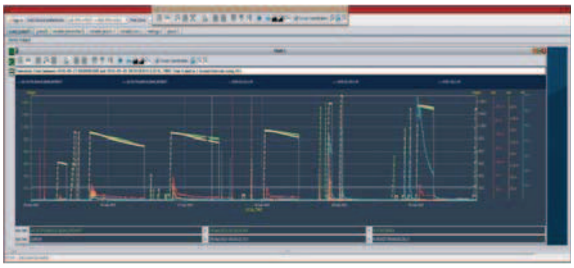

Figure 2: The vacuum pressure in the warm part of the common beam pipes near the experiments for fill 1381 with injection of trains of 8 bunches with 150ns separation as a function of time. The solid red curve shows the beam energy, the green and yellow curves shows the currents of the two LHC beams and the orange and blue lines show the vacuum pressure at Pt1 during the injection and ramp process. The first three fills on the left featured 104 bunches per beam and the last two attempts on the right are for operation with 152 bunches per beam. (Source: TIMBER).

On the bright side, the operational observations showed that, following the operation with 152 bunches and switching back to the operation with 104 bunches showed a much reduced vacuum activity as compared with the initial operation with 104 bunches. This observation clearly indicates a positive effect of surface conditioning by the increased electron cloud activity during the operation with 152 bunches. Conditioning the surfaces of the LHC vacuum system with the electron cloud activity therefore seems to be a viable way of mitigating the electron cloud problem during operation.

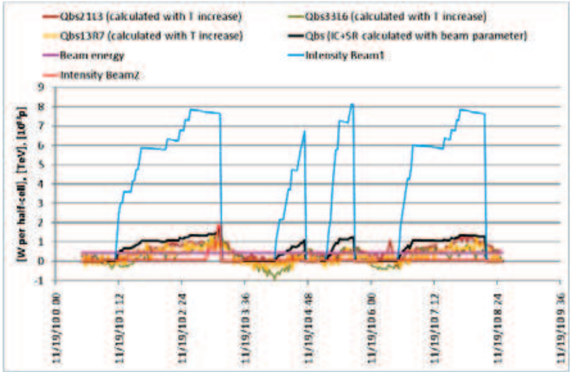

Figure 3: The cryogenic load in one of the cold arcs of the LHC for operation with 444 bunches with 50 ns spacing. The blue curve shows the total beam current for Beam1 as a function of time. The yellow and red lines show the measured heat load in sectors L3 and R7 respectively. (Source: Gianluigi Arduini at LMC 24.11.2010).

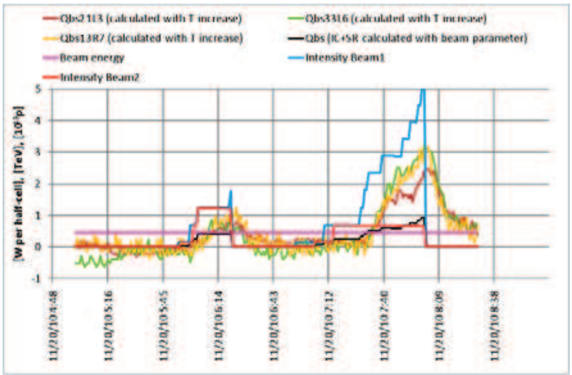

Figure 4: The cryogenic load in one of the cold arcs of the LHC for operation with 824 bunches with 75 ns bunch spacing. The blue curve shows the total beam current for Beam1 as a function of time. The yellow and red lines show the measured heat load in sectors L3 and R7 respectively. (Source: Gianluigi Arduini at LMC 24.11.2010).

Measurements of the Cryogenic load in the cold regions of the LHC vacuum system also showed clear evidence of electron cloud related heating. The Figure 3 shows the cryogenic load in one of the cold arcs of the LHC for operation with 444 bunches with 50 ns spacing. Figure 4 shows the cryogenic load in the same arc for operation with 824 bunches with 75 ns spacing. One clearly observes the correlation between the heat load and the Beam1 beam intensity for the operation with 50 ns bunch spacing. The operation with 75 ns bunch spacing does not show any beam intensity correlated heat load even though the measurement was done with approximately twice the beam current as compared with the measurement with 50 ns bunch spacing. Similar to the vacuum measurements in the wars sections next to the experiments, the measurements of the cryogenic load showed a reduction of the electron cloud related heat load after operation with 50 ns bunch spacing indicating again a reduction of the electron cloud activity due to beam scrubbing.

In order to assure an optimum beam scrubbing during the beginning of the machine operation it would be desirable to have an online display of the electron cloud activity in the machine. In the warm section of the machine this information is already available from the vacuum pressure readings. However, for an efficient execution of the beam scrubbing runs it would be beneficial to have a dedicated vacuum display available that shows the locations and vacuum pressure values of the top 10 regions with the highest vacuum activity. Such a display could help in steering the beam parameters during a beam scrubbing run such that the vacuum activity is maximized while keeping the pressure below the vacuum interlock levels.

A similar type of display would be desirable for the heat load measurements in the cold parts of the LHC. For example, a display of the type shown in Figure 5 would be very helpful for optimizing the beam parameters during a scrubbing run for maximum electron cloud activity while keeping the total heat load below the maximum capacity of the LHC cryogenics system. In this example, the brown colored wide histograms show the total heat load in the 8 LHC arcs. However, such a display might be difficult to realize as the initial measurements in Figures 3 and 4 relied on fixed cryo valve positions which might not be feasible during operation with large beam currents. At minimum, it would be desirable to have a binary type display, as illustrated in the narrow blue histograms, that indicate if an increased heat load due to electron cloud activity is detected.

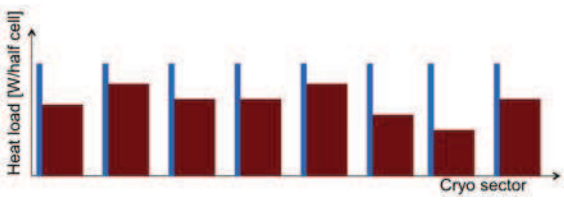

Figure 5: Example for a potential heat load display for the cold regions of the LHC.

Measurements of the beam emittance using the LHC Synchrotron Light monitor have also shown that the bunch emittances increase along the bunch trains in the LHC when the electron cloud effect is active (see Figure 6). A online display of the measured bunch changes of the bunch emittances along the bunch trains in a Mountain range style display as illustrated in Figure 7, could be another efficient tool for steering the beam parameters during the scrubbing run periods. Such a display could facilitate the chromaticity adjustments during the beam scrubbing runs.

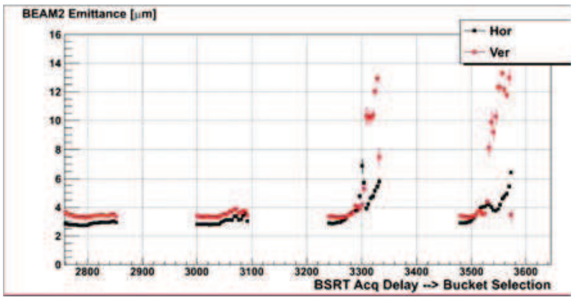

Figure 6: Measured bunch emittances along the bunch trains in the LHC in the presence of electron cloud activity. Trains of 24 bunches with 8 μs spacing. (Source Federico Roncarollo).

Figure 7: Example for a Mountain range type beam emittance display for the LHC beams. Time progresses along the vertical axis, starting with injection, and the horizontal axis identifies the bunch numbers.

UFOS

Beam loss spikes due to the UFOs present another potential performance limitation for the LHC. Observations during the LHC machine operation in 2010 have shown that

- UFO events occur at all locations along the LHC rings;
- The UFO rate is proportional to the total beam current;
- No UFO events have been observed at injection energy during the beam scrubbing with high beam intensities [1];
- most UFO losses are blow the BLM threshold limits.

However, it remains to be seen if the last statement remains valid when the beam intensities are further pushed in the 2011 operation. Figure **??** shows the measured UFO rate in 2010 as a function of the total number of bunches in the machine. Extrapolating the measurements from Figure 8 to the target value of bunches for the 2011 operation ($\rightarrow$ operation with ca. 900 bunches) implies a UFO rate of one to two UFO events per hour or approximately 10 to 20 UFO events per fill and 100 to 200 events per week. In order to facilitate the evaluation of the UFO occurrence during the machine operation in 2011 it would be interesting to have two types of displays available in the CCC:

- A simple counter adding the UFO occurrence over a fill - day - week;
- A histogram indicating the distribution of the UFO occurrence in the machine that is updated online.

Such displays could help in observing UFOs during the scrubbing runs (at injection energy!) and help detecting patterns of occurrence (or cleaning) during the machine operation.

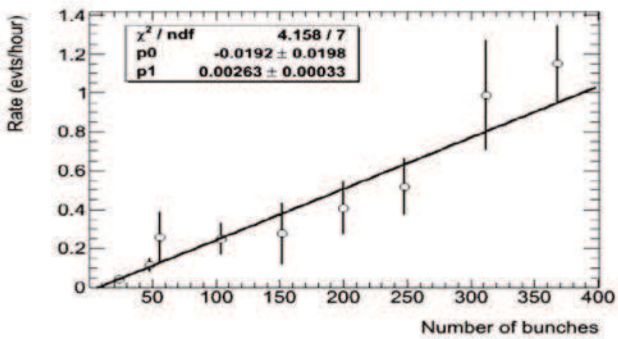

Figure 8: Measured UFO rate during the 2010 LHC operation as a function of the total number of bunches in the machine. (Source: E. Nebot).

BEAM-BEAM

The head-on beam-beam interaction in the LHC leads to an additional defocusing force for the particles that depends on the particles oscillation amplitude (the slope of the force changes sign for particles with large ($> 2\sigma$) amplitudes) with very strong non-linear dependence for particle amplitudes around $1 - 2\sigma$ and that diminishes for very large oscillation amplitudes ($> 10\sigma$). The head-on beam-beam parameter gives the maximum tune change due to the head-on beam-beam interaction. For round beams it is given by

$$\xi = \frac{r_p}{4\pi} \frac{N_b}{\epsilon_n}, \tag{1}$$

where r_p is the classical proton radius, N_b the number of particles per bunch and ϵ_n the normalized transverse beam emittance. The two LHC beams share near the interaction regions a common vacuum beam pipe that gives rise to approximately 30 parasitic beam-beam collisions per Interaction Region (IR). In order to avoid such parasitic collisions the beams are separated by dedicated crossing angle orbit bumps that transform the parasitic collisions into long-range beam-beam interactions. These long-range beam-beam interactions give rise to additional tune changes of

[1] a more detailed analysis of the logged data after the workshop showed that at least one UFO type event could be found at injection energy in 2010

the particles within a bunch. The tune shift and spread due to the long range beam-beam interactions diminishes for large beam separations and should be small compared to the head-on beam-beam tune spread for beam separations larger than 10σ. Figure 9 shows the total tune beam-beam related tune spread for the nominal LHC configuration with four IRs and alternating crossing schemes. The total tune spread is approximately $\Delta Q = 0.01$ for the nominal LHC configuration. The beam-beam tune spread together with the the non-linear forces of the beam-beam interaction can result in amplitude growth. The beam-beam limit in Hadron colliders without strong synchrotron radiation damping is loosely referred to as the maximum acceptable total tune spread that can still be accommodated in the tune diagram without exposing particles of the beam to too strong resonances. Experience of previous colliders have shown that resonances of order 12 or lower are decremental to the beam distributions and the beam-beam limit can therefore be estimated as the maximum tune spread that can be accommodated in the tune diagram without exposing particles within the beam to resonances of order 12 or lower. The LHC working point is placed between the $1/3^{rd}$ and $3/10^{th}$ resonance and particles can experience the $4/13^{th}$ and $5/16^{th}$ or higher order resonances. Figure 10 shows schematically the LHC working point and beam-beam tune spread of the LHC in the tune diagram. Depending on the required distance to the coupling resonance, the total resonance-free space (up to 10^{th} order or lower) in the tune space varies between 0.01 and 0.02.

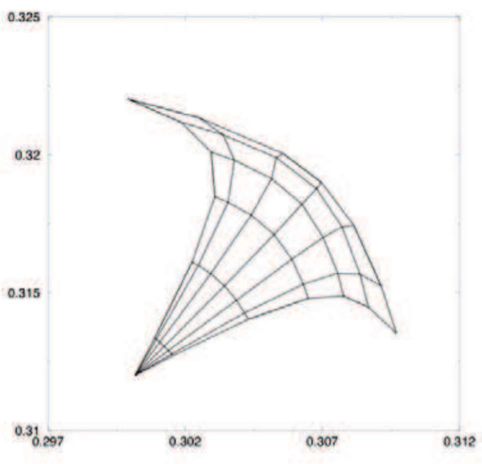

Figure 9: Total beam-beam related tune spread for the nominal LHC configuration. (Source: Werner Herr).

Operation experience in 2010 has given indications that even resonance of 10^{th} order might be tolerable for the LHC operation and that beam-beam parameters of more than $\Delta Q = 0.02$ might be feasible. For example, Fill 1409 featured 256 bunches with a normalized transverse emittance of $\epsilon_n \approx 1.4\mu$m and nominal bunch intensities of 10^{11} particles per bunch yielding a beam-beam parameter of $\xi = 7.710^{-3}$ and a total beam-beam tune shift of $\Delta Q = 0.0258$ for bunches with three collisions. Figure 11 shows the losses of the beams during Fill 1409 as a function of time for the different bunch classes with one, two and three head-on beam-beam collisions. While one clearly observes higher losses for bunches that have three head-on collisions as compared to bunches with one or two hean-on collisions, the overall losses still seem to be acceptable.

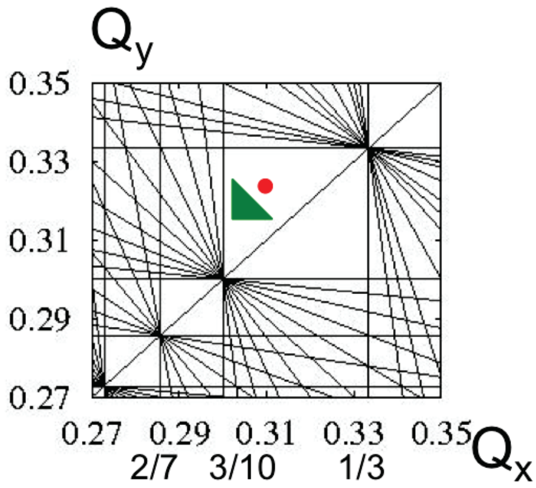

Figure 10: The LHC working point and schematic beam-beam tune spread of the LHC in the tune diagram.

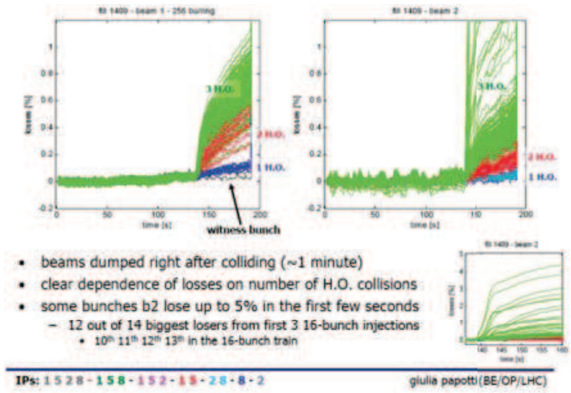

Figure 11: The losses of the beams during Fill 1409 as a function of time for the different bunch classes with one, two and three head-on beam-beam collisions. While one clearly observes higher losses for bunches that have three head-on collisions as compared to bunches with one or two head-on collisions, the overall losses still seem to be acceptable [source Giulia Papotti].

So far, the tune in physics operation has not been optimized during the 2010 operation and was fixed at the nominal design set that was optimized for a total beam-beam tune-spread of $\Delta Q = 0.01$. In order to optimize the machine operation for beam-beam parameters higher than $\Delta Q = 0.01$ the actual working point in the LHC should be optimized for a given beam-beam parameter and should be varied over a physics fill when the beam-beam parameter decreases due to the reduction in beam intensities and increase in beam emittances.

In order to facilitate this tune optimization it would be desirable to have a bunch by bunch tune measurement available for the LHC and to display the bunch tunes in the LHC tune diagram with indications of resonance lines of order 13 or lower. For example, Figure tevatron shows the measure bunch tunes in the Tevatron machine in the Tevatron tune diagram [1]. The red and green lines are various sum and difference tune resonances. The yellow crosses are the weighted average tunes for each antiproton bunch as measured by the 1.7 GHz Schottky monitor. The blue (pink) dots are the calculated tune distributions for all 36 antiproton (proton) bunches. The tune spread for each bunch is calculated up to 6σ amplitudes taking into account the measured intensity and emittance parameters.

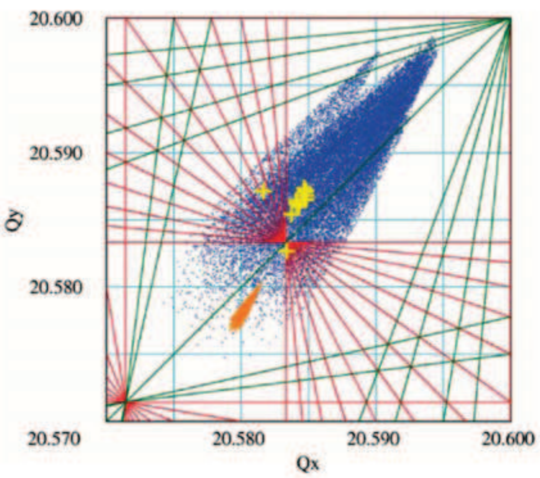

Figure 12: The Tevatron proton and anti-proton tune distributions within tune diagram. The red and green lines are various sum and difference tune resonances. The yellow crosses are the weighted average tunes for each antiproton bunch as measured by the 1.7 GHz Schottky monitor. The blue (pink) dots are the calculated tune distributions for all 36 antiproton (proton) bunches. The tune spread for each bunch is calculated up to 6σ amplitudes taking into account the measured intensity and emittance parameters.

Such a display would allow the LHC operation to fine tune the tunes before the beams are brought into collision and to optimize the beam tunes over a physics fill when the beam intensities and emittances evolve with time.

ONLINE STATISTICS

Steering the performance of the machine during routine operation requires the regular monitoring of the operational progress and time spend in and reasons for eventual down times and faults. The preparation of week by week statistics on the machine performance in terms of machine availability, fraction of time spend in physics, peak and integrated luminosity per fill and reasons for faults and interventions and beam dumps could greatly benefit from an automatic procedure for the generation of such data. During the 2010 operation there was not yet a consistent operational coding mechanism available for identifying key operation modes in the LHC logbook (e.g. preparation of fills, physics and down time) and still required a manual shift-by-shift analysis of the operation.

Examples for such an automated performance evaluation based on logbook entries can be found for the Tevatron operation [2]. Figure 13 shows the run-by-run store time of the Tevatron and Figure 14 the Tevatron beam lifetimes as a function of peak luminosity in the Tevatron as examples from the Tevatron online statistical information. Similar statistical evaluation tools for the online analysis of the machine performance on a daily or weekly basis would clearly be beneficial for steering the performance optimization of the LHC in the coming years.

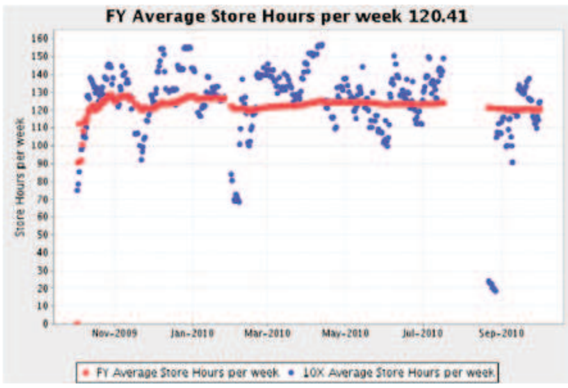

Figure 13: Summary of the Tevatron store length for different fills.

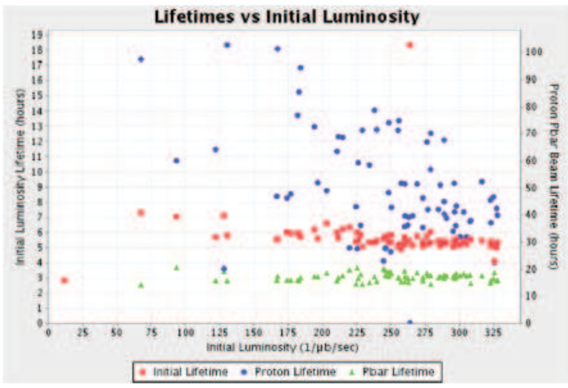

Figure 14: Summary of the Tevatron beam lifetimes as a function of peak initial luminosity for different fills.

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BUNCH BY BUNCH MEASUREMENTS AT LHC

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Abstract

Most of the beam instrumentation developed for LHC has been designed to allow bunch-by-bunch measurements: Beam Position Monitors, Beam Current Transformers, Wall Current Monitor, Wire Scanners, Synchrotron Light Monitors, Schottky Monitors, Longitudinal Density Monitors and Luminosity Monitors. The current status of all these devices is presented highlighting their already achieved performances in 2010 and their known limitations (hardware or software). The plans for upgrades in 2011 will finally be discussed.

INTRODUCTION

LHC will be colliding 2808 x2808 proton bunches when reaching its nominal performance, the commissioning of the machine has started with a single bunches per ring of reduced intensity. The number of bunches and the intensity per bunch was increased in steps for safety reasons. After six months of operation, trains of nominal intensity bunches were injected in the LHC and collisions with up to 368 bunches per ring were routinely performed by the end of the year. While increasing the number of bunches, beam-beam effects [1] and coupled bunch instabilities from impedance [2] inducing emittance growth, head-tail oscillations and beam losses were observed. Moreover when the bunch spacing was finally reduced from 150 to 75 and finally 50ns, electron cloud effects [3] became clearly visible with strong vacuum pressure rise causing beam instabilities and emittance growth along the train. Many collective effects were observed in 2010 and bunch-by-bunch measurements are becoming important in order to understand the behaviour of the beams. This paper presents the status of the bunch-by-bunch measurements developed for the LHC.

BEAM POSITION MONITOR

The LHC BPM front-end electronic works by design in bunch-by-bunch mode [4] and can in certain acquisition modes provide the position for each bunch. Orbits and trajectories are then calculated at the firmware and software level. Several synchronous modes of operation are already implemented. The Post-Mortem mode, available whenever a beam dump happens, gives the average position over all bunches for the last 1024 turns. The Synchronous orbit, being commissioned at the moment, provides the average horizontal and vertical positions (1 value per plane) and bunch positions (3564 values per plane) over 225 turns at a nominal update rate of 0.1Hz. Finally the capture mode has the flexibility to store N (bunch) x T (turns) samples. The current digital acquisition board limits the number of values to 128k samples but during operation, a strong limitation comes from the LSA concentrator, which cannot handle more than 2000 values per plane.

To overcome this limitation, it has been proposed to calculate in the BPM front-ends turn by turn data averaged over all bunches and to return these values as a new field to be used for Injection Quality Checks (IQC) and Beta-beat measurements. Some dedicated BPMs, with higher memory cards (512k) could be upgraded and would allow retrieving the bunch-by-bunch values for coupled-bunch studies.

HEAD-TAIL MONITOR

In point 4, two strip-line BPMs (one per beam) are used as head-tail monitors. A hybrid converts the four strip-line output signals into 'sigma' and 'delta' signals. These signals are digitalized with a 3GHz 10Gsa/s oscilloscope, which can either be used to look at turns, trains or bunches by adjusting the frame length. The main limitation comes from the memory of the oscilloscope, capable of recording for example 100us x 10 turns or 500ns x 5000 turns. Typical signals, measured during a high intensity fills are displayed in Figure 1. In this particular case the beam was instable because of electron clouds.

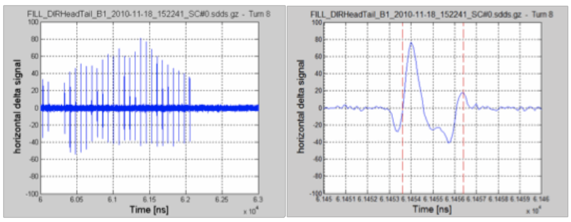

Figure 1: Variation of the beam horizontal position in time as seen by the Head-Tail monitors: looking at a train of consecutives bunches (a) or inside a bunch (b)

FAST BEAM CURRENT TRANSFORMER

The LHC Fast BCTs [5] were designed to provide bunch-by-bunch measurements as illustrated in Figure 2. The output signal of the transformer is split in several channels with low or high bandwidth and different sensitivities. There are two high bandwidth channels with a 20MHz high cut-off frequency and sensitivity ranges for pilot and nominal bunch intensities. Typical resolutions are $1.5\ 10^{6}$ and $2.2\ 10^{7}$ protons respectively for high and the low gain channels. Bunch intensities (3564 slots) are averaged over 1 s and stored in the logging database every minute.

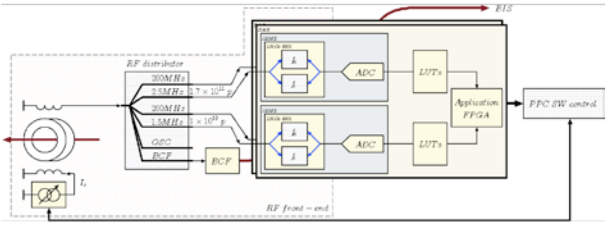

Figure 2: Schematic of the FBCT detection system

The Fast BCTs are operational since the very first days of beam operation since they only allowed measuring the low intensity pilots however some accuracy issues have been observed. The dependence on bunch length must be investigated and there are still some improvements to be done to provide an accurate calibration procedure.

TRANSVERSE PROFILE MONITORING

Wire Scanners

A schematic presented on Figure 6 shows the working principle and the hardware configuration of the LHC wire scanner [6]. The shower of secondary particles generated by the interaction of a thin wire with the beam itself is measured by a detector consisting of a scintillator, a set of variable attenuators and a photomultiplier. The bunch-by-bunch acquisition mode is installed as an alternative for the normal acquisition chain and is using a pre-amplifier in the tunnel (200MHZ bandwidth), long high-quality cables and a 40 MHz integrator card (IBMS card) on a DAB module installed in the WS VME crate located in an adjacent service area (US45).

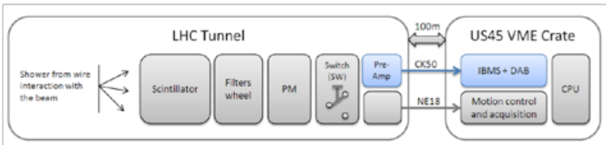

Figure 6: Schematic of the LHC Wire Scanners

The 40MHz mode was tested at the end of run and preliminary comparisons with the standard turn acquisition mode have agreed to within 10%. Few modifications are nevertheless planned to avoid saturating the pre-amplifier. The system should be operational for the coming run in 2011.

Synchrotron Light Monitors

Synchrotron Radiation (SR) is used in LHC for transverse and longitudinal profiles monitoring. A description of the system can be found in [7]. The continuous monitoring of the transverse beam sizes relies on the use of intensified video cameras [8] (Proxicam HL4 S N IR with a red-enhanced S 25 photocathode and an image intensifier). In normal operation the camera integrates over 20ms (all bunches over 224 turns), beam profiles are calculated and the data published every second.

In 2010 bunch-by-bunch images were also acquired with the same camera using a different set-up. The image intensifier was gated to 25ns exposure time using a trigger signal synchronized with the LHC revolution clock, by adjusting the delay any bunches in the machine could be measured independently. The camera sensitivity is sufficient to observe a pilot proton bunch at injection energy. Bunch-by-bunch measurements were for the moment only available on demand but this mode was used extensively during the commissioning of bunch trains. An example of bunch-by-bunch emittance measurement is depicted in Figure 7. The data refers to Beam 2 with the machine filled with 4 trains of 24 bunches spaced by 50ns, each train being spaced by 1.83us. Electron cloud build-up is clearly visible as an emittance blow-up along the trains.

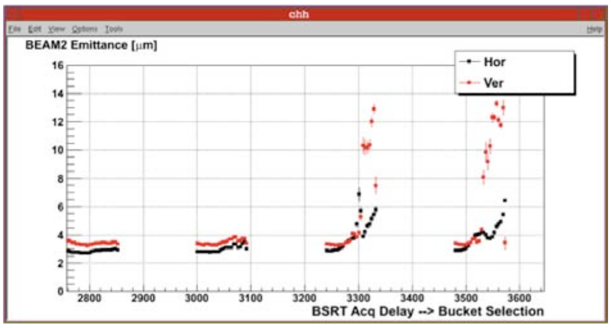

Figure 7: bunch-by-bunch horizontal and vertical beam emittances measured using a gated camera. The horizontal axis is expressed in RF bucket (slot of 25ns)

The slow acquisition rate (1Hz) currently limits the speed at which the transverse profile of all bunches can be obtained. A fast-framing camera, capable of bunch-by-bunch and turn-by-turn acquisitions will be installed during the winter shutdown and will provide faster measurements in 2011.

LONGITUDINAL PROFILE MONITORING

Beam Quality Monitor (BQM)

A Beam Quality Monitor, similar to the one developed few years ago for the SPS [9] has been installed on LHC to provide bunch length estimate and the filling pattern of the machine. The system, presented in Figure 3, is based on a Wall Current Monitor connected to 8G sa/s 10bits 100us ADC. The latter is triggered by a precise timing signal derived from the LHC Radio-Frequency system. An Acquisition (~ 1 turn) is performed every 5 s and several beam parameters like FWHM bunch lengths, peak amplitudes and bucket numbers are calculated and logged.

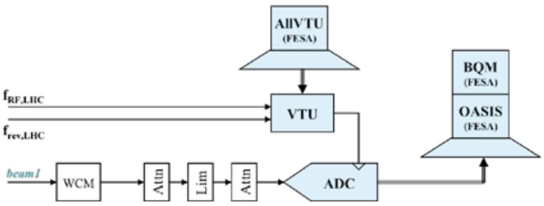

Figure 3: Principle of operation of the Beam Quality Monitor

Injection Quality Checks verify that the bucket number corresponds to the one requested by the injection sequencer. The BQM has been used daily in 2010 for online bunch length measurements and has demonstrated its capability to follow changes during the fill and identify problems when they occur. An example of the evolution of the bunch length during a fill is shown in Figure 4. The bunch length shrinks at the beginning of the energy ramp, and then starts to increase as the beams starts to collide due to beam-beam interactions. In this example, the monitor captured an RF cavity trip, which is characterized by a sudden bunch lengthening, returning to the initial value when the cavity came back.

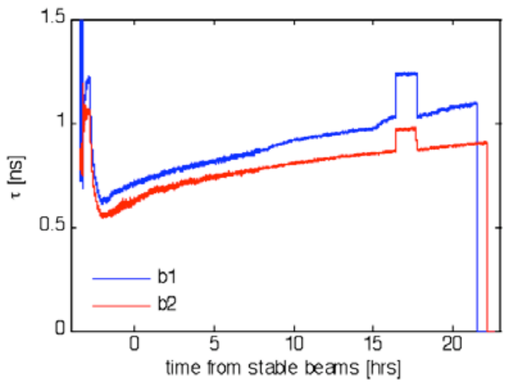

Figure 4: Bunch length evolution during a fill as measured by the BQM

Future improvements will focus on performing multiple turn acquisitions to study longitudinal oscillations.

Wall Current Monitor (WCM)

Two other wall current monitors (one per beam) have been installed in point 4 and provide complementary information of the longitudinal beam structure. The signal is directly acquired by a 3 GHz 10GSa/s oscilloscope every 10s, which corresponds to the average over 300turns. Compared to the BQM, the sensitivity is increased to the level of few per mil and enables the measurement of bunches and satellites. A lot of parameters are post processed like bunch length and bunch shape estimates using different fitting distribution (cos2, Parabolic, Gaussian). An estimate of the bunch and satellite population is also computed. All parameters are stored on a bunch-by-bunch basis and logged at 0.1Hz. An example of a bunch spectral power is given in Figure 5, and clearly indicated that bunches are not Gaussian.

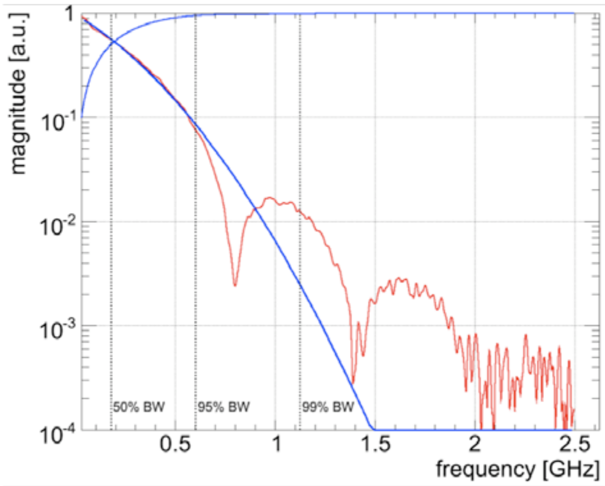

Figure 5: Bunch spectral power measurements from a WCM. The red curve is the measured spectrum and the blue one corresponds to the Gaussian fit.

Longitudinal Density Monitors (LDM)

Synchrotron radiation produces an almost perfect light replica of the proton density in the time domain. A monitor capable of providing longitudinal beam profile with a 50ps time resolution and a high dynamic range is currently under development [10]. The system is based on time stamping SR photons with fast avalanches photo-diodes operated in Geiger mode. A first prototype was installed during summer 2010 on Beam 2 and has been commissioned successfully. As presented on Figure 8, the LDM can sample the whole LHC ring with 50ps resolution and thus measure individual bunch lengths within a few seconds. Using longer integration times (10-20mins), the monitor has reached a dynamic range higher than 10^5, being able to see ghost bunches from LHC and SPS, see Figure 9(b).

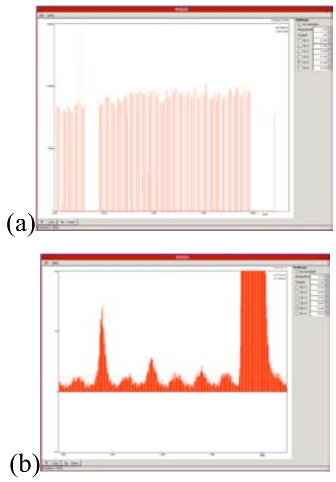

Figure 9: LHC Longitudinal beam profile as seen by the LDM, (a) over a full ring or (b) zooming on a nominal bunch and its satellites.

A second LDM will be installed on beam 1 during the winter shutdown. An upgrade of the present system is also under study to be able to reach even higher dynamic range and/or shorter integration time.

SCHOTTKY MONITORS

Transverse Schottky monitors has been designed and installed in LHC [11]. They rely on the use of 60x60mm aperture, 1.5m long slotted waveguide structures resonating at 4.8GHz. Horizontal and vertical position signals are processed using band-pass filtering and 3 consecutives mixing stages, converting the 4.8GHz signal to baseband frequency. The electronics chain is gated allowing bunch-by-bunch measurements.

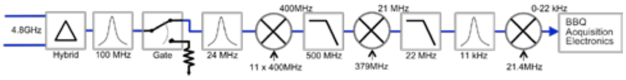

Figure 10: Acquisition system for the LHC Transverse Schottky Monitors

The system was brought into operation during the summer and has been used since then with protons and lead ions. Typical Schottky signals measured on Beam 1 in the horizontal plane are displayed in Figure 11 for both protons and lead ions. The distance between the main peaks is the revolution frequency of the machine. Schottky sidebands are visible on either side on the main peaks. Tune, chromaticity, energy spread and emittance can be estimated from the analysis of these sidebands. Most of these values must be cross calibrated with other instruments but the Schottky monitors have already shown great performances especially during the ion run, providing almost perfect textbook spectrum.

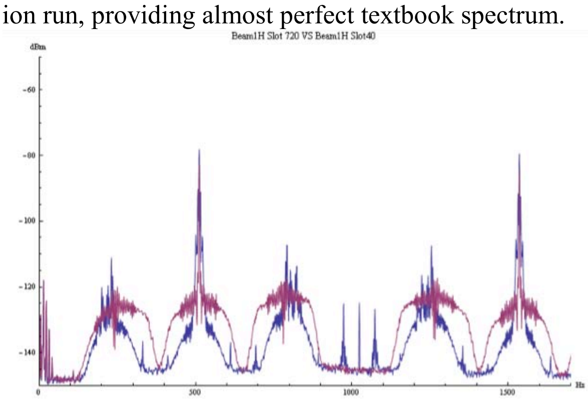

Figure 11: Schottky spectrum measured for protons in blue and heavy ion in red.

The system is currently under commissioning and a detailed study is on going to determine the optimum hardware settings and the most accurate software algorithms.

LUMINOSITY MONITORS

There are 3 different types of luminosity monitors installed on the LHC. In ATLAS and CMS, plastic scintillators (BRANP) have been used in 2010 to cover the first part of the run with slow collision rates. These detectors are not very radiation hard and will have to be removed as the luminosity increases. Ionization chambers (BRANA), developed in collaboration with LBNL [12], will take over but are not very well suited for luminosity below $10^{30}cm^{-2}.s^{-1}$. In LHCb and ALICE, where the collision rates are lower, luminosity detectors were chosen based on CdTe (BRANB) [13] technology developed by CEA/Leti in Grenoble/France. These three technologies have a bunch-by-bunch capability and the details on their read-out electronics can be found in the corresponding references. A typical measurement is given in Figure 12. The total and bunch-by-bunch luminosity values is published and logged respectively at 1Hz and 0.1Hz. All detectors work in counting mode and for the BRANB and BRANP, this is the only mode available. With high luminosity, pile-up is an issue that needs to be corrected. The correction algorithm depends on the detector technology and has to be optimized for the next run. The absolute calibration of the different detectors is not yet reliable and would have to be improved for the 2011 run.

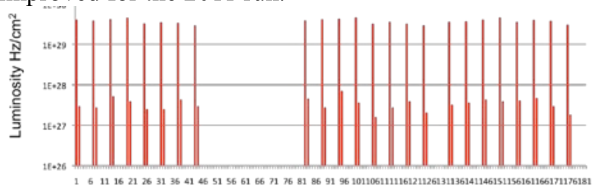

Figure 12: Bunch-by-bunch luminosity signals as observed by the BRANP.

FAST BEAM LOSS MONITORS

In parallel to the LHC beam loss monitoring system, mainly using ionization chambers [14], fast beam loss monitors are being developed for the detection of injection losses and the detection of Unidentified Falling Objects (UFO). A diamond detector with 5ns time response was installed in the collimation region (LHC-point 7) for development study. Preliminary results were very positive as depicted in Figure 13, where its signal is compared to the one of an ionization chamber installed in the same region.

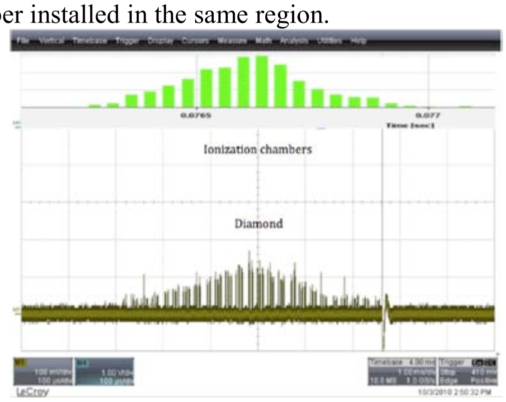

Figure 13: Beam loss monitor signals measured by an ionization chamber and a diamond detector

For 2011, additional diamond detectors will be installed in the injection region (1 per beam) and in the collimation region where the signature of UFOs is typically observed and we are presently looking into the integration on the LHC control system

CONCLUSION AND PERSPECTIVES

On LHC, 11 instruments can actually provide bunch-by-bunch measurements and almost all the beam parameters are available in this mode. Most of the devices are still in the commissioning phase and are not fully integrated in the control system yet. Even if they still require hardware and software improvements, at the end of the run in 2010, a large fraction of the devices already produced useful data for beam operation and optimization.

Except beam size monitors (wire scanners and synchrotron light monitors), bunch-by-bunch data are available in parallel to the normal continuous beam observation mode. Schottky and Synchrotron light monitors, which work in a gated mode measuring a single bunch at a time, currently need several minutes to scan all bunches stored in the machine.

The amount of data published by these monitors is considerable and a general strategy on how to log and display their results needs to be defined in 2011.

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FEEDBACKS: STATUS, OPERATIONAL DEPENDENCIES AND OUTLOOK FOR 2011

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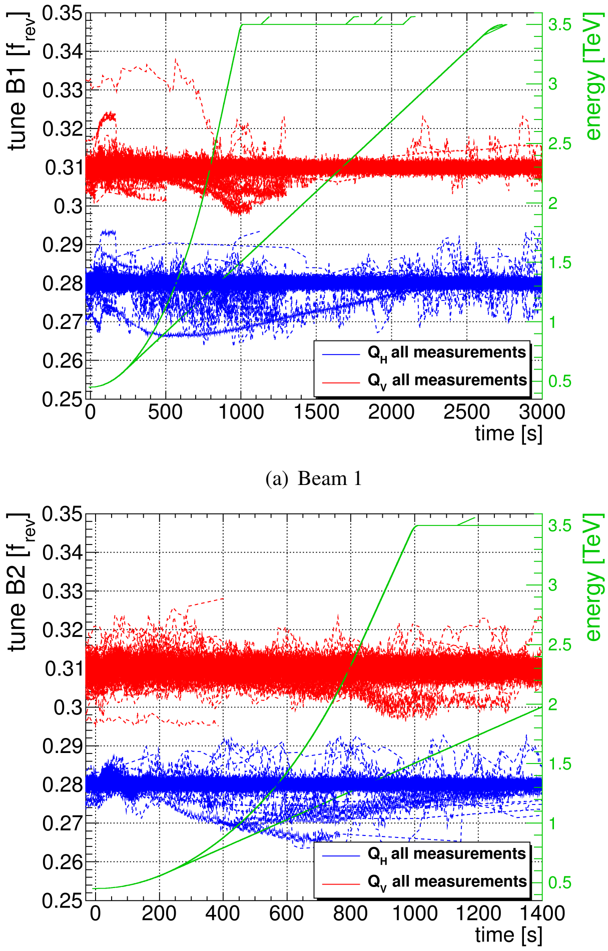
Abstract

This contribution summarises the feedback performance during LHC's first full year in view of higher-intensity operation in 2011. While all involved systems generally performed exceptionally well, this contribution focuses on issues specifically related to operational dependencies and operation of the tune and chromaticity diagnostics instrumentation. Possible mitigation, some of which have been already explored during the year, are being discussed.

INTRODUCTION

Since the LHC restart in 2010, the Orbit, Q and Q' diagnostics and feedback systems (OFC) were used during almost every fill with the exception of a few ramps used to evaluate the decoupling scheme between chromaticity and the tune feedbacks loop and the few that were affected by outages of the base-band-tune system (BBQ, [1]) discussed below. While the Tune Phase-Locked-Loop (PLL) has been commissioned and used during a few ramps, due to the BBQ's nm-level sensitivity, most day-to-day Q/Q' diagnostics were nevertheless performed based on passive monitoring of the beam spectra only, limiting potential impact on beam size growth. The change of paradigm of deriving the tune and chromaticity from only passive monitoring instead of resonant excitation of the beam required some adaptations in the digital post-processing, which after the appropriate strategy was established performed better than expected (compared to other hadron colliders where similar attempts were made [3]) and soon became the workhorse and base-line mode of operation of the feedbacks.

The feedbacks facilitated a fast and reliable commissioning of the LHC: the orbit-FB kept the largest orbit excursions during the ramp typically below 70 μm and down to the residual BPM measurement noise of about $5-10\,\mu$m during the other operational phases. The tune was stabilised typically better than 10^{-3} with initially larger excursions during the snap-back which were further optimised to the same nominal performance. Figure 1 shows the superimposed residual tune stability for beam one and two during 2010. Being used on every ramp to physics, losses could be kept at a minimum. Out of a total of 275 ramps, excluding the early ramps in 2009, a total of 155 (122) ramps achieved more than 99%, 169 (155) ramps more than 98% and 178 (168) ramps more than 97% transmission for B1 (B2). Only 12 (10) ramps were lost due either to direct or indirect feedback involvement, out of which 6 (5) were during the initial 3.5 TeV commissioning.



(a) Beam 1

(b) Beam 2

Figure 1: Residual tune stability. Outliers are due to a few test ramps without Q/Q' feedbacks for diagnostics purposes and BBQ outages further discussed in the text.

This contribution summarises some of the feedback issues observed in 2010, the present status of their mitigation measures and possible improvements related to Q/Q' diagnostics and feedbacks in view of 2011 operation.

FEEDBACK ISSUES AND MITIGATION

The few beam dumps related to feedbacks were limited to their initial setup and commissioning during the first months and had a small (below percent-level) impact on overall machine operation [4, 5]. Most of the beam dumps where feedbacks were involved were due to either false-positive QPS trips which have been mitigated by introducing a dead-time in the evaluation of the QPS threshold, and due to locking of the BBQ tune diagnostics on non-tune resonance lines in the spectrum. The tune tracker was modified early on in response to this, and most of these non-tune interference lines have now been identified and eliminated using a multi-stage, median-filter based search algorithm that removes lines based on their bandwidth. Some other software error handling of exceptional conditions and common to all feedbacks ('NaN' user-reference and input data, energy transmission errors over the timing system, etc...) were identified timely and fixed by the end of July. Since August, the remaining issues were mainly related to instrumentation quality and integration, such as:

- systematic effects related to the stability of the BPM measurements, discussed in [2],
- interferences of the nominal transverse bunch-by-bunch feedback operation (ADT) with the tune diagnostics, discussed below,
- kernel software updates and denial-of-service security scans of the operational OFC machines during beam operation (causing some beam dumps and down-time) which are necessary but which are to be scheduled during technical stops in the future, and
- integration and automation of reference changes and feedback operations via the operational sequence,

all of which are being addressed in view of the upcoming 2011 operation.

BBQ Diagnostics Outages

Intrinsic to all feedback systems, the ultimate performance of any such system is determined by the performance and reliability of the initial measurements they are based on. In order to reduce the residual dependence of bunch-length and -shape oscillations, a 400 MHz low-pass filter has initially been installed prior to the BBQ to further improve the (in-)dependence of the measured spectrum on longitudinal effects. While this scheme worked well initially for beams with single or a few sparsely distributed bunches, the detector became more sensitive to longitudinal effects with increasing number of bunches. The tune signal-to-noise ratio reduced with every bunch added up to the point (about 50 bunches) where it completely vanished within the noise, subsequently thwarting a reliable tune diagnostics and consequentially feedback operation as illustrated in Figure .

Fast intra-bunch shape measurements performed with LHC's head-tail monitors indicated that the time when these outages occurred coincided with periods of increased longitudinal activity of bunch shape oscillations, a side-effect of the required longitudinal blow-up during the ramp. At the same time it was found that the 'single-bunch peak-detection characteristic' of the BBQ is only valid for bunch filling patterns beyond about 50 bunches. Below this number, the detector can be sensitive to coupled bunch-to-bunch modes and intensity variations.

In response to this, the BBQ has been reverted to the initial detector scheme, removing the low-pass filter prior to the BBQ detector (since it reduced the effective Tune S/N by about 6 dB but had a minimum impact on the sensitivity on longitudinal effects) and improving the high-voltage rating of some of the components, necessary due to the higher voltage and power-requirements without the low-pass. After this modification, the original sensitivity and spectral performance was restored to some degree, as shown in Figure . The tune signal-to-noise ratio improved by more than 6 dB reducing the impact of the remaining longitudinal activities. This also indicates that an important part of the signal that the BBQ detects, is derived from oscillations that are above 400 MHz (aka. head-tail motion). However, though reverting to the previous scheme helped, the exact mechanism of the original issue (driving source of the head-tail motion, etc.) is still not fully understood and should be closely monitored while increasing the number of bunches and intensities in 2011.

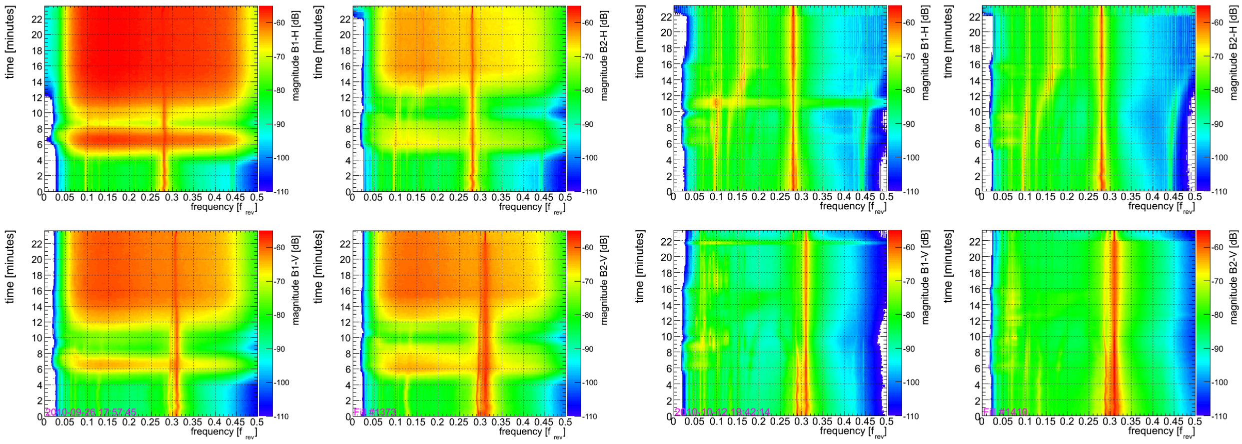
FEEDBACK AND Q/Q' DIAGNOSTICS PERFORMANCE

For the first year of operation, the LHC performance supported by many feedbacks is impressive and transmission losses could be kept below 3% for most ramps. However, these percent-level losses could become more critical for the planned ramp-up of nominal intensities in 2011. A fill-to-fill overview of the evolution of the stored intensities, transmission losses, peak-to-peak tune stability and corresponding required feedback trims is shown in Figure 3. The steady increase in stored intensity per fill is visible. Two markers were added to separate a) the initial commissioning periods of establishing first injection, ramp, squeeze and collisions with low intensity beams, b) operation with nominal proton bunches and later bunch trains, and c) ion operation. Most losses occurred when switching mode of operation e.g. changing from single bunch injection, to trains and to ion operation. Some (scraped) halo losses have been seen but it is believed that these particles would have eventually been lost in the collimators anyway, and for the few ramps and periods where radial modulation were applied systematically to measure $Q'(t)$, little or no direct impact of the modulation ($\Delta p/p < 2 \cdot 10^{-4}$) could bee seen on transmission losses or beam size growth.

Tune-FB Stability

The tune-FB performance was fairly steady over the fills and largely dominated by the snap-back as shown in Figure 1. A direct decay of main quadrupole currents or feed-down effects coming from the main dipole's b3 decay could be the cause of these variations, as discussed in [6].

Initially, very conservative feedback settings were cho-



(a) Fill 1373: beam spectra with 400 MHz BBQ pre-filter.

(b) Fill 1410: beam spectra without 400 MHz BBQ pre-filter.

Figure 2: BBQ outage during ramp before and after the 400 MHz low-pass filter removal.

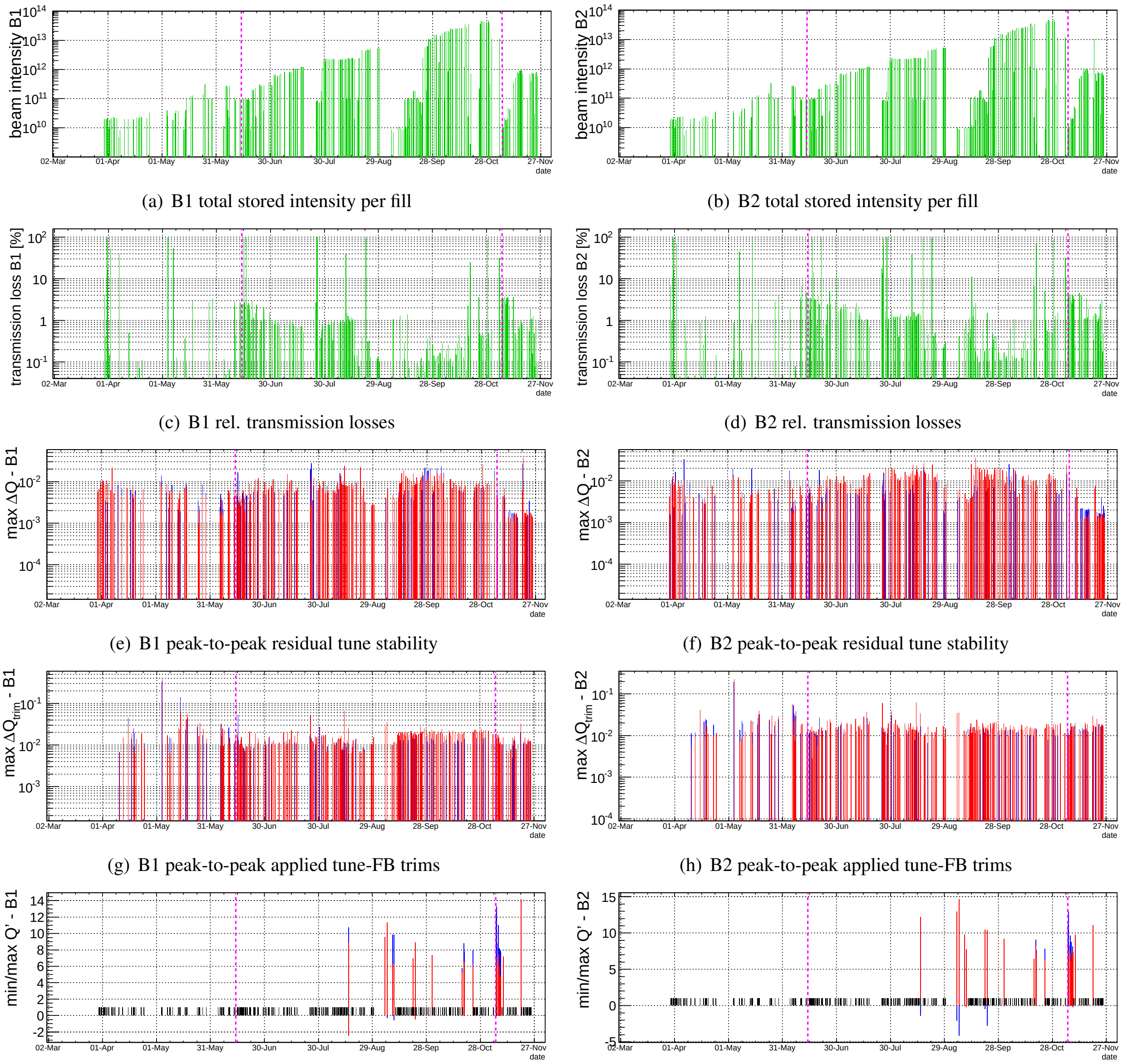
sen, which resulted in exceeding the initial tune stability requirement by about 10^{-2} mainly during the first 120 seconds of the ramp. At a later stage, once operating the LHC with ions and after a reliable BBQ and feedback operation was widely affirmed, this stability was further improved to below $3 \cdot 10^{-3}$ as visible in Figures 3(e) and 3(f). In any case, the stability is limited by the resolution, stability and reliability of the Q/Q' diagnostics rather than the feedback controller or loop itself.

Operational Dependence on Feedbacks

As visible in Figures 3(g) and 3(h), the corresponding tune trims rather increased than decreased over time which correlated with the progressively reduced frequency with which the systematic dynamic real-time tune trims were incorporated into LSA's static feed-forward function. Also, for some fills the real-time trim action substantially exceeded the typical correction range compared to previous fills. In these cases, the feedback compensated for effects that were introduced either directly (human and/or incorporation errors) or indirectly through feed-down effects that were otherwise not accounted for by the day-to-day operation (such as incomplete pre-cycles after accesses, newly measured $Q'(t)$ incorporation into the ramp functions). These examples nicely demonstrate that – even with perfect feed-forward incorporation of the recurring real-time actions – feedbacks can and did provide some additional safety margin to operation by indifferently suppressing and absorbing unexpected perturbations. At the same time, it should be pointed out that the beams without feedback support would have been probably lost which reduces the merit of 'additional' to 'mandatory' safety by the feedbacks. Unfolding the effect of the real-time trims on the tune, out of 275 ramps that were executed in 2010: 56 (83) would have been lost on low-order resonances (3rd,4th,C-), 150 (157) would have exceeded a $\Delta Q = \pm 0.01$ tolerance which probably would have caused transmission losses and all were above the $\Delta Q = \pm 0.001$ stability requirement for nominal beams [9]. In order to reduce this dependence on feedbacks, which is the mandatory requirement to have them fully operational and always operating at with nominal performance for every fill, it is strongly recommended to systematically monitor and transfer recurring real-time feedback actions into the ramp and squeeze functions.

Chromaticity Stability

While the availability of the intensity, tune and feedback trim data is extensive and generally available for nearly every fill, the data on beam size evolution and in particular $Q'(t)$ is very sparse. However, for the few consecutive fills for which $Q'(t)$ was measured indicated a fairly reproducible behaviour as shown in Figure 4. A first order magnetic field correction of the chromaticity has been applied to the ramp using the MCS spool pieces. The remaining largest fill-to-fill variations occurred as expected during the first 200 seconds of the ramp reaching up to $\Delta Q' \approx \pm 5$. Once reaching 3.5 TeV another decay of about 6 units of chromaticity is evolving and to allow this decay to settle, the ramp was artificially extended by about 6 minutes. In between the chromaticity was found to be stable within about $\Delta Q' \approx \pm 2$ which indicates that beside the snap-back most of these effects could be compensated by a feed-forward function nearly down to nominal requirements. Still, all ramps exceeded the initially required chromaticity stability of $\Delta Q' = 2 \pm 1$, often with systematically negative chromaticity as can be seen in Figure 3(j). While the effect of operating with negative chromaticity was partially absorbed by the ADT, it is recommended – similar to the tune perturbations and feedback – to correct for this systematic effects to reduce the unnecessary systematic dependence on feedbacks.



(a) B1 total stored intensity per fill

(b) B2 total stored intensity per fill

(c) B1 rel. transmission losses

(d) B2 rel. transmission losses

(e) B1 peak-to-peak residual tune stability

(f) B2 peak-to-peak residual tune stability

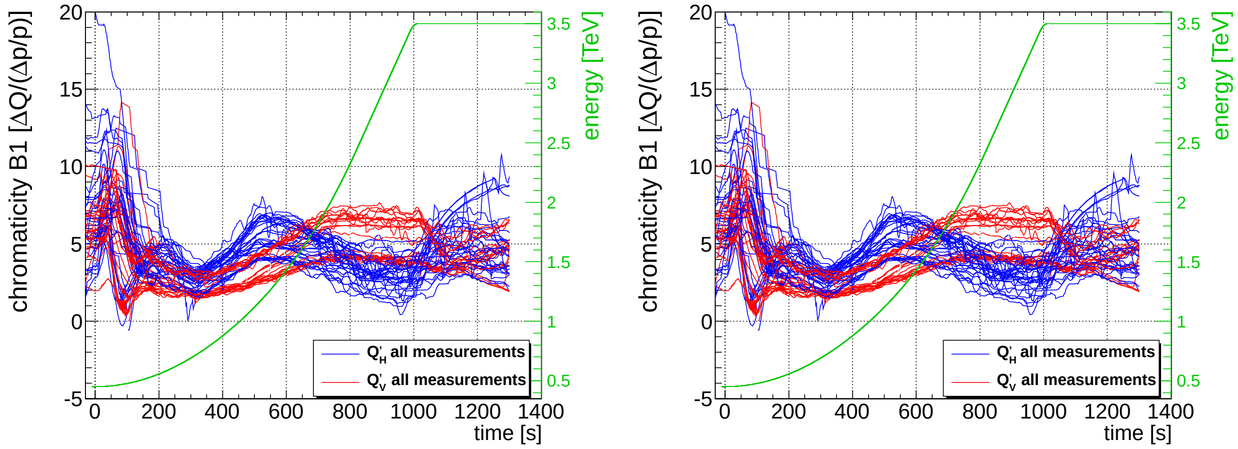
(g) B1 peak-to-peak applied tune-FB trims

(h) B2 peak-to-peak applied tune-FB trims

(i) B1 fill-to-fill chromaticity variations

(j) B2 fill-to-fill chromaticity variations

Figure 3: Q/Q'-related fill-to-fill performance overview of 2010: evolution of the stored intensities, transmission losses, peak-to-peak tune stability and corresponding required feedback trims. The two magenta markers indicate the two major changes of mode of operation: a) from inital commissioning to gradual intensity increase and b) from proton to ion operation. Parameters related to the horizontal plane are indicated in blue and for the vertical plane in red.



(a) Beam 1

(b) Beam 2

Figure 4: Residual superimposed $Q'(t)$ stability during the ramps in the time periods indicated in Figures 3(i) and 3(j).

Impact of Q/Q' Stability on LHC Operation

The actually observed Q/Q' perturbations are in good agreement with the expected perturbations and initial design assumptions [7]. With exception of the measurement and control of $Q'(t)$ that – while the diagnostic and feedback was available – has been given less priority, all parameters could be kept just above the initially targeted limits. To be further investigated: are this slight out-of-tolerance parameter stabilities acceptable for operation with nominal beam, or equivalently, is the achieved feedback performance adequate? Or does it require further improvement?

Thus an extensive analysis of transmission losses and beam size growth as stability indicators with biggest impact on luminosity production has been performed, to assess the impact of feedback performance on operation. Since the largest and fastest tune and chromaticity variations occur during the ramp, the presented analysis focuses on a total of 275 ramps for which the given parameter, feedback actions as well as the beam stability indicators were available. In this analysis, the transmission loss is defined as intensity loss between the start and the end of the ramp, excluding the loss of un-captured beam at the very beginning. As discussed in [8], for the analysed period, neither the synchrotron light nor ionisation profile monitor could provide reliable beam size growth measurement during the ramp. In order to nevertheless assess some form of fill-to-fill beam size growth changes, the beam sizes at injection were compared with those at flat-top, including some best effort correction factors which were constant over the analysed periods. While this does not provide an absolute measure of the relative beam size growth, it is remains a rough indication whether the beam size changed during the ramp from a fill-to-fill perspective. The corresponding correlation plots are shown in Figure 5. Comparing the individual stabilities during the ramp on a fill-to-fill basis seem to indicate an (anti-)correlation between 0.5 and 0.7 between the residual peak-to-peak chromaticity variations and transmission loss and beam size growth. Thus, the higher the chromaticity swing during the ramp, the less particles are lost but also the larger the beam size growth. This result would to first-order relate well with expectations of the beneficial effects of large(r) chromaticities on collective instabilities and detrimental with respect to higher-order head-tail modes causing emittance blow-up. While the statistics supports the case of Q'-related transmission losses, the effect on beam size growth, in particular the absolute magnitude, remains substantially limited by the systematic errors on the beam size measurement. In order to assess the full magnitude of this effect, it would be useful to further explore this effect through a controlled experiment at constant energy for which both the synchrotron light monitor and ionisation profile monitor provide better beam size estimates.

MAINS HARMONICS

As can be seen in Figure 5, no direct correlation between residual tune stability and beam size growth is visible. There is a limited correlation between residual tune stability and intensity transmission during the ramp, with the exception that for fills with stabilities better than 0.005 more intensity was lost than for those with poorer tune control. This is a bit counter-intuitive and would naively suggest not to control the tune. Revisiting the spectra of the given ramps revealed that in these cases the tunes were kept on the horizontal nominal LHC tune working point, which is located exactly on one of the mains harmonic as shown for example in Figure 6. A set of mains harmonic are visible and more pronounced for high-intensity beams as the BBQ detector becomes more sensitive down to the nm-level. These mains harmonic are typically very small and compatible with the measured and specified main dipole ripple[10]. Their impact is a priori not a big issue and similar to evading the 'hump' could easily mitigated e.g. by shifting the nominal working points by 0.001 only.

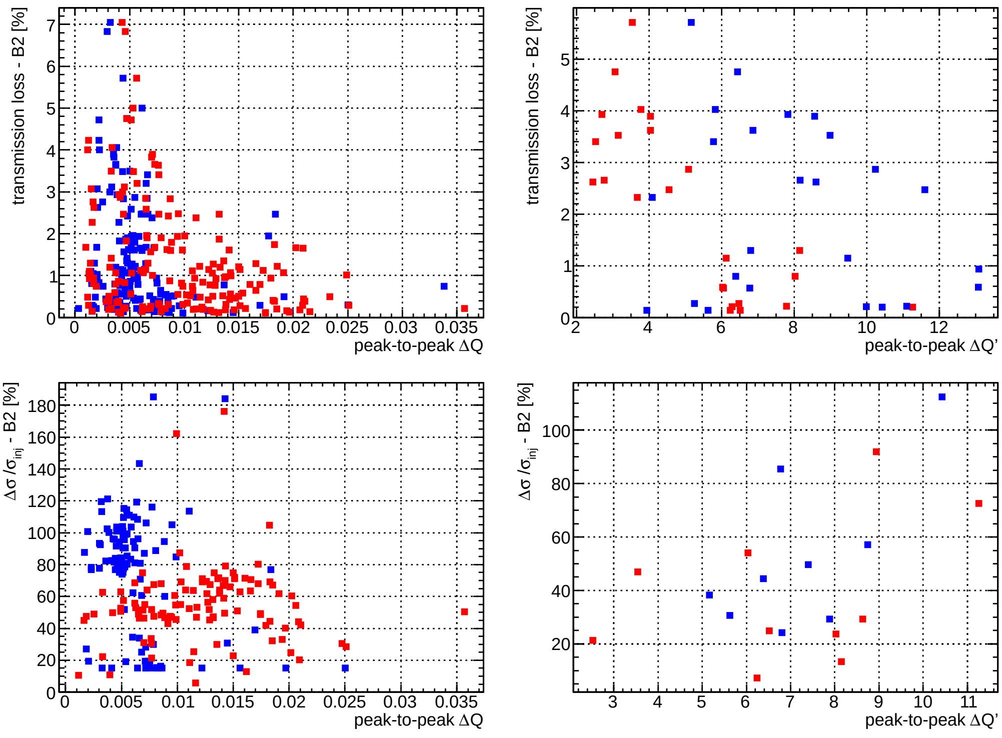


Figure 5: Correlation plots showing transmission loss and relative beam size growth versus peak-to-peak tune and chromaticity stability during the ramp. Beam 1 (blue) and Beam 2 (red) are indicated. The relative beam-size growth should be interpreted only as a linear measure of the fill-to-fill variation. At the time of the analysis there were still significant uncertainties on the synchrotron-light and BGI based beam size measurements with strong uncertainties on the absolute scale – however the scale being reproducible from one fill to another fill.

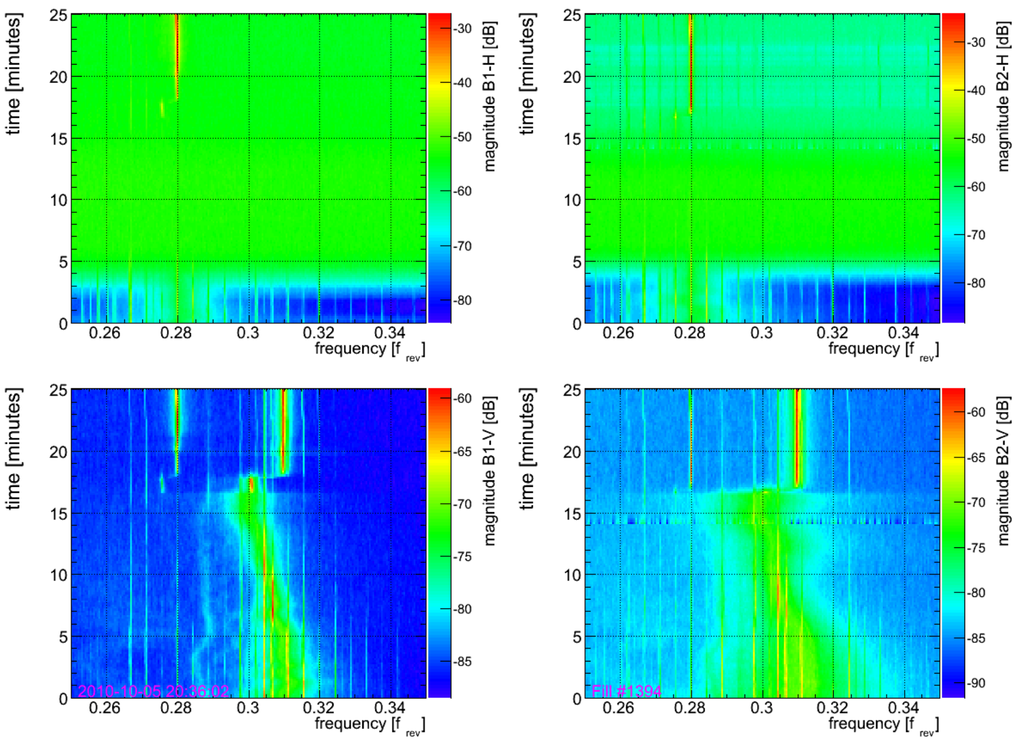


Figure 6: Tune spectra during the ramp of fill 1394. The resonant beam excitation at the higher-order mains harmonics and due to the particular choice of nominal horizontal LHC tune $Q_h = 0.28 * f_{rev} = 3150\,\text{Hz}$ is visible.

COHABITATION OF ADT AND Q/Q' DIAGNOSTICS SYSTEMS

An important issue affecting the reliability and function of the Q/Q' diagnostics and feedback systems is the intrinsically competing requirement of the transverse bunch-by-bunch feedback system (ADT) targeting the minimisation of beam oscillations on the tune frequency and the fact that a certain amount of these oscillations are required to actually measure and stabilise the tune. The nature of these opposing requirements were already recognised in [9].

The initial tune diagnostics design assumed no residual tune signatures on the beam and hence a constant driving of the beam (e.g. a 'kick', 'white noise', 'chirp' or 'PLL') was envisaged. To limit the required excitation levels and consequently minimising the resulting potential emittance blow-up, the highly-sensitive BBQ system was developed, which has been further exploited by a real-time FFT spectrum analysis and PLL system[1]. The working hypothesis was that the BBQ's nm-level sensitivity would be sufficient to operate below the oscillation level, which would/could be damped by the ADT, and which would impact machine operation or protection. Initial tests at the RHIC, SPS and Tevatron, and likewise early experience after the start-up and present LHC operation seemed to confirm this hypothesis with beam: the BBQ can provide a turn-by-turn resolution of better than 30 nm, more than 50 times' sensitivity than any other LHC systems (ADT: $1\,\mu\mathrm{m}$ [11], BPM: $50\,\mu\mathrm{m}$ [2]). At the same time, ever-present residual tune oscillations are visible on the LHC beam with amplitude in the order of 100 nm to a few micro-metre level. This "luxurious" 30 to 40 dB signal-to-noise ratio facilitated a passive monitoring, tracking and feedback without additional excitation, which proved to be sufficiently reliable from Day one, controlling large tune variations during almost every LHC ramp (and most squeezes). The substantial resolution also helped to identify other beam perturbation issues such as electromagnetic interferences originating from mains and ADT, the 'hump', and other effects documented elsewhere[11, 12].

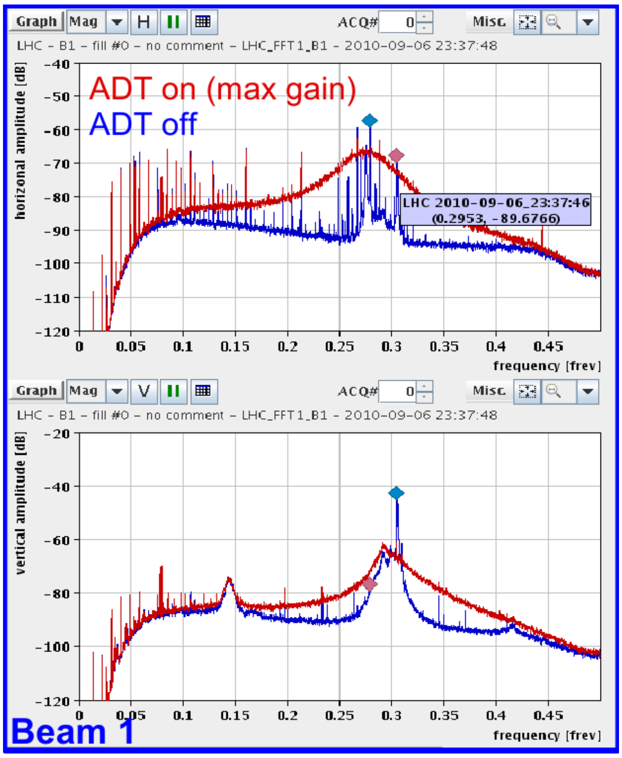
While these μm-level oscillations are a-priori beneficial for a passive detection of the tune, they are incoherent 'noise' from a FFT or PLL diagnostic point of view. Regardless of whether using a driven FFT- or PLL-based diagnostic tune system, the beam needs to be exited about 20-30 dB above this 'noise' to recover the same reliable performance as using residual oscillations only. The corresponding absolute amplitude of about $10 - 100\,\mu\mathrm{m}$ that is excited on top of the residual tune oscillations are in conflict with collimator requirements ($< 200\,\mu\mathrm{m}$ and shown to cause beam losses in the machine. Thus driving the beam to such ample signals seemed to be inefficient and less robust compared to the performance achieved with the passive-only system and was considered to be used mainly if the signal dropped.

ADT Interferences

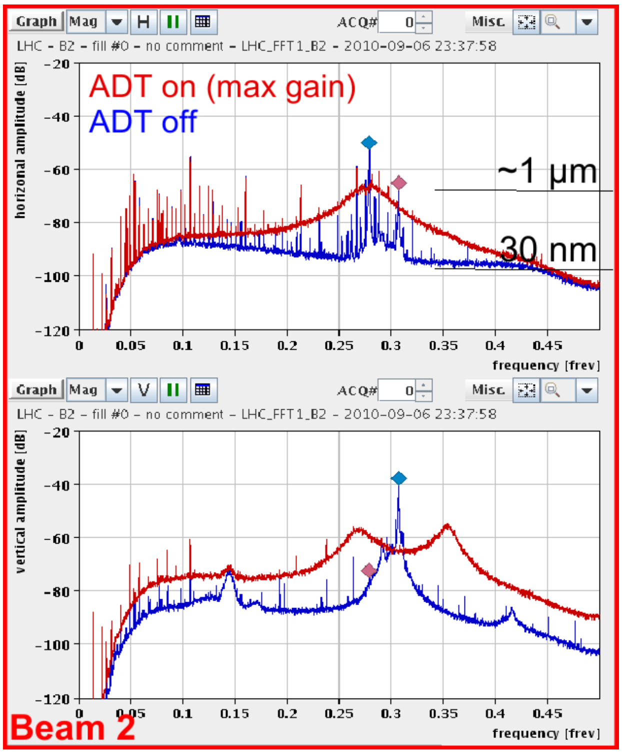
The ADT has been successfully operated since July, damping injection oscillations on a regular basis, and being kept 'on' also during ramp and during collisions with an impressive performance of damping times of few hundred down to 50 turns[11]. At the same time and, as one of the limiting factors of any feedback, part of the ADT measurement noise is propagated onto the beam as illustrated in Figure 7, compromising the BBQ high-sensitivity capabilities by up to 30 dB and reducing the tune resolution by at least two orders of magnitude. By comparison of the unperturbed and damped spectra, the particular shape of the noise probably originates from the particular internal ADT filters and feedback gains, and in many cases, the maxima being unrelated to the actual tune-resonance. In addition, the ADT – used as an abort gap cleaner – creates ringing excitation. This ringing prevails up to 250 ns and resonantly excites e.g. the first bunch after the abort gap with the given frequency that does not necessarily correspond to the tune. This effective ADT-induced noise floor and observed bunch-to-bunch cross-talk hinders, and in some cases, prevents reliable operation of LHC's Q/Q'-diagnostics and related feedbacks.

Some mitigation options – of which some have been tested in 2010 – that could make the Q/Q'-diagnostic compatible with the ADT function are:

1. low(er) ADT gain after injection until end-of-squeeze
2. high-ADT gain for first N-turns after injection, then lower-gain
3. sacrifical (e.g. non-colliding) bunch for which ADT is disabled or operated at a low-gain
4. dead-band in ADT gain function which masks oscillations slightly above its BPM noise floor
5. deriving tune from ADT's residual exciter signal
6. operating with high ADT gain and Q-PLL exciting about 30 dB above ADT's noise floor. This option was tested during 2010 but was found to be impractical because of the measurable emittance blow-up, particle loss and complex dependence on ADT gain, energy, intensity and other collective effects.
7. operating with high ADT gain and Q-PLL exciting about 30 dB above ADT's noise floor. This option is similar to the previous one, but preferred since the excitation levels are less critical and on the $10\,\mu\mathrm{m}$. However the technological feasibility of this noise reduction needs to be demonstrated.
8. operating with high ADT gain and deriving the Q/Q' signals from the tranverse Schottky monitor, methods involving off-resonance and/or exciting outside the ADT bandwidth



(a) Beam 1 spectra



(b) Beam 2 spectra

Figure 7: Comparions of BBQ tune spectra with ADT feedback being active with nominal settings (red) and being 'off' (blue). The increase of the beam noise floor and additional introduced structures is visible.

The first two options are presently the only viable, reliable and available options until the end of 2010-11, the second differing just by the ADT being adapted to changing requirements. The third option cannot be exploited for the time being due to the afore-mentioned ADT ringing and lack of bunch selector capabilities for the BBQ. The latter would require further research and development to not compromise the existing system's signal-to-noise performance and reliability. Beside the first two options, all have in common that besides some additional simulations and hardware development, all are 'long shots' and require more operational and long(er)-term experience with respect to robustness, resolution and bandwidth prior to being used within the Q/Q'-feedbacks.

PLANNED FEEDBACK MODIFICATIONS

Most of the modifications planned for 2011 are minor, limited to communication protocols, additional logging requirements and clean-up of dead-code or functionalities that have been implemented but found to be unused or unnecessary during day-to-day operation.

The handling of dynamic orbit reference has been in place since 2008 but needs further testing and integration into LSA, sequencer and operational GUIs (YASP). This integration should, for the time being, also eliminate the frequently used but error-prone masking of BPMs during squeeze that 'blind' the feedback with respect to dynamic changes inside the insertions. The disabling was an effective workaround, but providing the OFC with shape and time-evolution of the changing reference is the cleaner and more reliable solution.

An automatic feedback gain scheduling is planned for 2011, in order to allow a more fine-grained control of the various feedback bandwidths, depending on the operational condition: fast feedback action (/high bandwidth) when fast perturbations are expected (e.g. during the start of the ramp) and slow feedback action (/small bandwidth) which otherwise reduces the noise that is propagated from the beam instrumentation to the beam via the feedbacks (e.g. during collisions). The target is to make the dynamic change dependent on the variation of the residual feedback error signal, but a simple switch will be put in place that will control the 'high' and 'low' extremes of bandwidth.

CONCLUSIONS

The beam-based feedbacks on orbit, tune and chromaticity performed well in 2010 and facilitated fast and reliable re-commissioning with minimal losses and with near nominal beam parameter stabilities. Urgent issues have been resolved in a timely manner, and (less critical) systematic BPM and Q/Q' performance issues are being followed up in view of nominal LHC operation. Analysis of the feedback actions of more than 280 logged ramps indicated that more than half of all fills would have been lost without feedback support and the others likely affected by some measurable particle loss. Despite the good overall performance and small transmission losses related to Q/Q' and orbit feedbacks, this year's percent-level particle losses may become more critical with the increased stored intensity foreseen, and should continue to be carefully monitored also in 2011.

The measurement and control of $Q'(t)$ received less attention than was initially planned, with systematic negative chromaticities and large relative variations during the ramp. The few measurements performed during the ramps indicated an intrinsic trade-off between beam stability (and low transmission losses) and beam size growth as a function of chromaticity. There are still some important uncertainties on the absolute scale of this effect and it would thus be useful if these dependencies could be assessed in more detail during controlled measurements at injection and top energy.

If operated at maximum gain, the effective ADT-induced noise floor and observed bunch-to-bunch cross-talk of the current abort gap cleaner implementation hinders reliable operation of LHC's Q/Q'-diagnostics and related feedbacks. Mitigation options compatible with a high-gain ADT operation will be further explored in 2011. At the same time, the indifferent high-gain ADT operation should be validated against the actual instability growth times to optimise the required damping constants against the noise that is propagated on to the beam.

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LHC TRANSVERSE DAMPER OBSERVATIONS VERSUS EXPECTATIONS

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Abstract

As part of the 2010 LHC start-up the LHC transverse feedback system was successfully commissioned with beam. Damping times better than nominal were achieved and the system was run at high gain on the 450 GeV plateau. Following successful tests during the ramp and with colliding beams, operation of the LHC with the transverse feedback system on rapidly became the standard procedure. This included operation with Pb-ions, but excluded the squeeze and periods of chromaticity measurements. The transverse feedback system contributed to the preservation of the smaller than nominal emittances by limiting emittance increase due to injection errors, the impact of external perturbations ("hump") and curing instabilities observed with chromaticity close to zero. Interferences observed with the tune measurement system will be addressed in a number of ways: In the long term a tune measurement based on the analysis of the residual oscillations in the damper feedback loop seems feasible, but short term improvements for the tune measurement system will be prepared for the 2011 LHC run. Further improvements foreseen for 2011 and beyond address controllability, diagnostics, data acquisition and interlocking as well as the frequency response of the system.

INTRODUCTION

Hardware commissioning of the transverse damper power system had finished in time for the 2008 LHC start-up [1] and the system was regularly used during the brief period of operation in 2008 as an exciter for the tune measurement system [2]. Beam commissioning of the transverse damper system also started in 2008 [3] with observation of the pick-up signals, setting-up of the electronics for demodulating the wide band signals and digitizing these bunch-by-bunch with the aim of resolving oscillations of the individual bunches at the micrometer level. Such a high resolution is necessary as the feedback loop gain will amplify any noise from the pick-up system thus setting a lower limit for the rate of emittance increase achievable with the feedback loop closed. The short 2009 LHC run served to gain further experience, in particular a first test of the abort gap cleaning was carried out [4]. Issues with electromagnetic interferences were identified and corrected [5]. Two sections of 7/8" cable between pick-ups and surface were changed due to damage in the vertical access shaft. More cables are planned to be changed for the same reason during the next long shutdown.

EXPECTATIONS AND LIMITATIONS

System overview

Fig. 1 shows a block diagram of the transverse damper system reproduced and explained in detail in [2, 6]. There are a total of 16 power amplifiers installed directly under the kicker tanks in point 4 of LHC. Per plane and beam a set of two coupler pick-ups is available to detect the transverse oscillations. Pick-ups and kickers are installed at locations with high beta function in order to have a high signal and a large impact of the correcting kicks on the beam normalised oscillation. In point 4, at the relevant locations for the damper system the optics functions (version 6.503) do not change from 450 GeV to 3.5 TeV collisions with $\beta^\star = 3.5$ m. This eased setting-up the system throughout the cycle, as only the change of fractional tune during the squeeze has to be taken into account in the damper signal processing.

The signal processing comprises an FIR filter to shape the response of the system with frequency in amplitude and phase as well as a scheme to combine the signals from the set of two pick-ups as vectorial sum either directly or after shifting them in phase using an FIR filter (Hilbert filter) [7, 8]. In 2010 the system was run at the full available bandwidth (20 MHz low pass filter in the digital part) and with a phase compensating filter adjusting for the *theoretical* phase response of the power amplifiers with a 3 dB point of 1 MHz. The phase response of the 3/8" drive cables has been corrected by an analogue filter at the end of the cables in UX45 which was added in the shutdown 2009/2010. In particular this filter improves the pulse shape for the abort gap cleaning [1].

The pick-up signals are normalised to the bunch intensity in the digital part of the processing. The gain of the analogue front-end before the mixers can be adjusted to optimize the use of the dynamic range of the ADC located after the mixer and digitizing the base-band signal at a rate of 40 MS/s synchronously with the bunch repetition frequency of 40 MHz.

[1] The phase response of a lossy cable (skin effect) leads in time domain to a long trailing edge when a pulse is transmitted. This response cannot be corrected perfectly as the tail has an infinite length surpassing with significant parts the 32-tap (at 40 MS/s) FIR filter implemented in the damper signal processing.

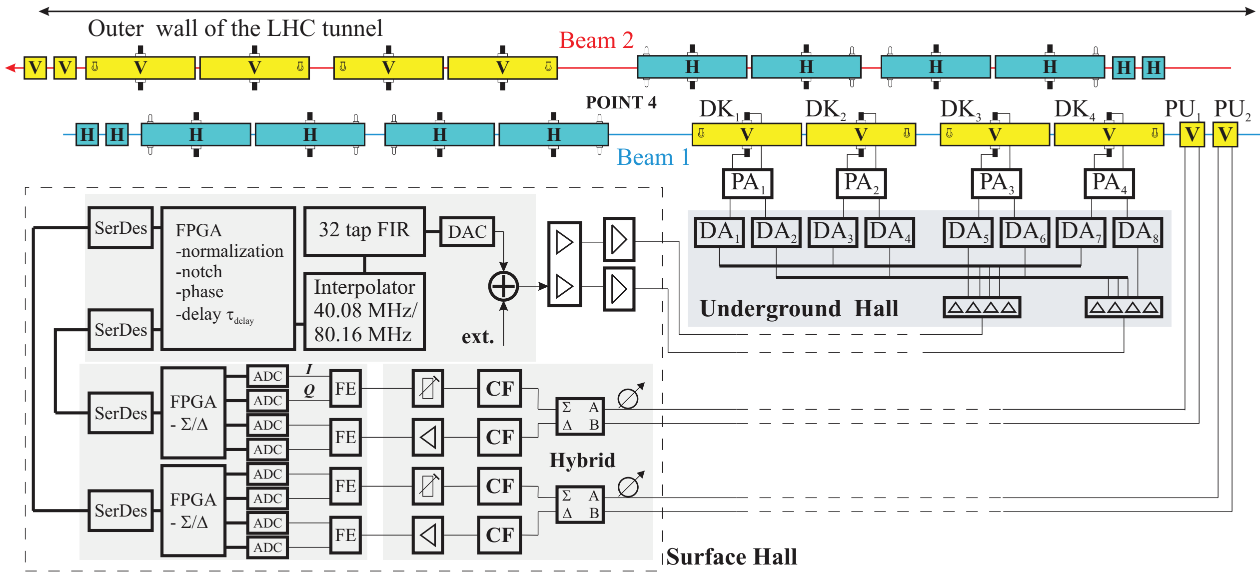

Figure 1: Block diagram of transverse damper system, reproduced from [2, 6].

Design goals

The principle design goals for the transverse feedback system were damping times of 40 turns at 450 GeV [9] and a resolution at the micrometer level in order to permit the feedback to be used with stored beams. The maximum kick strength at low frequency of 7.5 kV per kicker leads to a total combined kick angle (4 kickers) of maximally 2 μrad. Due to beta functions higher than the assumed 100 m at the design stage for the kicker location, the capabilities exceed expectations with respect to the maximum possible kick.

Limitations

A known limitation of the principle underlying the power system (tetrode amplifier driving directly a set of kicker plates), is the relatively low 3 dB bandwidth of 1 MHz defined by the kicker capacity and the resistance in the tetrode anode circuit [10]. This type of system permits a large kick strength at low frequency as needed for batch by batch damping of injection errors and would also be adapted to the frequency dependence of the resistive wall impedance which falls off with frequency and is thought to be one of the main driving impedances of coupled bunch instabilities that the feedback should cure. Digital signal processing permits the system to be used up to 20 MHz, albeit at reduced power. During the design stage, when it became apparent that higher frequencies were present in the injection kicker wave form, the consequence of the reduced power bandwidth was investigated and was found adequate for injection damping [11]. Further modification of the signal processing to boost the gain at frequencies between 1 MHz and 20 MHz may be necessary to match the damping rate with requirements given by the dependence with frequency of the impedance driving instabilities. More studies with bunch trains are required to optimise the signal processing.

For the 2010 run a sample hold scheme was used optimised for different bunch spacings. For the single bunch mode the hold time was 625 ns, for bunch trains with spacings of 150 ns, 75 ns and 50 ns the sample hold time was chosen to be equal to the bunch spacing. This reduces the overall gain for the same electronic gain setting in LSA, as the bunch spacing is reduced.

COMMISSIONING OF THE FEEDBACK LOOP

Procedure and results

Commissioning of the feedback loop started in spring 2010 and damping was first achieved in April 2010. Fig. 2 shows a comparison of the turn by turn injection oscillation recorded with the damper system, with the damper feedback loop open and closed. With the loop open the injection error filaments (top picture), depending on tune spread, due to non-linearities in the optics as well as collective (space charge) effects. In contrast to this the injection error is very quickly damped with the feedback loop closed (bottom).

In the SPS the adjustment of phase in the feedback loop is done using a vector sum of both available pick-ups spaced at 90° in betatron phase space and measuring the open loop transfer function with a network analyser [12]. This method was also tried in the LHC. However, due to the different absolute values of the beta function at the pick-ups and a phase advance considerably different from 90 °, it proved easier to use the pick-ups one by one together with the digital phase shifters (Hilbert filter) to adjust the phase individually for each pick-up and then combine both signals digitally. This gives also a better-signal-to-noise ratio at the expense of additional turns of loop delay. This additional loop delay limits the range of tunes for which the

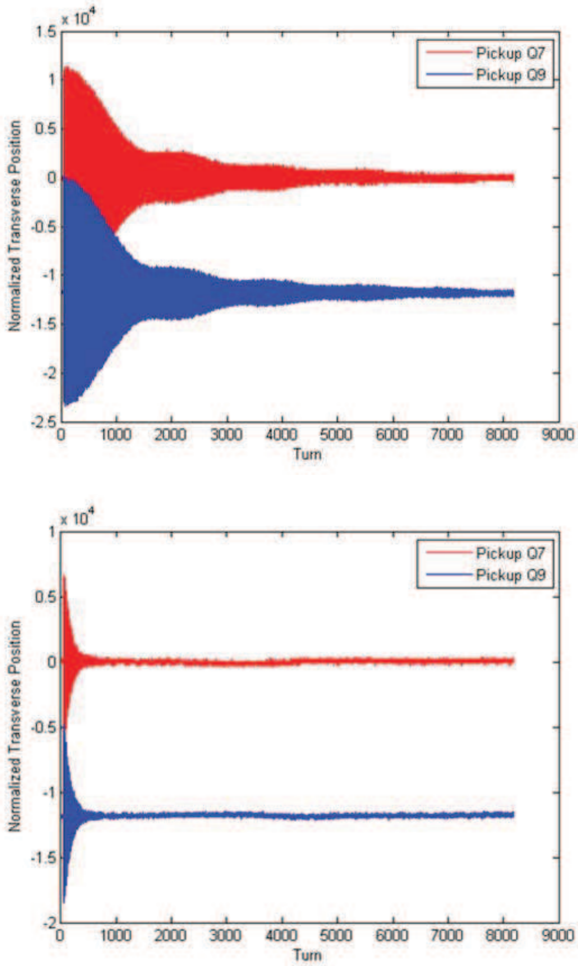

Figure 2: First successful Injection Damping, damper off (a) and damper on (b).

feedback works correctly.

Fig. 3 shows a network analyser open loop transfer function measurement around a betatron side band. For perfect damping the circle has to be orientated to the negative real axis, i.e. the phase setting is wrong by approximately 135° in this example. Feedbacks were roughly set-up using the network analyser. In a second pass the feedback phase adjustment was improved by scanning the phase setting for each pick-up individually and looking for the peak damping rate.

Peak damping is not very sensitive to the phase setting. A better setting of the phase can be achieved by looking at the tune shift introduced by the feedback as a function of the phase setting. Fig. 4 compares measured tune shift and damping rate as a function of the phase shift that is applied to the pick-up signal. The correct adjustment for resistive feedback is at the maximum damping rate which coincides with zero tune shift when compared with the case of the feedback loop open.

Due to the limited time allocated for setting-up the damper the more precise tune shift method was not used on all dampers resulting in phase errors that are estimated as up to 25° (by comparing with values expected from the theoretical optics). The phase settings should be re-visited during the 2011 start-up. Moreover, the set-up of the direct vector sum should be completed. The 1-turn delay (time

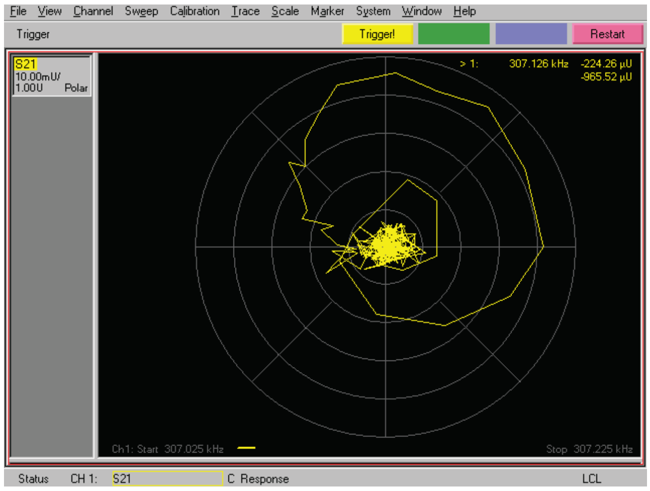

Figure 3: Network analyser measurement of open loop beam transfer function; single pilot bunch — the measurement leads to a loss of beam intensity.

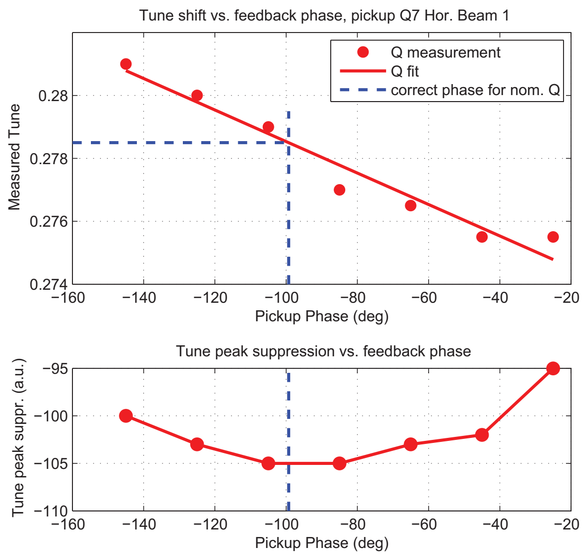

Figure 4: Damping rate and tune shift introduced by the feedback as function of phase setting [13].

alignment of kicks and beam) was adjusted by looking at the damper higher order mode (HOM) ports and observing the signal from the passing bunches and the applied kicks. This method worked quite well, but adjustments need refinement for the short bunch spacings of 50 ns and 25 ns — the latter has not been tested in 2010.

Summary of time line

In the following, a brief history of the 2010 time line for the damper commissioning and operation is given with the important milestones listed:

22.04.	first damping loop successfully closed
17.06.	full operation for nominal bunch intensity at 450 GeV with attenuators and ”low intensity” settings
30.06.	new firmware fully operational with automatic synchronization for the digital links
04.07.	damper becomes operational with colliding beams; standard gain settings documented as in [15,16] with damping times of approximately 40 turns at 450 GeV and 880 turns at 3.5 TeV
05.09.	signal-to-noise improvement by a factor 2; operation with higher gain from 06.09. onwards
17.11.	”scrubbing run” with bunch trains of 50 ns and 75 ns, optimization of sample hold for different bunch spacings
21.11.	Commissioning for ions at 450 GeV completed
23.11.	Following tests at 3.5 TeV damper operationally used with colliding ion beams.

DIAGNOSTICS USING DAMPER SIGNALS

The data present in the damper system can be used to evaluate not only the transverse injection errors and their damping but it also gives an abundant amount of information that can be used for beam diagnostics purposes. From summer 2010 onwards data from all eight pick-ups used by the damper system was stored in the logging data base for the first 8192 turns after each injection, and also visualized with the injection oscillation display. Data from the first bunch of each injected batch is recorded and displayed. Dynamic gain switching between pilot and nominal intensity remains to be implemented for a full exploitation of the data — usually damping was inhibited for the pilot and the threshold set such that the acquisition did not trigger for pilot intensity, in absence of the dynamic gain switching.

Fig. 5 shows the filamentation of an injection error of a pilot bunch with damper off. By comparing with a numerical simulation as in [14] an estimate of the chromaticity (5.5), synchrotron tune (0.0056) and non-linear detuning (6×10^{-5}) can be extracted from the measurement.

Fig. 6 shows the injection oscillation display for beam 1 (top) and beam 2 (bottom) for a pilot beam injection. The horizontal injection oscillations (top set of plots for both beams) with a modulation at the synchrotron frequency points to a non-zero chromaticity while for the vertical plane the chromaticity is close to zero and the filamentation smooth without beating. One of the horizontal pick-ups (Q9) has about 1 m of dispersion while the other (Q7) is installed at a dispersion close to zero. This dispersion makes visible an injection error in energy (bottom plot, top right quarter).

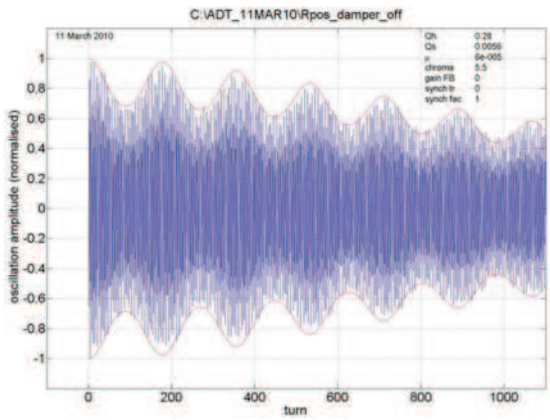

Figure 5: Filamention of injection error without damper.

An example of the injection oscillation display with feedback on is shown for ions in Fig. 7. The top plot shows the first ion injection and the bottom plot the last. Again a small energy transient is visible as oscillation in the top right quarter where pick-up Q9 horizontal is displayed. For the first injection (the top plot), the phase loop locks the RF onto the beam and the synchro-loop transient quickly brings the beam to the correct energy, while for the last injection (bottom plot) the oscillation in energy of the last injected bunch persists for many synchrotron periods. Moreover, bunch by bunch oscillation data has also been made available with an on-demand trigger as part of the MultiQ application. The examples presented demonstrate the high quality of the data available within the damper feedback system. A joint effort between the RF and OP teams is needed to develop the software tools to fully exploit the data.

HUMP CONTROL, GAIN AND TUNE MEASUREMENT

During the stable operating period in August, the feedback system was always used both for injection oscillation damping and during stable beams. Fig. 8 shows an analysis of the damping for fill 1268 where the average damping time was 44.6 turns for beam 1 horizontal oscillations. More plots can be found in [15] where the fit method employed is described in more detail.

Damping times at 3.5 TeV were measured using a non-colliding bunch in an end of fill study (August 20, 2010) at different electronic gains [16]. This exemplary data analysis done permits estimation of damping times for other fills using the stored values of the electronic gain in the logging.

In order to further reduce the impact of external perturbation found to induce beam oscillations, such as the ”hump” the gain of the damper system was pushed to its limits and

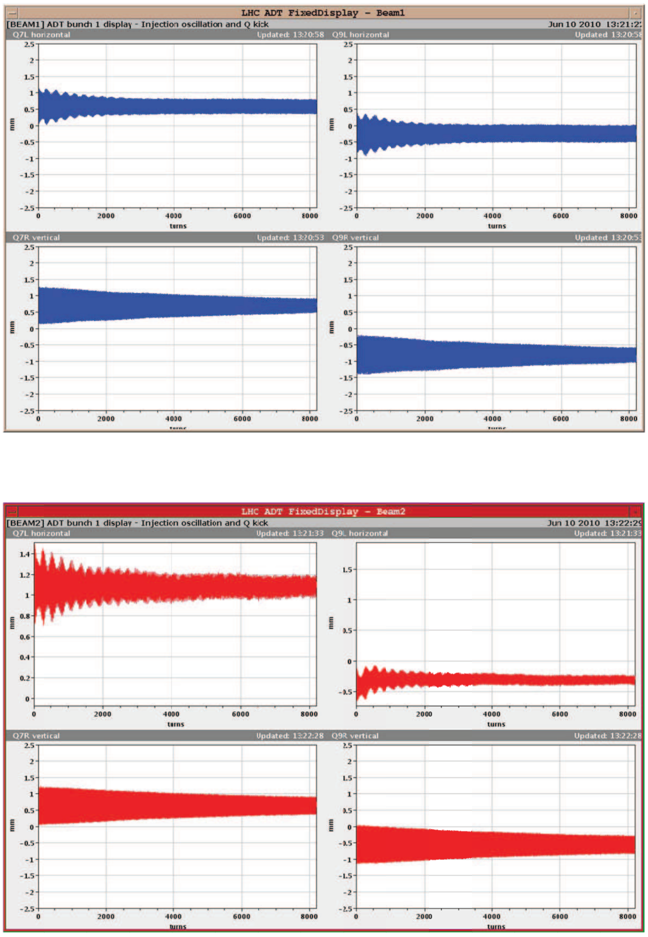

Figure 6: Example of injection oscillations without damper for beam 1 (top plot) and beam 2 with energy error (bottom plot).

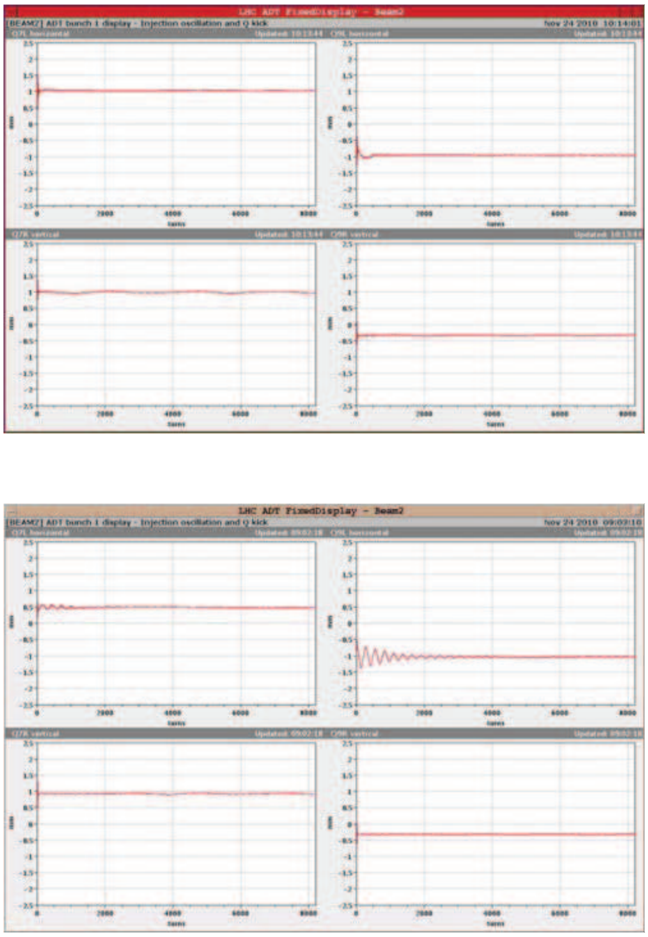

Figure 7: Example of injection oscillations for the first injection (top plot) and last injection (bottom plot) with damper on for beam 2 with an energy error (ions).

running with increased gain at 450 GeV became standard practice, for details see [17]. The operation at high gain interferes with the tune measurement system.

Fig. 9 shows an FFT of 8192 turns of damper data of a single bunch, clearly exhibiting a notch in the noise floor at the betatron frequency where beam response and feedback interact to create the dip. This observation together with simulations started [18] seem to indicate that it should be possible to extract the tune information from the damper signals with feedback loop closed. The question is if a sufficiently large measurement bandwidth and a high precision can be obtained at the same time.

A better tune precision can be reached if FFT spectra are averaged. Fig. 10 shows the average over 999 spectra for three different electronic gains . Clearly the 8 kHz sharp line (perturbation on beam) is reduced proportional to the feedback gain, but at very high gain lobes develop at the tune values limiting the range in which the feedback works in a stable regime. The figure also shows how by averaging 999 spectra it is possible to more accurately locate the tune, however this takes a very long time, consequently the measurement bandwidth is small. As only data from one bunch was recorded a similar result should be obtainable by looking at the data of all bunches and averaging the spectra of the individual bunches. This would lead to a higher measurement bandwidth. A considerable hardware and software development effort is required to build a system that could provide an on-line tune measurement due to the high data throughput (in excess of 1 GBit/s). A first step that will be undertaken in 2011 is to show the feasibility by off-line analysis of multi-bunch data.

IMPROVEMENTS FOR 2011 AND BEYOND

Abort gap cleaning pulse shape

Since the first abort gap cleaning tests in 2009 [4] it is clear that trailing bunches located after the abort gap will suffer small residual kicks. An improvement was intro-

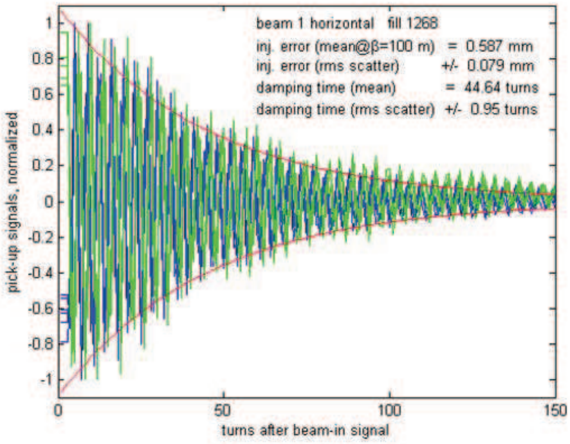

Figure 8: Injection oscillating of all injections of fill 1268 (August 9, 2010) with average damping fitted [15].

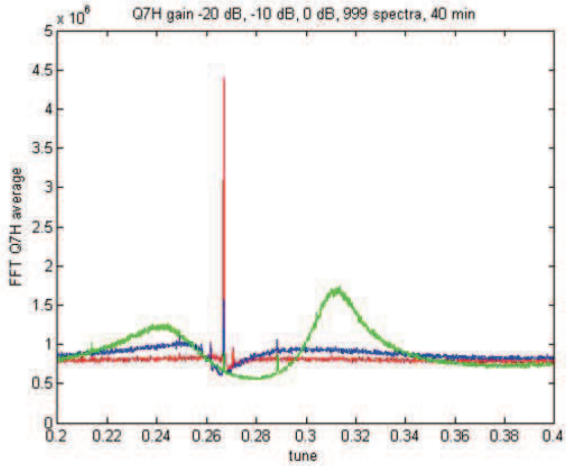

Figure 10: Average of 999 spectra with different gains of the damper feedback.

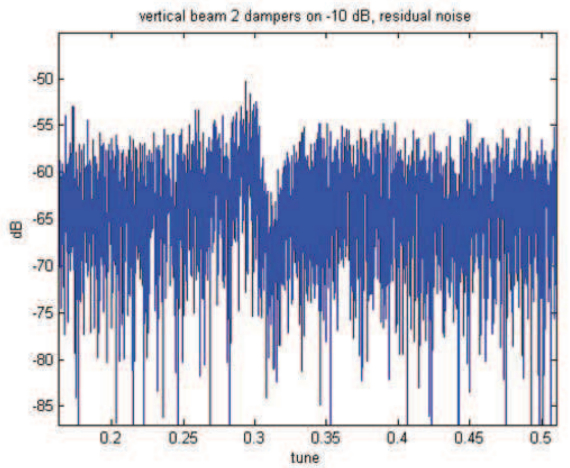

Figure 9: Feedback on, residual damper signal, FFT of 8192 turns.

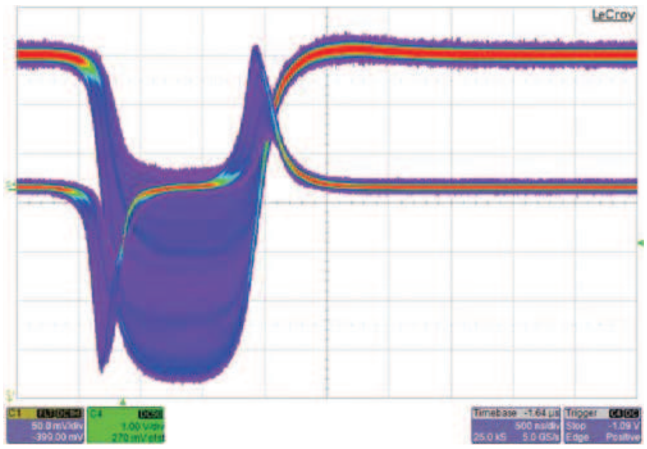

Figure 11: abort gap cleaning pulse directly measured in tunnel inside the amplifier and via the HOM ports; the latter signal is differentiated due to the capacitive coupling at the HOM ports.

duced in the 2009/2010 shutdown in the form of an analogue filter compensating the phase response of cables used to transmit damper signals from the surface building to the underground cavern. This improvement has permitted operation with abort gap cleaning in 2010, although a perturbation of the tune measurement remains. Inspection of the kick wave form in Fig. 11 shows that the filter may slightly over correct and may possibly be further improved in a long shutdown. Moreover, as part of the improvements for the pulse shape, tetrodes in the power amplifiers were regularly checked in 2010 and in a campaign during the summer sorted to have matching pairs of tetrodes in the individual power amplifiers. Note that these power amplifiers are running in class AB in push-pull mode and consequently will only produce an undistorted output pulse if the two tetrodes employed in each amplifier are identical.

List of improvements for 2011 and beyond

The 2010 run identified a number of improvements and extensions of the operating mode that can be planned for 2011:

- automatic loading of settings to adapt to different bunch intensities and spacings
- improving the frequency response and adapting the bandwidth to what is required for a given bunch spacing
- fine adjustment of phase and delay to a higher precision than in 2010
- commissioning of the vector sum as a more robust scheme with respect to tune variations
- programming of the damper gain via a normalised

function (scale with energy), in physical units, e.g. damping time τ
- extending the multi-bunch acquisition to more than eight bunches
- definition of what should be logged for "post mortem" analysis followed by implementation
- move the beam cleaning (abort gap / injection) functionality to standard operation
- further improve the abort gap cleaning pulse shape
- commission the damper during the squeeze
- study the noise properties of the system and propose improvements to be implemented in a future long shutdown
- work on a scheme to restore acceptable compatibility with the tune measurement system (sacrificial bunch?)
- study the feasibility to extract an on-line tune signal from the damper data
- develop and test a scheme for a controlled emittance increase to be used for example to generate loss maps for the collimation set-up and verification

Most of the above require small software or firmware changes that can be implemented without change of hardware. Some of the optimisations require input from the Chamonix workshop, such as the range of bunch intensities at which LHC will run, bunch spacings for trains as well as the energy. Certain items involve finding better parameter sets for the damper requiring dedicated study time with beam. Due to the shortness of the present shutdown it is not realistic to implement all modifications that can be envisioned. The emphasis will be to guarantee an operation with as low as possible down time while still permitting an evolution to more functionality in 2011.

SUMMARY AND CONCLUSIONS

The transverse feedback system in LHC has been successfully commissioned in 2010 with beam for all planes and beams. With the system being used operationally with colliding beams the performance has exceeded expectations. Damping times better than nominal were achieved at 450 GeV and operation at high gain was successfully used to reduce residual oscillations of the beam induced by external perturbations. The system was also used with ions, initially for injection damping and during the last part of the ion run also with colliding beams. The abort gap cleaning will be extended to provide a cleaning of the "injection slot" in 2011. Main changes for 2011 concern software for better operability and the use of the abundant data present in the damper feedback loop. The evaluation and reduction of the noise remains a priority as an improvement is needed to maintain the same performance at 7 TeV as has been achieved at 3.5 TeV due to the smaller beam size at the higher energy. The issue of compatibility with the tune measurement system will be addressed, with a short term solution as well as a long term option that aims at extracting the tune from the damper data itself. To investigate the feasibility of the latter will be one of the priorities of 2011.

ACKNOWLEDGEMENTS

The design of the hard- and software of the LHC transverse damper has been a project spanning a period of more than ten years. The authors share responsibility for the transverse damper operation and the necessary improvements. Contributions by P. Baudrenghien, O. Brunner, V. Rossi, D. Stellfeld, U. Wehrle and F. Weierud to the design and commissioning of soft- and hardware for the low-level electronics and for installation planning are acknowledged. For help during testing, and commissioning, as well as shutdown work on the installed hardware the authors would also like to thank D. Landre and the members of the field support units (FSUs) attached to the RF group. D. Jacquet and V. Kain have contributed with software to the good operability of the system from the CCC. We have to thank M. Lamont, M. Meddahi, LHC Machine Coordinators, EICs and the entire LHC OP team for the efficient beam commissioning and their help as well as the confidence in the damper system.

It has been a pleasure to share knowledge with V. Lebedev (FNAL), U. Wienands (SLAC) and V. Zhabitsky (JINR) who have all, as visiting scientists, made contributions to the commissioning of the LHC transverse damper in 2011. In particular we thank V. Zhabitsky and his team from JINR, Dubna, Russia to who we owe credit for the collaboration which spanned the project from the initial concepts of the transverse damper system and the prototypes of the power amplifiers and kickers to their commissioning with beam.

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BPM: STATUS, MEASUREMENT RELIABILITY AND OUTLOOK FOR 2011

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Abstract

This paper presents an overview of the performance of the LHC Beam Position System during the 2010 run. Its dependence on beam intensity and on ambient surface temperature variations are discussed in detail, while the modifications currently envisaged to improve the present system are also covered.

INTRODUCTION

The LHC Beam Position System is one of the largest beam instrumentation systems at CERN. It consists of 2140 measurement channels that depend on an extensive acquisition chain of 1070 monitors, 3820 electronic cards distributed along the LHC underground tunnel and more than 1070 digital post-processing cards located in surface buildings. Despite its size and complexity the performance of the system during the 2010 run has been very good, with 97% of these channels providing reliable data. Nevertheless some issues were uncovered during operation in 2010. This paper will comment both on these issues and on the proposed solutions.

The first part of this contribution discusses the reasons behind the necessity to mask some channels. The second part describes the dependence of measured position on intensity, while the final section covers the observed temperature dependence of the system.

BPM CHANNELS MASKED IN THE ORBIT FEEDBACK: CAUSES AND SOLUTIONS

By the end of the 2010 LHC run, only 3% of the BPM channels were masked for potentially being erroneous in the Orbit Feedback system (OF). The main reasons for this masking were:

- Systematic non-physical offsets. During 2010, several BPMs were found with loose connections in the flexible cables between the cryostat flange and the front-end electronics. However, this issue is easily detectable and was solved during the technical stops. On rare occasions, such as for channels BPM.30L1.V2 and BPM.20R6.V2, the defect is inside the cryostat and will only be possible to correct with an opening of the interconnect.
- Noise. The average RMS value of each BPM channel is about ~5um in orbit mode and about ~100um in bunch by bunch mode. When this noise level is significantly higher the OF automatically disables the channel. This is the case for the directional couplers in the common beam pipe regions due to crosstalk between beams.
- Error rate. If the ADC out-of-range error rate is abnormally high for a particular BPM channel, the OF also masks it.

A deeper look into the masked channels showed that close to three quarters of them are monitors placed in the LSS regions. There, two technical constraints compromise their operation.

Firstly, due to the radiation tolerance limits of the electronics, the front-end equipment is deported to the alcoves. This implies that electrode signals must travel tens of meters through coaxial cables leading, in some cases, to interferences or ground loops. Diagnosing this issue is difficult, since access is limited to technical stops when most other equipment is switched off. In such conditions, interferences were often not detected.

The proposed method for addressing these undesired effects is to add so-called “cable adapters” at the input of the front-end cards. These consist of a Gaussian low pass filter combined with galvanic insulation.

Secondly, most of these monitors are directional strip-line couplers. They allow the position measurement of each beam independently in locations where they share the same beam pipe. Since the directivity of this type of monitor is only about 25dB, Beam 1 bunches can therefore wrongly trigger a signal on Beam 2 channels and vice versa for beam intensities >2e10 p/bunch in high sensitivity mode. The proposed solution to mitigate this crosstalk effect consists of using a new “Synchronous orbit” mode, which will validate all triggers with beam synchronous timing.

ORBIT MODES

Due to the difficulties experienced at LEP, it was decided that the front-end electronics of the LHC BPM system should have no need for external synchronization signals and be directly triggered by the beam.

Nevertheless, the post-processing card on the surface (Digital Acquisition Board or DAB) is able to synchronize these signals with the Beam Synchronous Timing system (BST), and tag the data with the bunch it belongs to.

The LHC beam position system therefore has several different parallel orbit modes.

- The default mode is called “Asynchronous orbit”. Here, each incoming bunch data from a particular BPM enters a moving average filter (implemented as an exponential response IIR filter). The time constant of this filter can be configured and will determine the number of bunches required for converging to a good average approximation.

- The new "Synchronous orbit" (to be used mainly in the directional strip-line monitors) allows certain bunches to be masked (i.e. not taken into consideration) for calculation of the orbit. Here the average position of selected bunches are averaged over a set number of turns (usually 225 in order to reject the 50Hz mains ripple).
- A new "bunch orbit" mode will also be made available to provide the orbit of individually selected bunches

Data from the standard asynchronous and the new synchronous orbit will, from 2011, both be published in parallel at a rate of 25Hz. The OF will decide which data stream to use for the feedback based on pre-defined preferences, availability and measured noise. The bunch orbit mode will be published at a much lower rate and is not foreseen to be used by the OF system.

INTENSITY DEPENDENCE

During collimator setting-up and calibration at the beginning of the year some doubts arose about the BPM system reproducibility. This fact motivated two tests with beam during May and June that aimed at analysing the beam position dependence with respect to the bunch intensity.

During the first experiment, one single bunch of 1e11p was stabilised for beam 2 and slowly scraped using the primary collimators in IR7. The sensitivity of the system was manually switched every ~10 seconds to obtain two characterization curves. Taking the initial orbit as reference, the drift due to the intensity variations was calculated and it is shown in Fig.1.

The optimum switching point for changing the sensitivity was found to be around 5e10p/bunch. In such conditions the maximum drift in each range was smaller than 20um and the "jump" due to the sensitivity change <40um, well within the system specifications.

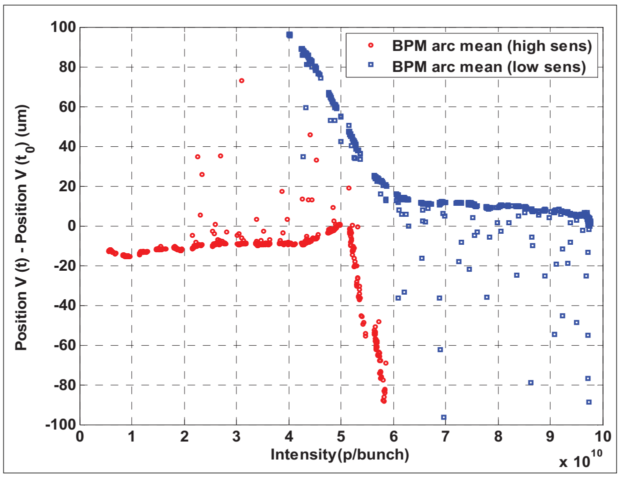

Figure 1. Characterization curve of the BPM system response with the bunch intensity for B2.

During the second experiment, similar scraping was performed for Beam 1, with the results shown in Fig.2.

Surprisingly this time no optimum switch point could be found. With bunch intensities of 4e10 p/bunch, the drift between working in high or low sensitivity was ~300um, and larger than 600um at 5e10 p/bunch. Below 3e10 p/bunch and above 6e10 p/bunch, the linearity was within specification and similar to that observed for beam 2.

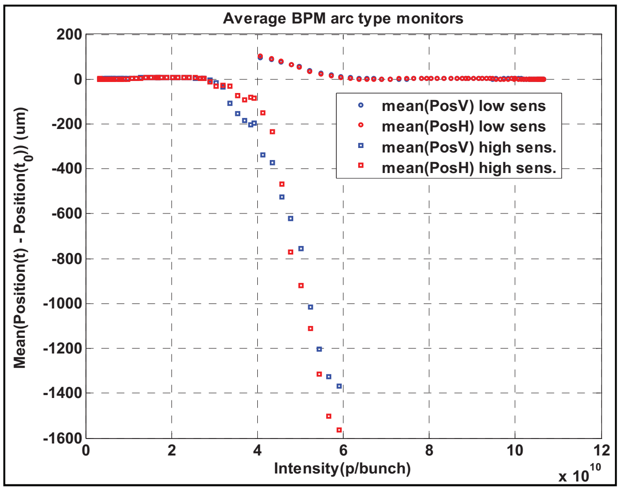

Figure 2. Characterization curve of the BPM system response with the bunch intensity in B1.

The Beam 1 and 2 acquisition chains are identical and all front-end cards were calibrated, measured and qualified for having a linearity with bunch intensity better than ±1% with respect to the half radius of the BPM (i.e. better than ±120um for the arc BPMs).

It was found that the intensity dependence does not come from the boards processing the beam position, but from the adjacent "Intensity measurement board". This card estimates the bunch intensity from the sum of the BPM electrodes signals of the selected beam. A small impedance mismatch in its input was subsequently identified and found to produce a signal reflection that affects the position measurement. The input to this card is switchable, but on Beam 1 by default, explaining the poorer linearity observed for this beam. .

All BPM chassis contain such an intensity card, amounting to more than 530 installed all along the LHC tunnel. To solve this issue requires a new design, production, calibration and installation phase that will take more than one year.

The proposed short term solution for the next LHC start up therefore consists of replacing these cards by "Termination boards" for all the critical LSS BPMs.

TEMPERATURE DEPENDENCE

It has been observed that the beam position measurement also depends on the temperature of the Data Acquisition Board (DAB) integrator mezzanine cards located in the SR and SX buildings on the surface. The large temperature swings seen in these buildings, variations of up to 10 degrees, severely affected the operation of the system during the first half of the year.

Several attempts for removing the thermal cycles by installing local Peltier modules were tried, but they did not improve the thermal stability enough and were found to have a very low efficiency.

A much more successful solution consisted of a software algorithm that calibrates the temperature dependence of each channel in the absence of beam and compensates for the observed drifts. This algorithm is currently operational and has been shown to be very efficient.

In a first stage, the algorithm uses test signals to obtain the initial position calibration values at a reference temperature. Then, the fan speed of the VME crates is slowly changed while acquiring position calibration values and the new temperatures, which are measured via sensors on each DAB, Finally it calculates the gradient of the position change with temperature for each channel.

During beam operation, the system periodically measures the temperature of the cards and corrects the digital data accordingly.

The average temperature gradient was found to be about 2.2 ADC bins/ºC (which corresponds to ~50um/ºC for a standard arc BPM). Fig 3 shows the temperature evolution during a period with stable beams along with the compensated and non-compensated position. Notice that the correlation between temperature and beam position is drastically reduced.

However, this technique has several limitations. First of all, the fan speed change only allows the characterization of the temperature variation within a range of 5-6ºC. Secondly, the gradient calculation and the later interpolation uses a linear fit. As a consequence, if the temperature drift observed since the last calibration is beyond this margin, the correction applied is no longer sufficient.

In order to improve the residual long term drift it is proposed to make a calibration of the BPM system before each first injection of beam. A task to implement such operation has been included in the sequencer and will be operational for the 2011 start-up.

It is hoped that these periodic calibrations will "reset" the long-term temperature drifts while the compensation algorithm still takes care of the short-term drifts.

A long-term solution that consists of replacing the BPM electronic racks with water-cooled and temperature controlled racks is being evaluated. If it proves to be efficient it will be implemented during the long shutdown in 2013.

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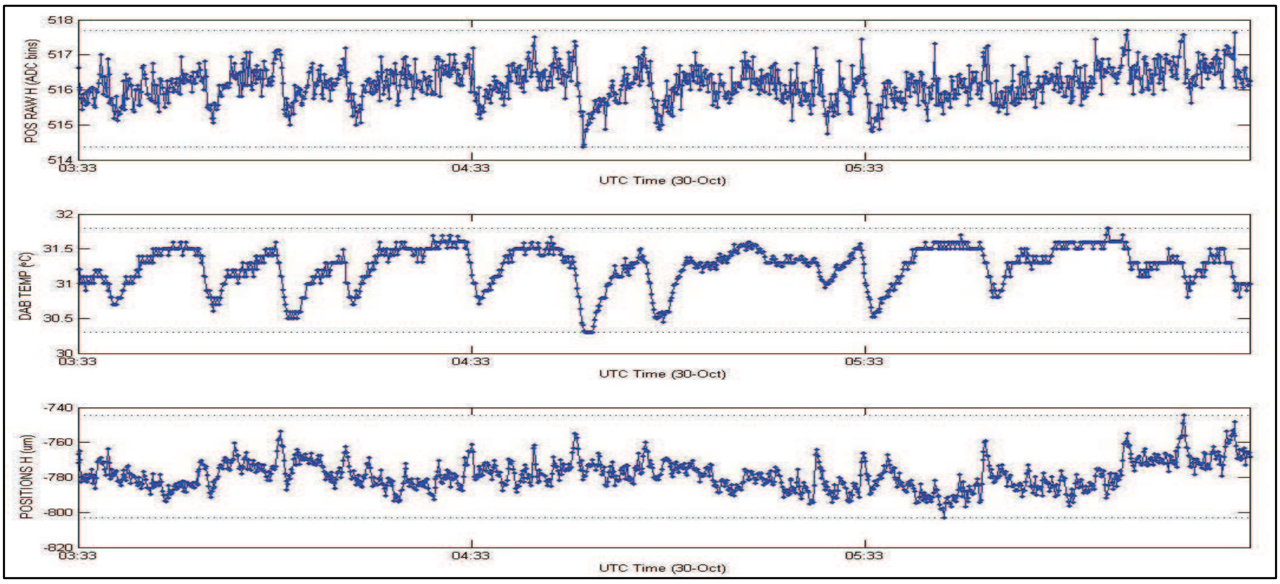

Figure 3. a) Beam position during stable beams (in ADC bins); b) Temperature of the DAB mezzanine. One can see that it is very well correlated with a). c) Position of the beam in um once the temperature drifts were compensated.

CAN WE GET A RELIABLE ON-LINE MEASUREMENT OF THE TRANSVERSE BEAM SIZE?

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Abstract

The transverse beam emittances of the LHC proton and ion beams can be inferred by measuring the beam sizes with Wire Scanner (WS), Synchrotron Radiation (BSRT) and Beam Gas Ionization (BGI) monitors. This presentation covers all aspects related to the operation of such devices in 2010. The absolute and relative accuracy of the emittance measurement is discussed, including cross calibration among the three instruments and with the luminous region estimation during collisions at the LHC experiments. This allows reviewing the reliability of the on-line data and of the values published in the logging database. In addition, an overview of the programmed hardware and software upgrades is given.

WIRE SCANNER MONITORS (WS)

WS monitors consist in a 30 um diameter carbon wire flying through the beam at a maximum speed of 1 m/s. The accuracy of LHC-type WS monitors has been studied in the SPS [1]. Assuming proper monitor settings and the knowledge of the beam optics, the absolute accuracy on the measured emittance is of the order of 1%. The measurement is 'on-demand' and the operator can switch between two types of electronics: at every turn the signal is sampled either i) on a single time window of about 10 us (TURN mode) or ii) a number of selectable time windows 25 ns wide (BUNCH-to-BUNCH mode). The maximum number of selectable bunches is at the moment limited to 75 by the front-end memory and firmware. A software interlock forbids the WS operation for beam intensities above $2 \bullet 10^{13}$ p at any energy. This is compatible with the intensity limits established at the WS design stage [1]: $5 \bullet 10^{13}$ p at 450 GeV to avoid the wire damage and $1.5 \bullet 10^{13}$ p at 3.5 TeV to avoid quenching the SC downstream elements. The software interlock has been set after some 'quench test' experiments in 2010 during which the wire speed was on purpose diminished in order to enhance the secondary shower and induce a quench. In 2011 the software interlock will be reviewed (likely allowing scans at higher intensities, after checking BLM thresholds downstream the WS).

SYNCHROTRON RADIATION MONITORS (BSRT)

The two BSRT detectors [3,4] are installed about 30 m downstream the D3 cryostats hosting the D3 dipole and a SC undulator. The latter has been built to provide enough synchrotron radiation (SR) at low beam energies. As the beam energy reaches 2.5-3 TeV, most of the useful SR power starts to be generated first by the D3 edge and then by the D3 centre. A retractable extraction mirror deviates the light below the beam pipe where an optical system performs the imaging of the beam spot on CCD cameras. The optical system is shown in Fig. 2 and is equipped with remote control in order to focus on the different SR sources.

The total SR power is shared between the Abort Gap monitor (PMT in Fig. 2) and the two cameras dedicated to transverse profiles. In 2010 only the Proxitronic cameras [4] (one per system, indicated as 'slow' in the figure) have been commissioned. Such cameras provide acquisitions at 1 Hz and have two operation modes:

- continuous (DC mode): each acquisition corresponds to the integration for 20 ms of all circulating bunches;
- gated (PULSED mode, available from September 2010): each acquisition corresponds to the integration over all the time windows (gates) programmed in 20ms.

When the camera is in PULSED mode, the minimum gate length is 25 ns and the maximum gate repetition rate is 200 Hz. This means that it is possible to measure a single LHC bunch for a single turn, sampled every 55 turns.

The SR power generated by protons and the system efficiency is such that there are no intensity limitations for proton beams: a single pilot gives a signal well above background. A minimum of about 30 lead ion bunches averaged for 20 ms (DC mode) are necessary to have enough light at injection energy.

This is due to the shift in frequency of the undulator light generated by ions.

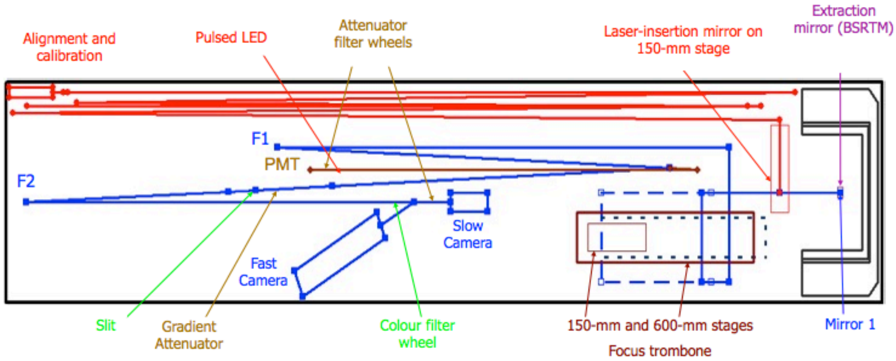

Figure 2: Schematic drawing of the BSRT telescope system sitting below the LHC beam pipe.

The BSRT absolute accuracy relies at first on the imaging at a calibration target illuminated by a lamp, installed on the same optical table at the beginning of the calibration line displayed in red on Fig. 2. The optical path is such that the target distance from the first focusing mirror is 32 m, the same as the distance between the same mirror and the centre of the undulator. This calibration allows determining the system magnification and optimizing the focusing, by tuning the camera position while imaging the target. The ultimate absolute accuracy and resolution depend on several effects affecting the imaging of an extended light source, which, in addition, is changing with energy. This includes aberration, diffraction and depth of field [5,6].

BSRT expected and measured signals

In 2010 it was possible to start comparing the measured SR power to what expected from the simulations. An example is shown in Fig. 4, where the number of photons per charge measured by the Abort Gap monitor as function of energy is compared to what simulated, both for protons and Pb ions.

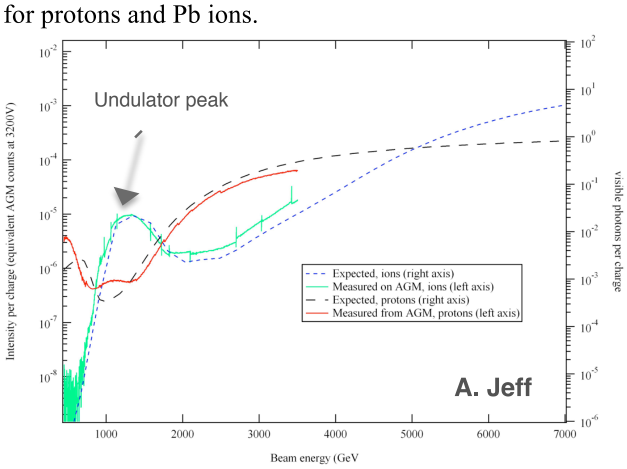

Figure 4: Number of photons per charge, as measured by the Abort Gap monitor as function of energy, compared to simulations, both for protons and Pb ions.

The agreement is rather good, even though the low energy region for protons and the 2-3.5 TeV regions for ions have to be studied in more detail. The plot shows that at 450 GeV the signal given by ions is at least a factor 10^4 lower than the one for protons.

BSRT bunch per bunch measurements

As explained above, during the second part of the 2010 run the BSRT cameras could be used in PULSED mode and monitor single bunches. Even though only a BI expert could enable this functionality, it was extensively used during the last part of the proton run and the entire ion run. The bunch per bunch emittances as measured along 12 trains of 48 proton bunches on Nov 8th, 2010 are shown in Fig. 5. Each measurement point is the average emittance over 2 or 3 periods (5 seconds long) separated by about 50 minutes. Therefore, the error bars represent the emittance variation from the beginning to the end of the measurement period.

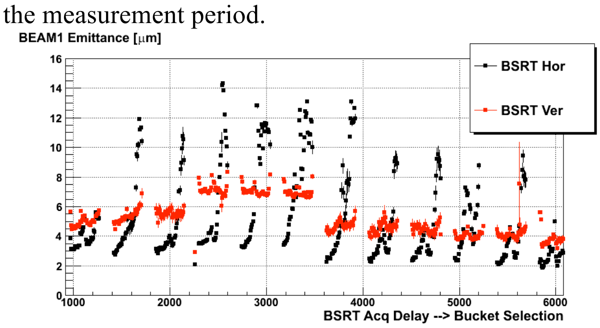

Figure 5: Bunch per bunch emittance as measured by the BSRT along 12 trains of 48 proton bunches each.

The measurement clearly showed the difference between bunch trains and between bunches inside a train.

Another example can be seen in Fig. 6, where the measured horizontal emittance of 17 lead ion bunches is shown as function of time. Since the filling from the SPS consisted in a single bunch followed by 4 trains of 4 bunches each, the plot evidences the larger emittance increase of the first bunch of each train.

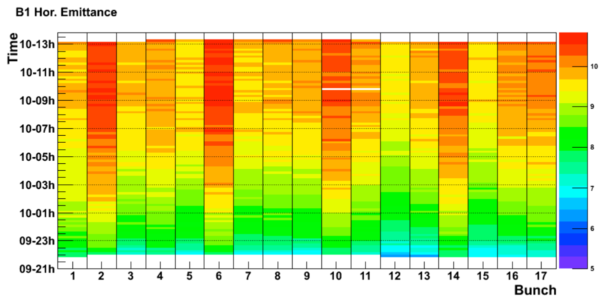

Figure 6: Horizontal emittance evolution during a fill with 17 lead ion bunches.

BSRT – WS comparison

The BSRT system are equipped with movable stages, optical density filters and chromatic band pass filters that, together with the adjustment of the video camera gain, allow optimizing the system resolution and accuracy for the different beam intensities and energies.

Despite the several degrees of freedom for optimization, the BSRT measured beam sizes are still biased by intrinsic limitations, like diffraction, and possible inaccuracies in the system installation in the tunnel (alignment, focusing etc…). Therefore the BSRT calibration is complemented with the comparison to WS measurements, which are considered as the reference.
An example of BSRT – WS comparison is shown in Fig. 7, where the BSRT emittances already include correction factors on the measured beam sizes intended to maximize the agreement with the WS. For the moment, a correction in quadrature on the beam size, according to

$$\sigma = \sqrt{\sigma_{meas}^2 - \sigma_{corr}^2} \qquad (1)$$

is considered the best approximation.

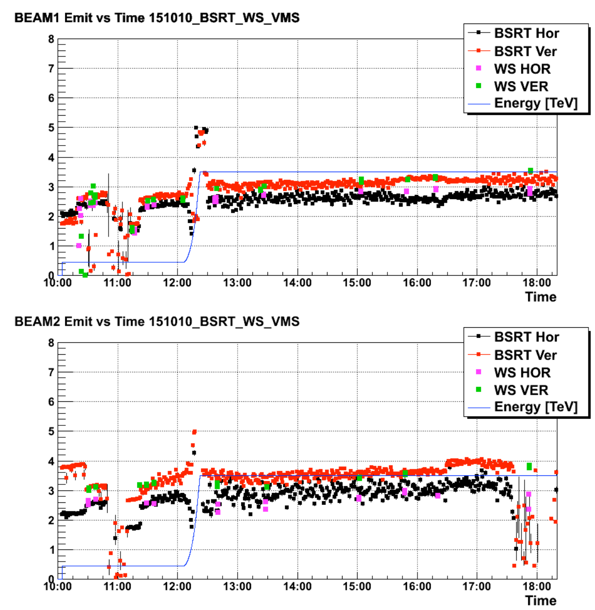

Figure 7: Normalized emittances for Beam 1 (top) and Beam 2 (bottom) as measured by WS and BSRT. These kind of measurements allowed calculating the BSRT correction factors.

Such correction factors are different for each beam and for each plane and changed during the 2010 run, mainly following interventions in the tunnel aimed at improving the overall system. As shown in Table 1, at least three sets of correction factors can be considered for the data logged in 2010.

Table 1: Correction σ_{corr} $[mm]$ to be applied to BSRT measured beam size (see Eq. 1) for the 2010 data.

Protons until 22 Oct		**450 GeV**	**3500 GeV**
B1	H	0.70	0.57
	V	0.63	0.50
B2	H	0.60	0.59
	V	0.50	0.77
Protons after 22 Oct		**450 GeV**	**3500 GeV**
B1	H	0.60	0.50
	V	0.95	0.55
B2	H	0.60	0.52
	V	0.65	0.42
Ions		**450 GeV**	**3500 GeV**
B1	H	0.60	0.40
	V	0.99	0.65
B2	H	0.60	0.55
	V	0.50	0.40

BEAM GAS IONIZATION MONITORS (BGI)

Collecting the electrons generated by the rest gas ionization induced by the beam is used to reconstruct the beam transverse profiles [7]. The electrons are accelerated by high voltage electrodes towards an electron amplification stage (MCP). The beam profile is reconstructed by imaging a phosphor that is placed at the MCP exit. Two orthogonal systems equipped with two video cameras provide the horizontal and vertical profiles.

The cameras can be gated to select bunches, but in 2010 were not remotely controllable and were only used in automatic mode. This meant that the camera gain was fixed at maximum and the gate length automatically adjusted depending on the amount of signal reaching the camera. The data are logged a 1 Hz.

The proton / rest gas ionization cross sections are such that gas injection is needed for proton beam intensities below 400 nominal bunches. In 2010, with about 2e-8 mbar gas pressure (10 times lower than the interlock limit) it was possible to measure a single bunch. This was verified before the scrubbing run and must be rechecked in 2011.

On the other hand, 2 lead ion nominal bunches were enough to image the beam without any gas injection.

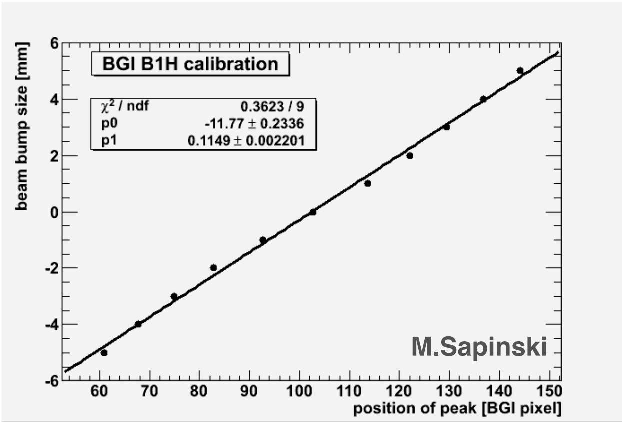

Figure 8: BGI calibration by comparing to BPMs while applying closed orbit bumps.

The BGI absolute accuracy relies on a reference Electron Generation Plate (EGP) calibration. In addition, a correction factor was calculating by comparing BGI and beam position monitors (BPM) while introducing local orbit bumps with different amplitude (see Fig. 8). This yielded to a correction of a factor 1.4 to be applied on the measured (and logged in 2010) beam size. As for the BSRT, the BGI absolute calibration is also being studied by cross calibration with WS. In general, the BGI data logged in 2010 should be treated carefully. Since the system is in a commissioning phase, the data quality, including the profiles fit, is sometimes affected by the specific conditions, namely the gas pressure and the camera gating (that was automatically changing depending on the signal). In 2011 the remote controls for both the gas pressure and the BGI detector will be improved.

BGI – WS – BSRT comparison

In addition to the calibration with respect to BPMs, the BGI can be compared to WS and BSRT. This has not been studied systematically yet, but two examples are shown in Fig. 9. Both examples refer to ion beams (Beam 2) and BGI and BSRT data have been already corrected according to the calibration factors discussed above (computed after calibration with respect to BPM and WS respectively).

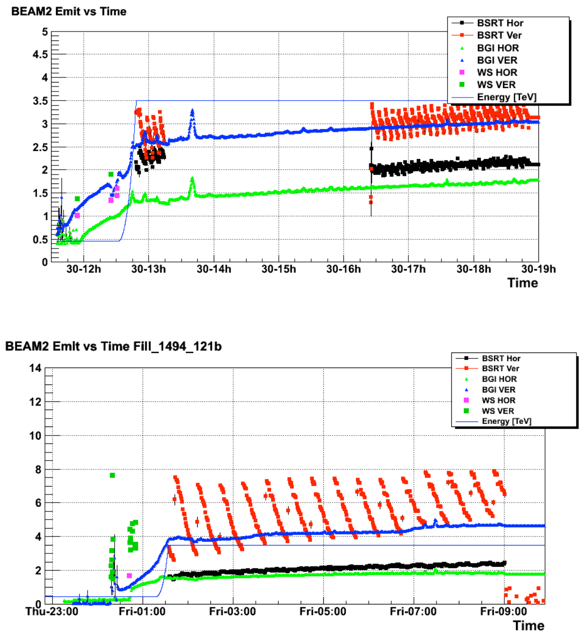

Figure 9: Examples of comparison between BGI, WS and BSRT while measuring the same ion beam during the VMS scans on Nov 30th, 2010 (top) and during the physics fill 1494 (bottom).

From these preliminary tests (to be repeated and improved in 2011) it can be assessed that:

- BGI H and V reproduce the emittance blow-up measured by WS at 450 GeV (top plot);
- BGI V is in good agreement with BSRT
- BGI H gives a smaller emittance than WS (at 450 GeV, top plot) and BSRT (at 3500 GeV, bottom plot).

In general, the emittance evolution monitored by the BGI during the energy ramp can be considered accurate, even though for the moment one should always check with off-line analysis the data fit quality and the absence of saturation effects (e.g. due to beam size shrinking during the ramp).

CONCLUSIONS AND OUTLOOK

The WS monitors act as a reference and are routinely used by OP. Bunch per bunch mode will become operational in 2011. In addition, it is foreseen to perform systematic studies on saturation levels (as done at the PSB in 2010).

The BSRT monitors provide a continuous relative emittance variation (at constant beam energy) that can be considered accurate at the 10% level. Even though calibration factors can be used to analyse the 2010 data, the BSRT absolute calibration and the ultimate resolution need to be studied in more detail.

The BSRT automatic settings of gain/attenuation following beam intensity and energy variations were considered reliable during the last months in 2010. Additional automatic settings, like 'auto-focusing' versus beam energy will be tested in 2011. At the moment the BSRT bunch-to-bunch mode takes at least 3 seconds per bunch and requires BI experts to perform the measurements. The implementation of OP software dealing with the bunch-to-bunch mode will be discussed. At least one 'fast' camera [8] will be installed before the 2011 run and will allow the test of bunch-per-bunch, turn-by-turn acquisitions.

The BGI monitors were in a commissioning phase for the whole 2010 run. The relative accuracy can be considered better than 10 % once the beam profile quality has been checked. The absolute calibration has to be studied in detail, to complement cross-calibration with respect to BPMs. In 2011 the remote controlling of both gas injection and video cameras will be improved.

As additional information, the logging DB is already equipped with virtual variables containing normalized transverse emittances. In 2011 the values with which they will be filled should become trustable, after applying the best estimated calibration factors to BSRT and BGI.

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DO WE UNDERSTAND EVERYTHING ABOUT MACHINE PROTECTION SYSTEM RESPONSE?

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Abstract

Understanding and assessing the performance of the LHC machine protection system (MPS) has been one of the key factors driving the LHC commissioning and operation during 2010. With beam intensities and stored energies being increased along the year by more than a factor of 10.000, many valuable lessons have been learnt which will serve to further enhance the dependability of the protection systems. This paper will give a brief overview on the performance of the machine protection system during the 2010 run. Improvements and mitigations of potential holes in the protection systems will be discussed along with their impact on the 2011 run. A summary of the currently available tools and necessary improvements for the assessment of beam dump events will conclude the paper.

REVIEW OF PROTECTION DUMPS DURING 2010 RUN

With a large fraction of the year 2010 still devoted to the commissioning of the LHC machine, a considerable number of activations of the machine protection systems have been observed, i.e.

- 1280 breaking of beam permit loops
- 640 with beam present in the machine
- 370 where the energy ramp had started (as shown in Figure 1)

Each of these events is exercising parts of the machine protection infrastructure and is used to assess the correctness of its response.

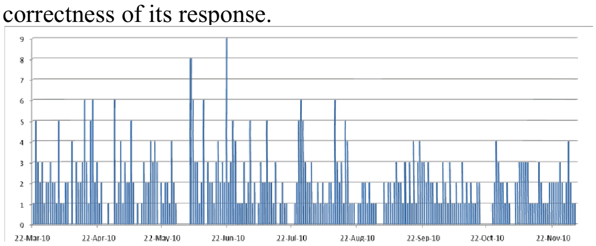

Figure 1: Beam dumps in 2010 as a function of time where energy ramp had already started (i.e. > 450 GeV).

This assessment is done in a completely automated way by the LHC Post Mortem System, which is gathering more than 3000 individual files (with a total data volume of ~ 50 GB/dump) from transient data recorders of various LHC equipment systems [1] and complemented by additional expert analysis by the operation crews and equipment experts in case of exceptional events. A summary of each beam dump request is stored in a publicly available database, allowing for web-based extraction and operational statistics [2].

The number of beam dumps as given in the above figure suggests to be more or less constant throughout the year, it is however not a very representative measure of the machine availability nor its efficiency as it includes all different causes of beams dumps, be it a deliberate machine protection test, a real 'protection dump' triggered by one of the machine protection systems or a deliberate dump of the beam by the operation crews at e.g. the end of a physics fill. When only taking into account beam dumps that were ended with a programmed dump at the end of the fill, one has an indirect measure of the machine availability as shown in Figure 2.

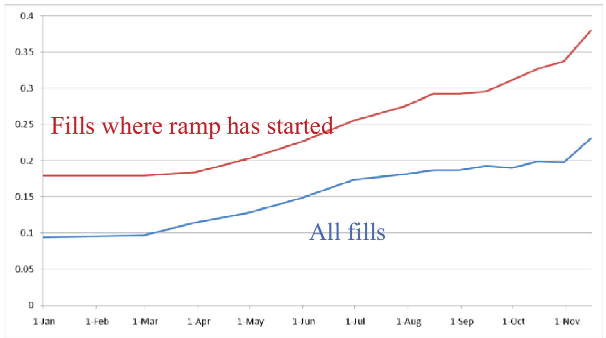

Figure 2: Fraction of fills terminated with a programmed dump by operations in 2010.

Despite increasing the intensity and beam energy throughout the year by more than a fact or of 10.000 (and thus increasing the probability of one of the machine protection systems such as the BLMs, Quench Protection System… to trigger), the number of physic fills that made it to through the complete cycle was more than doubled:

- Yearly average of LHC fills that were completed with a programmed dump: 8% of all fills, 17% of ramped fills
- During Ion run at the end of 2010: 23% of all fills, 38% of ramped fills

This evolution confirms the steep learning curve in both, the tuning and understanding of the machine protection systems as well as of the operational procedure and the good mastering of the machine by the operations crews. Further improvements of these figures can be expected once the machine enters more stable running periods as foreseen for 2011 and 2012, where the major limitations of machine availability will be determined by the dependability of the equipment systems.

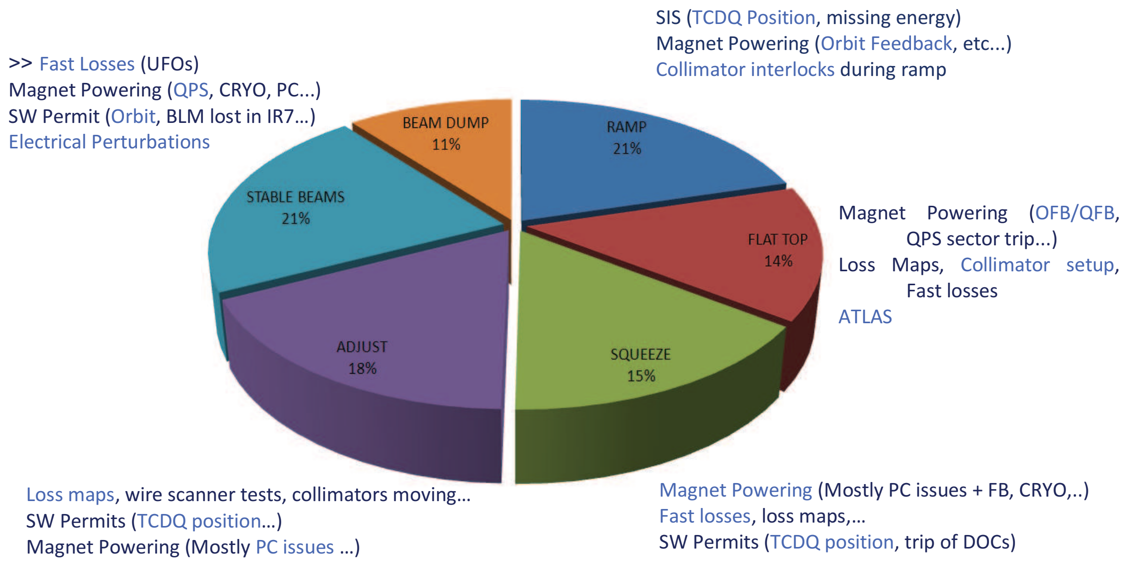

Figure 3: Beam dumps as a function of beam mode for fills where energy ramp started and respective main causes of loosing the beams.

Most Frequent Causes of Beam Dumps

Once the beams have been successfully injected into the machine, the machine will follow the nominal LHC cycle, comprised of the 6 beam modes RAMP, FLAT TOP, SQUEEZE, ADJUST, STABLE BEAMS and BEAM DUMP. Surprisingly, and despite the very different durations of these beam modes (from a few minutes to several hours) the beam dumps seem more or less equally distributed over the modes. The main causes of the beam dumps however come with little surprise. During the energy ramp, flat top and the squeeze the control of the orbit, the related orbit/tune feedbacks and their effects on the magnet powering system showed to be the predominant issue. When in stable beams the fast losses account to more than 75% of the lost beams, followed by issues in the magnet powering system and perturbations on the electrical network.

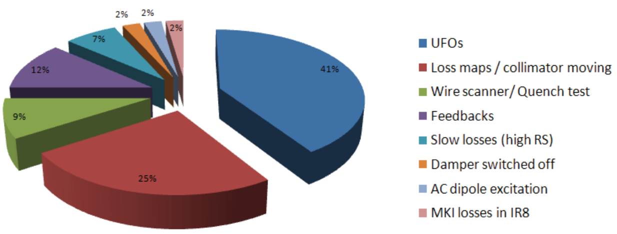

Figure 4: Reason for beam dumps being detected first by the LHC Beam Loss Monitors

For a very large majority of the beam dumps, the failure is detected and caught by more than one machine protection system. An example for this redundancy is e.g. present in the magnet powering system, where the powering interlock system will detect powering failures and dump the beams before any beam losses occur. Should this mechanism not work, the Beam Loss Monitors would eventually dump the particle beams.

During the 2010 run this redundancy has been working very well, and most failures have been timely caught by the respective equipment system before any beam losses have been observed. Only in around 13% of the protection dumps the Beam Loss Monitors have been the sole system to detect the failure and dump the beam. The phenomenon of fast losses has been the predominant cause for these BLM triggers, followed by deliberately provoked losses during collimator setups/loss maps and quench tests as shown in Figure 4. Only a very small number of failure cases such as damper failures, misfiring of the AC dipole or losses from the MKI could not be caught by a dedicated interlock and depend on the Beam Loss Monitors as the ultimate protection system.

DEPENDABILITY OF THE MACHINE PROTECTION SYSTEMS

Due to the very large number of interlock channels connected to the LHC beam interlock system and the underlying complexity, dependability and availability of the machine protection system has been a major design criteria and subject to extensive studies. This work has been performed in the framework of a sub-working group of the machine protection working group [3]. Detailed failure mode, effects and criticality analysis studies have been used to predict the dependability of the systems building the backbone of the LHC machine protection systems. While the main goal of these studies is a minimization of the expected unsafety per year, this number is very difficult to compare with operational experience. A much better way of comparison is the number of false dumps/year that the system will cause due to failures of the internal redundancy or other component failures. The according predications are summarized in Figure 5, and after around 10 months of operation they seem to correspond very well with the observed 31 false dumps from the LHC machine protection system (11 from the quench protection system, 9 from the LHC Beam Dumping System, 4 from the Software Interlock System, 3 from the BLMs and 2 from the powering and beam interlock system). It is very likely that these figures will further improve, as the observed false dumps have been mostly dominated by initial teething issues in hardware and software components of the machine protection systems which have already been resolved or improved during the 2010 run.

System	Unsafety per year	False dumps/y Average	Std.D.
LBDS[RF][(1)]	1.8×10^{-7}(2x)	3.8(2x)	+/-1.9
BIC [BT][(2)]	1.4×10^{-8}	0.5	+/-0.5
BLM [GG]	1.44×10^{-3} (Front-end) 0.06×10^{-3} (Back-end VME)	17	+/-4.0
PIC [MZ]	0.5×10^{-3}	1.5	+/-1.2
QPS[AV]	0.4×10^{-3}	15.8	+/-3.9
MPS	**2.3×10^{-4}** **5.75×10^{-8}/h is SIL3**	**41**[(3)]	**+/-6.0**

Figure 5: Dependability predications for the backbone of LHC machine protection

SUSPICIOUS EVENTS AND ENVISAGED IMPROVEMENTS FOR THE 2011 RUN

During the first year of operation, all beam dumps above 450 GeV have, in addition to the automated Post Mortem Analysis, been analysed by an MPS expert in order to verify the redundancy of protection as well as to identify possible loopholes still present in the protection scheme. It was found that for circulating beam the protection redundancy is working remarkable well, a fact that is also confirmed by the absence of any magnet quenches that happened in 2010, despite stored energies well beyond the initial target of 30 MJ (note that it only requires 10 mJ of energy deposition to quench a magnet). During the process of beam injection however, much less rigour was applied to fully understand the cause of the event which sometimes resulted in repetitive losses of the particle beams during or just after injection because of instabilities or fast kicks. The main causes for these events have been mostly wrong chromaticity, tune trims, injection losses or operational mistakes. Although all of these events were correctly caught by the MPS, one or several protection layers have been disabled/bypassed upon a few occasions (e.g. during MDs, when forgetting to unmask interlock channels…), which highlight the need for an increased rigour at injection level once a certain number of bunches is in the machine.

The tools deployed to assist in the analysis of protection dumps (IQC, LBDS XPOC and Post Mortem) did perform well during the 2010 run to detect potential problems or long term degradation of equipment. Still a number of improvements to enhance the rigor of acknowledgements and follow-up of the analysis outcome have been identified and will be implemented in the course of the 2011 run, such as:

- Splitting the PM SIS input into an (existing) maskable + a new unmaskable channel
- Possibility for analysis modules to propose “Advised Action” (to avoid e.g. repetitive trials to inject beam)
- Additional systematic check of TCDQ/TCT, TCP/Beam Dump Losses to verify hierarchy
- Automatic identification of beam loss shapes (UFO, dump losses, collimation, quench…)
- Additional granularity in PM checklist/categories

Additional changes of machine protection hardware and the related diagnostics and procedures will be put in place in order to further enhance the protection, especially during the injection process where little or no redundancy in protection is currently implemented. These changes include the installation of the Safe Machine Parameter System V3.0 (providing full redundancy for input data, energy read-back and new Beam Presence Flag), additional verifications of injection oscillations and the enforcement of intermediate injections by the SIS as well as the removal of the possibility to disable the Post Mortem event if the machine is above injection energy.

CONCLUSIONS AND OUTLOOK

The LHC Machine Protection Systems have been working extremely well during the 2010 run thanks to a lot of commitment and rigor of operation crews and machine protection experts. The large majority of the failures are captured before any effects on the particle beam are observed, which is confirmed by the fact that, apart from deliberately induced quenches, no magnet quenches have been observed during the 2010 run with circulating beam. Every beam dump above injection energy has been rigorously analyzed and documented. During the 2011 run more rigor and emphasis will have to be applied when dumping beams with high intensity beams at injection level. No evidence of major loopholes or uncovered risks have been revealed during the 2010 run, still we have to remain extremely vigilant to maintain the current level of dependability of MPS systems, especially when entering longer periods of ‘stable running’ in 2011 and 2012.

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LBDS AND ABORT GAP CLEANING

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Abstract

A number of possible failure scenarios and estimated occurrence were defined for the LHC Beam Dumping System (LBDS). An analysis of the LBDS performance during the first year of the LHC operation is presented and compared with respect to requirements and expectations. Several qualification tests have been regularly performed to assess the protection provided by the system in the eventuality of a failure. Possible hardware upgrades and improvements of machine protection tests and operation procedures are explored. Abort gap cleaning deployment, related diagnostic and interlocking are discussed.

INTRODUCTION

The LHC Beam Dumping System consists of 15 extraction kickers (MKD), 8 dilution kickers (MKB), 15 septum magnets (MSD), 1 absorbing block (TDE) and 4 protection elements (TCDS, TCSG, TCDQ and TCDQM) per beam [1]. Continuous monitoring of all the system elements and redundancy, at several levels, of the kicker generators guarantee the reliability of the system. Redundancy and surveillance make the system safer but more complex, affecting the number of false dumps and machine unavailability time. Detailed studies showed that 3.4$\pm$1.8 false dumps per beam per year are expected [2].

Any time a beam dump is triggered, an automatic post-mortem is generated and a series of internal (IPOC) and external post-operational checks (XPOC) is made [3]. These checks allow to control the LBDS status and recover an “as good as new” state after every beam abort.

The LBDS was designed taking into account some acceptable failure scenarios. The beam can be dumped, without inducing machine damages, when the MKDs are not synchronized with respect to the abort gap (asynchronous beam dump) or when one MKD module is missing [4]. Both events are estimated to occur once per year of operation, corresponding to 400 fills of 10 hours. Several validation tests have been performed, when changing machine and beam conditions, in order to asses the protection provided by the LBDS in case of a fault. Special tests have been dedicated to abort gap cleaning studies. Abort gap population must be minimized to avoid to overload the elements downstream of the dump insertion, even in case of normal operation of the extraction kickers.

LBDS PERFORMANCE

A limited number of LBDS failures, in agreement with requirements and expectations, were registered during the first year of the LHC operation. In particular:

- One Beam Energy Tracking System (BETS) error [5]. The deflection strength of each active element of the LBDS has to change with the beam energy in order to guarantee the correct extraction trajectory under all operational conditions. The BETS acquires the beam energy and checks that the MKD and MKB charging voltages follow the reference signals within defined tolerance windows. An instability of a 35 kV power supply induced a beam dump at the end of the first ramp to 3.5 TeV.
- One asynchronous beam dump at 5 TeV and two at 7 TeV, triggered while performing energy scan tests for machine checkout without beam. These events were due to sparks on the outside of a gate turn-off (GTO) thyristor. This problem depends on the operational energy and does not affect the system at 3.5 TeV, that was the nominal maximum energy foreseen for the 2010 run. Insulators will have to be installed before moving to higher energy.
- Four internal triggers induced by false pressure readings on the MKB for Beam 2. An internal interlock was added to the LBDS, as a redundancy to the LHC vacuum interlock, to stop the kickers and trigger a beam dump in case of pressure over thresholds. This redundancy was removed due to the high level of noise of the internal signal.
- Two beam dumps induced by TCDQ faults for Beam 1. In one case, collimator jaw and thresholds were at the wrong settings during injection and the beam was dumped by the losses in point 6 (dumping insertion). In the second case, a glitch in the resolver signal triggered a beam dump at the end of a ramp because of jaw position out of thresholds.
- One asynchronous dump with beam caused by a power driver failure which provoked the self-triggering of two MKD generators. Details of this event are explained in the following section.

None of these failures induced any quench or damage of the LBDS system and the downstream elements. Globally, the system behaved as expected and no major machine protection related issue was encountered.

TCDQ HW AND SW ISSUES AND POSSIBLE UPGRADES

In case of an asynchronous beam dump, several proton bunches (up to 120) enter in the extraction region when the MKD voltage is still rising and are swept across the machine aperture. Two movable horizontal collimators per beam are located downstream of the extraction septa to absorb part of the swept beam and protect the downstream magnets. The TCDQ is made up by one 6 m long carbon based jaw that is installed at the extraction side of the machine. The TCSG is a standard two sided secondary collimator [6] and is located after the TCDQ. Typically, collimators are moved by means of stepping motors with a 5 μm resolution (minimum step size). The TCDQ uses DC motors and a minimum resolution of ± 50 μm can be achieved. The reproducibility in the TCDQ positioning, over several operational cycles, showed to be better than ± 20 μm. The option of implementing stepping motors to the TCDQ is under discussion but, at present, the resolution seems to be mainly limited by the torque acting on the long jaw. The substitution of LVDT position sensors with potentiometer is also considered.

Position readouts (MDC) and interlocks (PRS), for the TCDQ, are presently installed on the same Central Processing Unit (CPU). This determines potential common mode failures and radiation hard issues. The upgrade of the system foresees to use different CPU and adopt the same low-level control as for the LHC collimation system [7].

Recent studies pointed out that the TCDQ jaw will be damaged by the impact of 28 nominal intensity bunches, spaced by 25 ns, at 7 TeV. This is a major issue since, during an asynchronous beam dump, the TCDQ can be hit by 32 bunches. A new more robust design is under development for this collimator. The upgraded solution will have to be ready to be installed during the shutdown planned for 2012.

THE ASYNCHRONOUS BEAM DUMP

On November the 19th 2010 the first, and unique, real asynchronous beam dump happened. A power driver in one MKD Trigger Fan-Out (TFO) unit of Beam 1 failed and started the self-triggering of two generators (MKD-C and MKD-D). The re-triggering of the remaining 13 generators worked perfectly and the beam was dumped without inducing any quench or damage of the downstream elements. This event generated a fault IPOC and XPOC and was caused by the unexpected breakdown of a standard electronic component (MAX4429EPA). The original design of the LBDS foresaw that only one MKD could fire spontaneously inducing the re-triggering of the remaining modules [8]. According to later studies, redundancy was added between the TFO and the Power Trigger Unit (PTU) in order to reduce the chance of having less than 14 MKDs firing during a beam dump (see Fig. 1). The actual wiring system should then improve the reliability of the system but, at the same time, could determine the pre-triggering of up to 8 generators. This new logic affects the beam sweep-

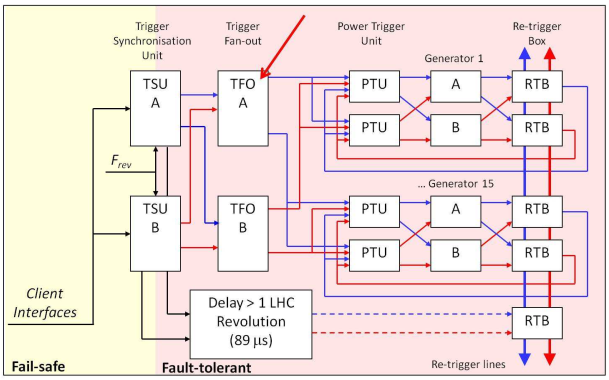

Figure 1: View of the LBDS trigger synchronization and distribution scheme. Redundancy was added to the original design in order to improve the reliability of the system. As a drawback, the new wiring scheme allows the pre-triggering of up to eight generators instead of one.

ing during an asynchronous beam dump and the resulting load on the TCDQ and downstream elements. In particular, as shown in Fig. 2 for up to 4 pre-triggers, the energy density is reduced on elements with an aperture smaller than 7σ (betatron collimators), while is increased on elements with bigger apertures. The TCDQ, that nominally sits at 8σ, would receive up to $\sim$40% more radiation than for the original design scenario. This would worsen the existing robustness problem of the TCDQ, as mentioned above. For this reason and to reduce the load on the downstream magnets, it was decided to change the trigger logic back to the original design.

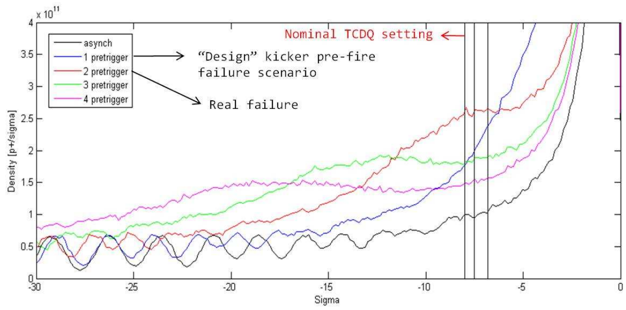

Figure 2: Energy density load as a function of the aperture (in σ units), in case of asynchronous beam dump and pre-triggering of up to 4 MKD modules.

MACHINE PROTECTION TESTS

A full series of tests with beam have to be performed after each shutdown or long technical stop, for machine protection purposes. Additional tests have to be systematically carried out for any change in machine and/or beam conditions (i.e. different optics, energy, intensity, filling pattern, etc.). They are presented in the following.

Asynchronous Dump Test

This test is performed by switching the RF cavities off, so that the beam starts debunching and populating the abort gap, and then triggering a beam dump. A local bump, away from the TCDQ jaw and close to the orbit interlock limit (1.2 σ), has to be applied in order to simulate the worst failure scenario. This check allows to validate the hierarchy of the collimation system and to measure the leakage from the TCDQ to the downstream elements. The post-mortem

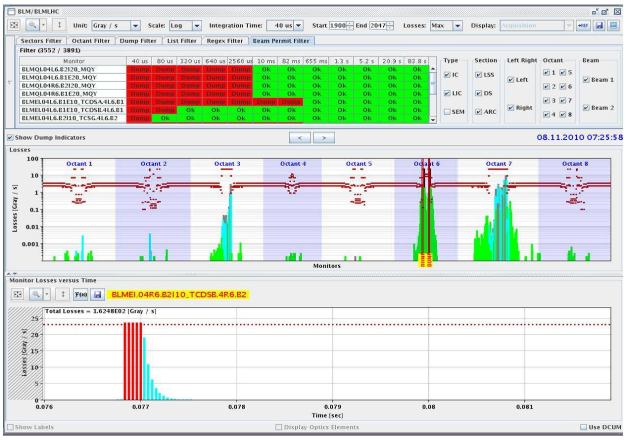

Figure 3: An example of a post-mortem loss map during an asynchronous beam dump test is shown.

analysis of the beam losses around the ring allows to qualify the protection provided by the system (see Fig. 3). The machine is declared safe when losses are concentrated in the extraction region (octant 6 in Fig. 3) and in the cleaning insertions (octant 3 and 7 in Fig. 3). One of the most critical elements is the Beam 2 tungsten tertiary collimator (TCT) in point 5 [9]. This is the first bottleneck encountered by the swept beam, which is not intercepted by the TCDQ. Losses at this element have to be kept as low as possible due to the low damage threshold of tungsten. In particular, the leakage from TCDQ to this element has to be smaller than 10^{-3}.

This is a destructive experiment which needs one dump per configuration. Special tests have to be envisaged for 2011 in order to define the retraction margin between the TCDQ and the TCTs at top energy and for small β* [10]. At least 10 ramps have to be taken into account for these studies.

IR6 Interlock Test

The protection provided by the TCDQ depends on its position with respect to the beam orbit. For this reason, a software interlock exists on the Beam Position Monitors (BPM) in point 6 and checks that the orbit, at this location, is within defined thresholds. Orbit stability was, up to now, better than 1 σ ($\sim$ 0.8 mm at 3.5 TeV) but it should be better than 0.3 σ for nominal operation at 7 TeV ($\sim$ 0.2 mm). Two different controls have to be performed:

1. Destructive: interlock limits are changed, in small steps, so that the BPM readout falls outside the thresholds and a beam dump is triggered. This test has to be performed for any change in the filling pattern scheme.

2. Not destructive: correctness of the readouts for interlocked BPMs and number of injected bunches have to be verified when increasing the beam intensity. No beam dump has to be induced, by changing the thresholds, if the filling pattern stays the same.

These tests took about 1-2 hours per new filling pattern/intensity step last year. The procedure has been revised and a minor time impact is expected for 2011.

XPOC UPGRADE

The XPOC performs a fully redundant analysis of the extraction and dilution kickers waveform with respect to individual references and tight tolerance limits. It analysis also measurements from beam instrumentation in point 6 and in the transfer line (i.e. losses, vacuum pressure, beam position, beam intensity and population in the abort gap). Several upgrades in the XPOC functionality are foreseen for next year. Losses at the TCTs will be monitored in all the interaction points. In addition, the Beam Loss Monitors (BLM) will be grouped in families and identified by one master element (example: TCDQ BLM). Losses of all the BLMs, belonging to a certain family, will be compared to losses at the master element (example: losses at the TCT with respect to losses at TCDQ). This will allow to have a further indication to analyze the quality of each beam dump (example: leakage from the TCDQ to the downstream elements). The possibility to integrate the XPOC with TCDQ position and beam orbit at the TCDQ is under discussion.

XPOC sign off

A faulty XPOC prevents to inject a new beam before the acknowledgment by an expert. At present, both “LBDS expert” and “EIC Machine Protection” Role Based Access Control (RBAC) have the same rights for XPOC sign off. Engineers in Charge (EIC) got the consign to acknowledge a faulty XPOC only when induced by losses above thresholds, due to debunched beam (BLM at TCDS, TCDQ, TCSG, MSDA, MSDC and MQY.4R6), or in case of missing data readings. They should instead call an expert in case of faulty provoked by MKD and MKB failures or unusual faults of any other LBDS component. The question if creating different RBAC roles for EIC and LBDS experts, in order to guarantee a safer supervision of the status of the system, is being addressed.

ABORT GAP CLEANING

Population in the abort gap has to be kept as low as possible (indicatively, $< 10^7$ p^+/m at 7 TeV and $< 10^9$ p^+/m at 450 GeV) to avoid quenches or damages of the elements downstream of the extraction region, during a beam dump. The principle of the Abort Gap Cleaning (AGC) is to kick out resonantly the beam in the abort gap by using the LHC transverse damper system [11]. Tests were successfully performed at 450 GeV with protons and the system is defined as operational at this energy. Further commissioning tests are instead needed at 3.5 TeV to optimize the parameters and finely tune the system. The AGC operation is not compatible with the tune feedback system. The goal is to switch the AGC automatically on via the sequencer, any time the tune feedback is off, and then permanently clean the abort gap [12].

The AGC is not operational for ions since the synchrotron light, that is used to measure the population in the abort gap (BSRA), is visible only for energies bigger than 650 GeV. This problem is under investigation and, when solved, same operational considerations as for protons will be applied.

The BSRA should be connected to the software interlock system (SIS) in order to trigger a beam dump when the population in the abort gap overcomes the thresholds. The system was not designed with this aim and relevant modifications and experience are needed before declaring it operational.

CONCLUSIONS

LBDS failures, which occurred during the first year of the LHC operation, were in agreement and not worse than requirements and expectations. Leakage from the TCDQ to the downstream elements showed to be within specifications and no damage or magnet quench was observed during synchronous and asynchronous beam dumps. Possible solutions for the upgrade of the TCDQ control and interlock system were analyzed. A more robust TCDQ jaw design is under study and has to be ready for the 2012 long technical stop. The logic of MKDs triggering, in case of spurious kicker pre-firing, has to be changed back to the original design in order to reduce the beam load on the TCDQ and downstream elements. Machine protection tests procedures have been revised and checks have to be re-performed, in 2011, for any step in beam energy and intensity. XPOC functionality upgrades and possible changes in the RBAC roles logic for XPOC sign off have been discussed. Abort gap cleaning has been declared fully operational for protons at 450 GeV. The commissioning for operation at 3.5 TeV and with ions has to be completed next year. A solution to connect the BSRA to the SIS has to be finalized.

ACKNOWLEDGMENTS

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HOW LOW CAN WE GO? GETTING BELOW $\beta^* = 3.5$ m

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Abstract

The LHC has made remarkable progress during 2010, fulfilling its demanding goal for the year in terms of integrated luminosity. For 2011, even higher performance goals are set. One way of increasing luminosity is to reduce the beam size at the interaction points (IPs), which is determined by the optical function β^*. However, when β^* is decreased, so is the margin to the triplet aperture in terms of beam σ. This aperture has to protected from beam losses by the tertiary collimators (TCTs), which in turn have to be shadowed by other upstream collimators and protection devices. This imposes a limit on the minimum achievable β^*.

In this article, we discuss estimates of the available triplet aperture as well as the margins in the cleaning hierarchy required to guarantee protection. All estimates of margins are based on assumptions on variations in central orbit and optical functions and we conclude on the achievable β^* for different running scenarios. We also discuss briefly the available margins during luminosity scans.

INTRODUCTION

The luminosity in any collider with round beams is inversely proportional to the optical β-function, called β^*, at the interaction point (IP) [1]. It is therefore, from the point of view of maximizing the accumulated statistics in the experiments, desirable to operate with β^* as low as possible. However, when β^* is squeezed to small values in the LHC, operation becomes increasingly difficult since the beam size in the quadrupole triplets in the interaction regions (IRs) increases [2], which leads to a decreased margin between the aperture and the collimation system that should protect it. In the 2010 LHC optics [3], the triplets become the limiting aperture of the LHC when $\beta^* < 7$ m during the squeeze at top energy. Furthermore, other effects such as the maximum achievable gradient in the quadrupoles and the beam-beam limit introduce additional constraints. In this article we discuss only the β^*-limitations caused by aperture margins, since they imposed the most severe limitations during the 2010 run.

The LHC uses a multi-stage cleaning system to intercept unavoidable beam losses and provide passive machine protection [2, 4, 5]. Tertiary collimators (TCTs) are installed in all experimental IRs. They are the third step in the cleaning hierarchy in the nominal collimation scheme. During the first run in 2010 intermediate collimator settings were used, which provide more margin [6, 7]. Later in 2010 even more relaxed margins were introduced between triplet aperture, TCTs and dump protection. The different collimator settings are presented in Fig. 1.

The TCTs must protect the triplets, and they in turn must thus be positioned outside the primary (TCP) and secondary (TCS) collimators. They must also be protected by the collimators installed in IR6 [2] in the case of a machine failure (asynchronous beam dump), where high-amplitude particles may not pass through the dedicated cleaning insertions before reaching the TCTs. In order to investigate possible values of β^*, we therefore have to review the value of the aperture itself, the required margins between the aperture and the TCTs, and the margin between the TCTs and the rest of the collimation system.

TRIPLET APERTURE

The normalized apertures in LHC were previously calculated [8] using the MAD-X program [9] from the so-called *n1* quantity. It is defined as the maximum acceptable primary collimator opening, in units of beam σ, that still provides a protection of the mechanical aperture against losses from the secondary beam halo. Uncertainties of the closed orbit, mechanical imperfections and tolerances, and possible perturbations of the optical functions are taken into account to find the worst-case aperture. Therefore, the results may be pessimistic. Based on *n1* calculations, the TCTs were placed at 15 σ from the beam center during the 2010 run with the $\beta^* = 3.5$ m optics.

During 2010, measurements of the global aperture have been performed. As an alternative method, we use these measurements to extrapolate the aperture to top energy with a method we call *aperture scaling*. In the following sections we describe first the method then we present results from both calculation methods.

Aperture scaling

Several aperture measurements have been performed in the LHC [10, 11, 12]. Apertures can be measured locally, with a variable orbit bump, or globally [13], for example by opening the collimators and then provoking beam losses by crossing a tune resonance. The beam loss monitors (BLMs) are then used to locate the global aperture limitation. In order to determine the limitation in units of σ, the TCPs are closed in steps, until the beam losses and therefore the limitation moves to the collimator. Both methods can be used independently in the horizontal and vertical planes.

The local aperture can not be estimated from a global measurement but any local aperture can not be smaller than the global one. Therefore, we can use the global measured aperture as a pessimistic estimate of the local one.

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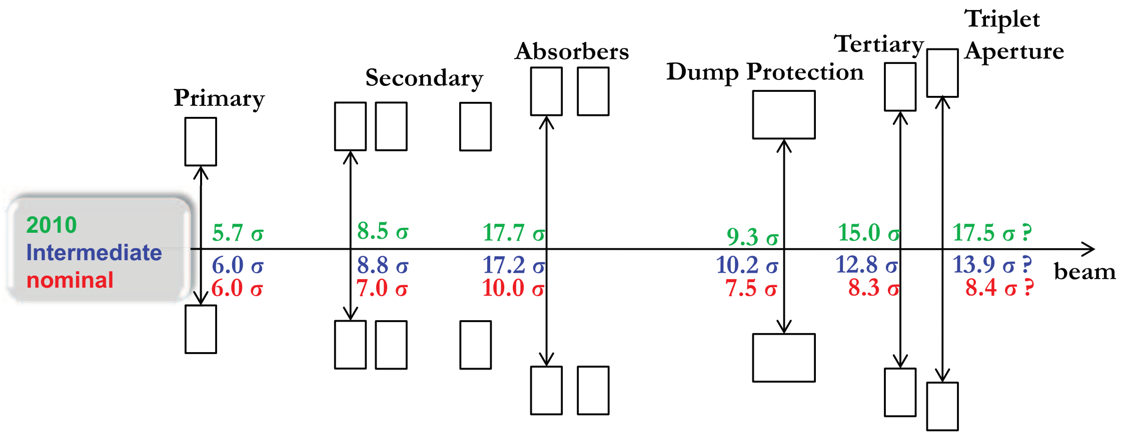

Figure 1: Schematic illustration (not to scale) of the collimator settings used during the 2010 run run with $\beta^* = 3.5$ m (green), the intermediate settings used during the 2010 run with $\beta^* = 2$ m (blue), and the nominal settings (red). These settings imply relaxed margins compared to the nominal case. We also show earlier estimates of the triplet aperture, done with the $n1$-method.

Table 1: Measured apertures of the LHC in units of beam σ (energy deviations not accounted for) at injection energy taken from Ref. [12].

	Horizontal	Vertical
Beam 1	12.5	13.5
Beam 2	14	13

In a general case it is not possible to calculate the aperture for a given machine configuration using data acquired in a another one (e.g. different optics, orbit etc.) without being overly pessimistic or applying additional assumptions. However, in special cases we can use simple scaling laws to estimate the aperture a different configuration. It turns out that this is possible in the triplets with good approximation.

Measurements of the global aperture in the LHC ring at injection energy (450 GeV), performed in September 2010, are presented in Ref. [12] and the results are repeated in Table 1. The measurements were done using the standard injection optics [3] with $\beta^* = 11$ m in IP1 and IP5 and $\beta^* = 10$ m in IP2 and IP8, separation bumps around the collision points activated and half crossing angles of 170 μrad in IP1 and IP5. In IP2 and IP8 the spectrometers were on and external angles of 170 μrad were used. We call this configuration *injection*. We use these measurements to estimate the aperture margins at 3.5 TeV energy or higher, squeezed optics [3] with varying crossing angles and $\beta^* \leq 3.5$ m, spectrometers on in IP2 and IP8, but the beam separation at the IPs still activated. We call this configuration *pre-collision*. This is the most critical point at top energy—when the separation bumps are collapsed, the aperture margins increase.

As an example we consider IR1 B1 (beam 1) and the 2010 pre-collision optics with 3.5 TeV energy, $\beta^* = 3.5$ m in all IPs, half crossing angles of 100 μrad in IP1 and IP5, external crossing angle of 110 μrad in IP2 and 100 μrad in IP8, and a 2 mm beam separation. In order to estimate the margins in the triplets at pre-collision, we first determine the s-location with the smallest aperture in this configuration from a $n1$-calculation including measured profiles. We consider the horizontal and vertical planes separately and select the slice inside the element where the minimum is found. Let us now study these s-locations in the two planes at injection. The parameters at each position are presented in Table 2. A transverse cross section of the ideal physical aperture together with the 16 σ beam envelope at injection (in red) is shown in Fig. 2 for both locations.

We use the measured global aperture as a pessimistic estimate of the local one at these s-locations. At pre-collision the beam size and center changes from injection, while the physical aperture is the same (see Table 2 and Fig. 2). It is clear that the aperture limitation stays in the same plane and on the same side of the beam pipe in both cases. Because of the shape of the vacuum chambers, the vertical change of the orbit in the crossing plane, caused by the reduction in crossing angle, does not influence the margin to the aperture in the (horizontal) separation plane. In the (vertical) crossing plane, the situation is more complicated—a horizontal orbit shift does have an influence on the margin because of the elliptic shape of the vacuum chamber and a detailed study should also account for the expected shape of the halo. In our simplified method, we neglect this effect. The introduced error is small since the change in the vacuum chamber is small over the distance that the orbit can be expected to vary horizontally. We thus reduce the 2D aperture calculation to 1D.

If we designate variables with subscript i at injection and with p at pre-collision, it must hold that

$$|u_i| + n_i\sigma_{ui} = |u_p| + n_p\sigma_{up}, \tag{1}$$

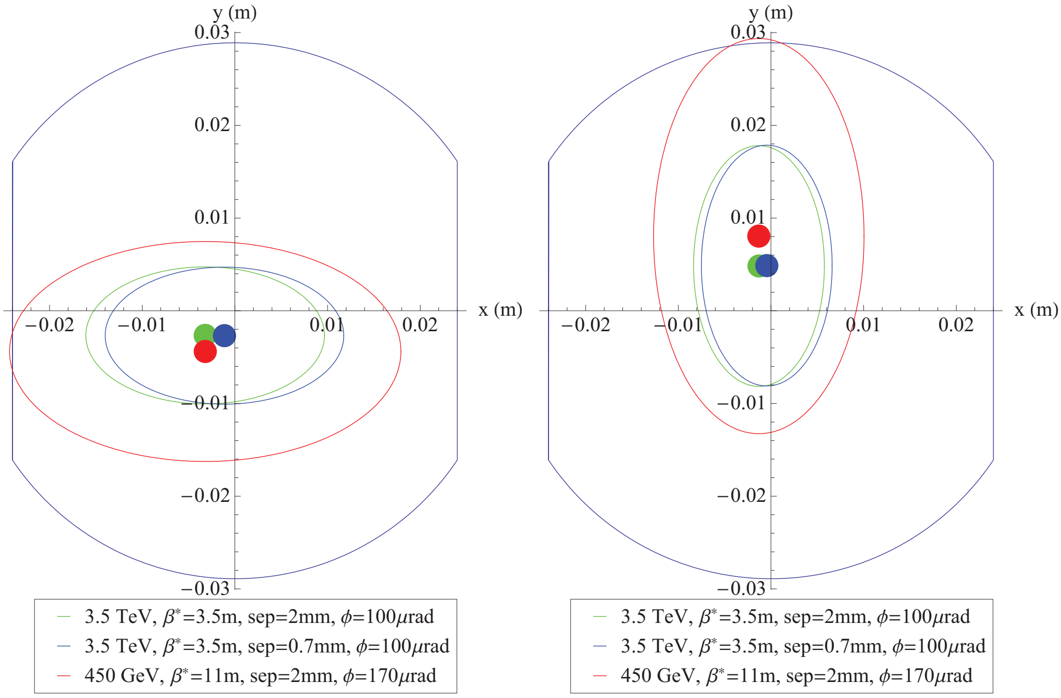

Figure 2: The transverse cross section of the triplet with the found horizontal (left) and vertical (right) aperture limitations in IR1 Beam 1. The 16 σ beam envelopes for injection (red), pre-collision (green) and pre-collision with the separation reduced to 0.7 mm (blue) are included. The dots indicate the central orbits.

where u is the transverse coordinate of the orbit in the limiting plane (we use the absolute value of u in order to account for cases where the orbit is negative), n the distance to the aperture in units of σ_u. Expressing the geometric emittance as $\epsilon_u \approx \epsilon_n/\gamma$, where ϵ_n is the normalized emittance and γ the relativistic factor, we solve Eq. (1) for n_p:

$$n_p = \frac{|u_i| - |u_p| + n_i\sigma_{ui}}{\sigma_{up}} = \frac{|u_i| - |u_p|}{\sigma_{up}} + n_i\sqrt{\frac{\beta_{ui}\gamma_p}{\beta_{up}\gamma_i}} \quad (2)$$

We can now insert the values in Table 2 in Eq. (2) for $u = x$ or $u = y$, using $n_i = 12.5$ in the horizontal plane and $n_i = 13.5$ in the vertical plane (see Table 1). We use the nominal emittance of $\epsilon_n = 3.75$ μm, since all collimator settings and the measured apertures in Table 1 are expressed in terms of the nominal beam size. With $\gamma_i = 479$ and $\gamma_p = 3730$, we get $n_p = 20.5$ for $u = x$ and $n_p = 26.0$ for $u = y$,. Assuming a 2.5 σ margin between the aperture and the TCT, the maximum settings are 18 and 23.5 σ_u for the horizontal and vertical TCTs.

In this calculation, we assumed that the ratio of the β-functions and the shift in orbit are accurately reproduced by MAD-X. To account for possible variations, we introduce first an additional orbit shift δu. Furthermore, we consider a possibly different β-beat at injection and pre-collision by assuming that the β-function is scaled by λ_i at injection and by λ_p at pre-collision. Eq. (2) then becomes

$$n_p = \frac{|u_i| - |u_p| - \delta u + n_i\sigma_{ui}}{\sigma_{up}} = \frac{|u_i| - |u_p| - \delta u}{\sqrt{\beta_{up}\lambda_p\epsilon_n/\gamma_p}} + n_i\sqrt{\frac{\lambda_i\beta_{ui}\gamma_p}{\lambda_p\beta_{up}\gamma_i}}. \quad (3)$$

If we assume pessimistically $\lambda_i = 1/1.1$ and $\lambda_p = 1.1$ (this gives an overall β-beat of about 20% between injection and pre-collision) and δu=1 mm, the estimated apertures at pre-collision become instead $n_p = 17.5$ in the horizontal plane and $n_p = 22.7$ in the vertical plane, implying TCT positions of 15 σ_x and 20.2 σ_y.

It should be underlined that the our method does not account the spurious dispersion, both from the crossing angle and from the *a2/b2* errors as pointed out by others [14], while on the other hand the use of the global aperture at injection is pessimistic. A better estimate can be made considering that, when the TCP is moved in during the measurements, the losses move gradually from the global aperture bottleneck to the collimator. The TCP thus first intercepts the secondary halo created by the aperture bottleneck and, once the TCP is the limit, the aperture catches a secondary halo from the collimator. The first losses are seen at a setting about 2 σ outside the point where the limit has moved to the collimator [15]. Thus, if the triplet aperture would be within 2 σ of the global limitation, a beam loss would be observed there as well. Since no losses are seen,

Table 2: The β-functions and transverse coordinates of the central orbit at the horizontal and vertical aperture limitations in IR1 B1 taken from MAD-X. The s-position is given relative to IP1, where a negative value indicates the incoming beam.

		s (m)	β_x (m)	β_y (m)	x (mm)	y (mm)
Hor. limit	injection	-40.8	238	75	-3.2	-4.4
	pre-collision	-40.8	690	227	-3.2	-2.7
Ver. limit	injection	39.6	69	243	-1.3	8.1
	pre-collision	39.6	207	702	-1.3	4.8

we conclude that the triplet aperture is at least 2 σ larger than the values in Table 1, which we used in later calculations.

One way of increasing the aperture is to reduce the separation at pre-collision to the nominal design value of 0.7 mm. Fig. 2 shows in blue the envelope of this configuration. As can be seen, the additional orbit shift increases the margins at the horizontal bottleneck so that the aperture is instead found at $n_p = 19.5$. Since there is no reason known to the authors to keep the larger separation of 2 mm, we recommend to use the nominal value of 0.7 mm. All calculations presented in the remainder of this article uses nominal separation.

Results of aperture calculations

Using both aperture scaling and the *n1*-method, we have estimated the triplet aperture for different values of β^* at an energy of 3.5 TeV. For each considered configuration a beam-beam separation $d = 12\,\sigma$ was assumed (larger than the nominal $d = 9.8\,\sigma$) in order to calculate the half crossing angle α, given by

$$\alpha = d\sqrt{\frac{\epsilon_n}{\beta_u \gamma}}, \tag{4}$$

with ϵ_n being the normalized emittance (we used The nominal $\epsilon_n = 3.75\ \mu$m), β_u the optical beta function in the transverse plane u, and γ the relativistic factor.

To estimate δ_u in the aperture scaling calculations, we considered the difference between the orbit at injection and stable beams in the ideal MAD-X model and in measurements from all fills between September 18 and October 31 2010 (data points were sampled every two minutes). We excluded data points from large luminosity scans and we will refer to this as our data set. In total 26 fills were analyzed. The maximum deviations between measurement and MAD-X that were found were smaller than 2 mm, which we used as a pessimistic value of δ_u for all IPs. The two BPMs closest to each aperture bottleneck were considered.

The β-beat parameters λ_i and λ_p were measured in late 2010 [16]. They were interpolated between BPMs and used directly in the aperture scaling calculation. Furthermore, we assume an additional 5% pessimistic error on the β-functions at injection and pre-collision motivated by the observed optics stability [16].

In the *n1*-calculations, we assumed a β-beat of 10%, which is compatible with observed performance in the end of 2010 [17]. An orbit tolerance of 2.3 mm was assumed, which equals the maximum error with respect to the ideal MAD-X orbit seen in the data set on the BPMs in the triplets. Measured profiles were used. Only IR1 and IR5 were treated and the minimum *n1* was taken for each scenario over both IPs, beams and planes.

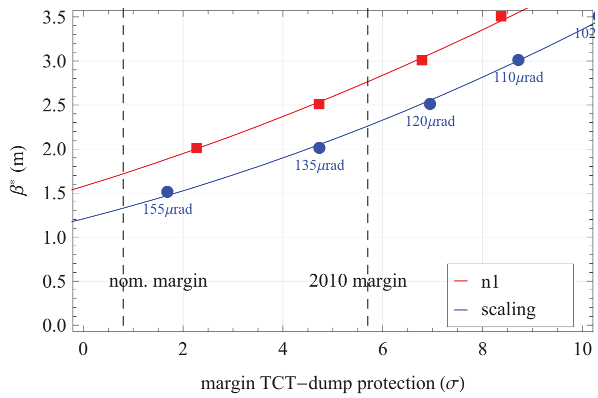

Figure 3: The minimum β^* at 3.5 TeV as a function of the margin between the TCTs and the dump protection, assuming a 2.5 σ margin between the triplet aperture and the TCTs. The crossing angles shown were chosen to keep a 12 σ beam-beam separation. The aperture was evaluated using both aperture scaling and *n1*-calculations. The latter were done for a β-beat of 10%, a closed orbit tolerance of 2.3 mm, and only for IR1 and IR5. The minimum aperture over all IRs, beams and planes was used.

The calculated apertures were used to estimate the minimum achievable β^* as a function of the margins in the collimation system. For each β^*, the minimum aperture was calculated over all IPs, both beams and both planes. Assuming either 2010 margins or nominal margins provides a given setting of the dump protection and the margin between the triplet aperture and the TCTs, which allows the margin between the TCTs and the dump protection to be calculated. The result is shown in Fig. 3, where for convenience we have instead plotted β^* as a function of the margin.

A better result could be obtained using a local measured triplet aperture in both planes at injection. Such a measurement, which we anyway think is necessary to benchmark the scaling model, could be performed with a safe low-intensity beam by first introducing a local orbit bump

Table 3: The margins in units of beam σ needed to compensate for various error sources. Orbit errors are treated separately in the following sections.

Element	β-beat	position	setup	scans	sum
TCT	0.73	0.1	0.025	0.2	1.06
TCSG6	0.45	0.06	0.015		0.53
TCSG7	0.41	0.2	0.05		0.66
TCP7	0.28	0.14	0.035		0.46

of known amplitude in the triplets, to create a global bottleneck, while keeping the collimators retracted. A TCP is then to be moved in stepwise, with provoked losses in each step. The position of the TCP when the global limitation moves from the triplet to the collimator and the amplitude of the orbit in the triplet allows for a more precise aperture estimate. This measurement might even be performed with a squeezed optics, as suggested by others [14].

It is also important to quantitatively understand in detail the discrepancies between the *n1* method and the measurements. This work is underway [18].

MARGINS IN CLEANING HIERARCHY

The margins between the collimator families and collimators and aperture have to be sufficiently large to compensate for errors in such a way that the cleaning hierarchy is not violated. The error sources are:

- Orbit variations can bring the beam closer to collimators. An analysis based on data is done in the following sections.
- β-beat: If the real β-function in the machine deviates from the theoretical model, the aperture at a collimator positioned at n_σ is changed by a factor $n_\sigma\sqrt{\beta_{\mathrm{real}}/\beta_{\mathrm{model}}}$. We use $\beta_{\mathrm{real}}/\beta_{\mathrm{model}} = 1.1$ as an estimate of the achievable β-beating [17].
- Positioning errors are introduced by the non-reproducibility of the end position of the collimators when they are moved in. This is estimated to 40 μm.
- The accuracy of the collimation setup is 10 μm, which is the step size used during the alignment procedure.
- During luminosity scans, an additional orbit shift is introduced at the tertiary collimators, which is less than 0.2 σ [19].

The resulting errors except orbit at key elements are shown in Table 3. Variations in positioning and setup errors caused by the change in beam size during the squeeze were neglected but this is very a small effect.

To estimate the margin between two components, which could be two collimators or a collimator and the aperture, so that one is always in the shadow of the other in units of σ, we add linearly the maximum change in aperture margin at both locations to account for the worst case.

At the triplet, the β-beat is already accounted for in the aperture calculation and should not be counted twice. If, in addition, a biased β-beat correction is done, with the beam size always increasing more at the TCT than at the triplet, only the drifts in β-beat must be accounted for. We assume this to be 5% at the TCTs which give a contribution of 0.35 σ to the margin.

ORBIT ERRORS

The collimators are centered around the reference orbit and a static orbit offset at the triplet is taken into account in the aperture calculation. Thus we only need to account for the orbit drifts from the reference when calculating the margins.

In order to see by how much the margin is reduced by orbit movement we consider two elements A and B somewhere in the ring where A should shadow B. Let the initial mechanical aperture in σ be n_A of device A in the transverse plane u. If the orbit later moves by an amount Δn_A, the new aperture is $n_A - \Delta n_A$ in positive u and $n_A + \Delta n_A$ in negative u. Analogous relations hold at B. If the betatron phase advance μ_{AB} between A and B is such that $\cos\mu_{AB} \geq 0$, the u-coordinate of a particle has the same sign at both A and B. The reduction ΔM of the original margin $M_0 = n_B - n_A$ due to orbit movements Δn_A and Δn_B is then

$$\Delta M_+ = (n_B - \Delta n_B) - (n_A - \Delta n_A) - M_0 = \Delta n_A - \Delta n_B \quad (5)$$

for the aperture at B in positive u and

$$\Delta M_- = (n_B + \Delta n_B) - (n_A + \Delta n_A) - M_0 = \Delta n_B - \Delta n_A \quad (6)$$

for the aperture in negative u. The reduction can thus be summarized as

$$\Delta M = |\Delta n_B - \Delta n_A|. \quad (7)$$

If $\cos\mu_{AB} \leq 0$ on the other hand is negative, the u-coordinate of any larg-amplitude particle changes sign between A and B and the aperture at B with $u < 0$ is shadowed by the aperture at A with $u > 0$. Therefore the reduction in margin on the two sides is

$$\Delta M_+ = (n_B + \Delta n_B) - (n_A - \Delta n_A) - M_0 = \Delta n_A + \Delta n_B \quad (8)$$

and

$$\Delta M_- = (n_B - \Delta n_B) - (n_A + \Delta n_A) - M_0 = -\Delta n_B - \Delta n_A. \quad (9)$$

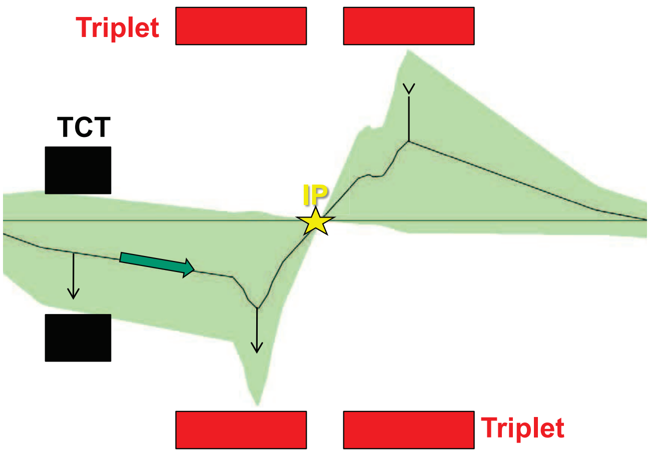

Figure 4: Schematic illustration (not to scale) of the beam envelope (green), the TCTs, and the triplet apertures in the crossing plane in an experimental IR (beam propagating from left to right). The vertical arrows symbolize the amplitude of a particle, which after a betatron phase advance of π is on the opposite side of the central orbit at the second triplet.

So the maximum reduction in margin is

$$\Delta M = |\Delta n_B + \Delta n_A|. \tag{10}$$

As an applied example, Fig. 4 shows schematically a TCT protecting the triplets on the incoming (0 phase advance) and outoing (π phase advance) beams. Because of the phases, Eq. (7) has to be used when calculating the reduction in margin on the incoming beam while Eq. (10) has to be used on the outgoing.

We now select the BPMs closest to A and B and use Eqs. (7) and (10) to calculate the reduction in margin at all data points. The resulting error distribution can then be used to decide the required margin between A and B. It should be noted that even if a margin is selected, such that no data points in the 2010 run violated the shadowing of B, it does not mean that B is guaranteed to always be protected, since the available statistics is limited and we cannot know future data samples. Instead we can use the data to define a confidence level with which B is protected.

We propose to use a margin such that A shadows B at least 99% of the time spent in stable beams. To see what this means in terms of expected rate of dangerous accidents we consider the case of asynchronous beam dumps. Assuming that only orbit errors are taken into account, one asynchronous dump per year, a probability of 0.01 that the TCTs are exposed and that 30% of the time is spent in stable beams, we expect a dangerous event to occur every 300 years. The real risk is however much lower since errors from other sources should be added to the final margin—the probability that all errors add in the pessimistic direction must be folded in.

Work is ongoing to quantify the damage to a TCT for the very unlikely event of a bunch hitting it. If it can be shown that damage is not catastrophic, e.g. downtime of the LHC will be less than a few days, the possibility of moving in the TCTs further could be considered.

The risk of an event in which the triplet is exposed is even smaller. We assume the reduction in margin between aperture and TCTs to be independent of the reduction between the dump protection and TCTs due to the local correction scheme. With a 1% probability of the triplets being exposed, a dangerous event is expected once every 30000 years.

Finally, interlocks can be added to dump the beam before the protection is violated. A less drastic method could be to have displays to monitor the reduction in margin so that the operators can perform corrections if the margins are close to the limits.

REQUIRED ORBIT MARGINS

Using the method described in the previous section we have calculated the reduction in margin during the 2010 run due to orbit movements between different steps in the cleaning hierarchy.

Margin aperture-TCT

In all experimental IRs we analyzed the orbit movements at the BPMs about 3 m upstream of the horizontal TCTs together with the BPMs in the triplets between Q1 and Q2. Since $\mu_{AB} \approx 0$ between the TCTs and the triplet on the incoming beam, Eq. (7) was used in this case, while at the triplet on the outgoing beam we have $\mu_{AB} \approx \pi$ and therefore used Eq. (10). The calculation was performed in both planes for both triplets and is still pessimistic, since in the crossing plane the protection is essentially one-sided due to the large orbit excursions (see Fig. 4), meaning that only one of ΔM_+ and ΔM_- needs to be considered.

The resulting reduction in margin is summarized in Table 4. The largest reduction was found in IR2 B2 and Fig. 5 shows an example of the orbit evolution during a fill on the three relevant BPMs in IR2 together with their respective reference orbits. Significant variations can be seen during the fill. The reduction of margin in IR2 comes mainly from large systematic offsets but fluctuations, likely to be caused by the luminosity leveling, give a small contribution. The luminosity was adjusted in IR2 by changing the magnitude of the separation bump, which decouples the orbit movements at the TCTs and the triplets

A histogram of the reduction in margin at all data points in the vertical plane in IR1 is shown in Fig. 6. This is the most critical case among the other IRs. Here a large static offsets with respect to the reference orbit was found. One example is shown in Fig. 7.

In our data set we have excluded times when large luminosity scans were performed (discussed in more detail in Ref. [19]). An example of a fill where this was done is shown in Fig. 8. In this case the maximum reduction of the margin was 2.2 σ. These variations can not be accounted

Table 4: The reduction of the margin TCTs-triplets and TCTs-dump protection during the fall of 2010 per IP, plane and beam as calculated with Eqs. (7) and (10). We show both the maximum values and the values below which 99% of the data sample can be found. Each number is the maximum over both triplets and planes.

(σ)		TCT-triplet			TCT-TCSG IR6	
beam	plane	mean	max	99%	max	99%
IR1						
B1	X	0.80	1.39	1.25	0.85	0.73
B1	Y	0.54	1.64	1.60		
B2	X	0.66	1.62	1.55	1.30	0.97
B2	Y	0.50	1.26	1.17		
IR2						
B1	X	0.52	1.17	1.14	1.29	1.10
B1	Y	0.80	1.88	1.78		
B2	X	1.38	2.46	2.37	2.18	2.10
B2	Y	0.41	1.10	1.00		
IR5						
B1	X	0.44	1.19	1.17	0.92	0.78
B1	Y	0.54	1.17	0.93		
B2	X	0.42	0.98	0.92	1.18	1.00
B2	Y	0.67	1.78	1.04		
IR8						
B1	X	0.33	0.77	0.74	0.83	0.50
B1	Y	0.71	1.81	1.63		
B2	X	0.61	1.68	1.58	1.41	1.10
B2	Y	0.17	0.65	0.55		

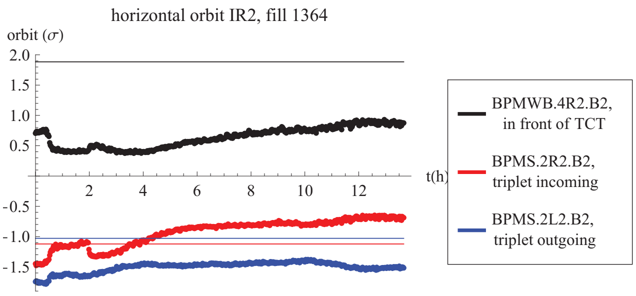

Figure 5: Horizontal orbit in IR2 B2 at BPMs close to the TCTs and the triplets on the incoming and outgoing beams with respect to IP2 during fill 1364. The solid lines are the reference orbit used during the collimation setup. During the fill, a large systematic offset from the reference orbit can be seen, as well as fluctuations likely to be caused by luminosity leveling.

for without a loss in performance so we propose that the TCTs should move with the beam during large scans.

If IR2 does not have to be squeezed to a small β^*, a 1.6 σ margin for orbit between the TCTs and the aperture could be used, covering 99% of the time in the other IPs (see Table 4). If also IR2 should be squeezed, the margin has to

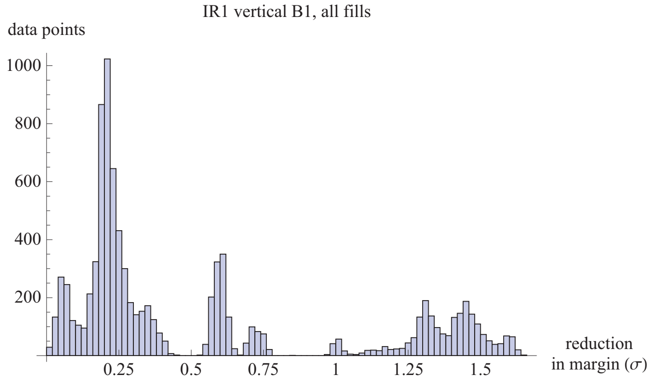

Figure 6: Reduction of margin between the vertical TCT in IR1 B1 and the aperture bottleneck in triplet on the outgoing beam. All data points from the run in fall 2010 in stable beams, except where large luminosity scans were performed, were accounted for.

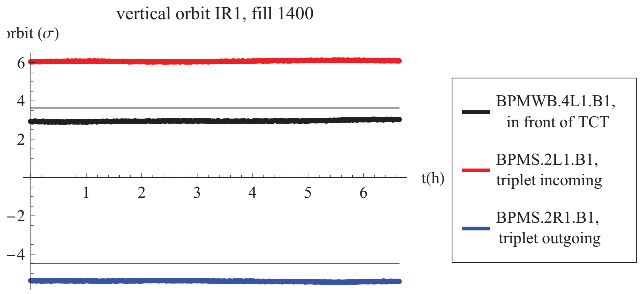

Figure 7: Vertical orbit in IR1 B1 at BPMs close to the TCTs and the triplets on the incoming and outgoing beams with respect to IP1 during fill 1400. The solid lines are the reference orbit used during the collimation setup. During the fill, a systematic offset from the reference orbit can be seen.

be increased to 2.4 σ unless the static offsets are improved.

Margin TCT-dump protection

A typical example of the orbit on the BPM closest to the secondary collimator in IR6 (TCSG6) and the horizontal TCT in IR5, beam 2, is shown in Fig. 9. The static offsets as well as the drifts during the fill are small. If we consider again a margin for which the hierarchy is preserved over 99% of the times in stable beams, 1.1 σ is enough for all IRs except IR2, where 2.1 σ is needed. Numbers for all IPs are given in Table 4.

We have not taken into account the phase between the BPMs and thus taken the maximum reduction given by Eqs. (7) and (10). Therefore, our calculation is pessimistic.

Margins between other collimators

A similar study has been carried out also in IR7. Here a pessimistic approach was taken in which we study the reduction of margin from orbit movements between the BPM

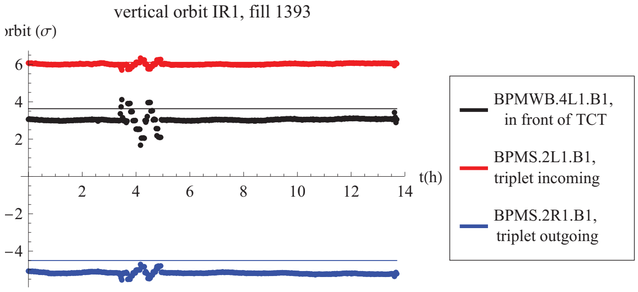

Figure 8: Vertical orbit in IR1 B1 at BPMs close to the TCTs and the triplets on the incoming and outgoing beams with respect to IP1 during fill 1393. The solid lines are the reference orbit used during the collimation setup. During the fill, a large systematic offset from the reference orbit can be seen.

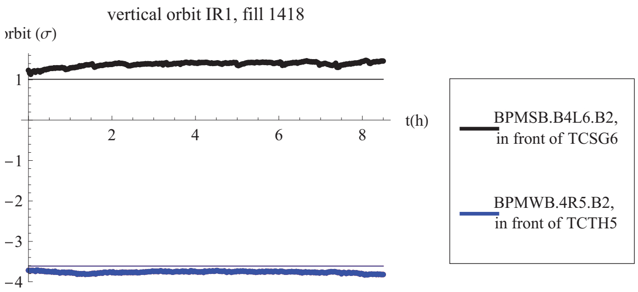

Figure 9: Horizontal orbit in front of the TCSG in IR6 and the TCT in IR5 B2. The solid lines are the reference orbit used during the collimation setup. This TCT is most critical in terms of protection since it is the first collimator downstream of the dump protection.

in front of the TCPs and all other BPMs in IR7 close to a TCS. Again the phase was not considered, so both Eqs. (7) and (10) were used. It was found that a margin of 1.7 σ preserves the hierarchy in both planes and beams on all BPMs more than 99% of the operational time. This value could possibly be reduced if a more detailed analysis is performed where the phases of all collimators is taken into account. This is left as future work.

We studied also the margin between the TCSs in IR7 and IR6. Based on the 2010 data set it can not be reduced without a risk of hierarchy problems.

PROPOSED MARGINS AND SETTINGS

Adding linearly the variations in orbit, shown in previous sections, to other errors in Table 3, we calculate the required margins in the cleaning hierarchy. Starting from a setting of the primary collimator at 5.7 σ we then calculate all settings and finally the minimum aperture that is protected. The result is shown in Table 5.

More aperture could be gained by moving in all collimators closer to the beam by the same amount. This could be motivated also because the emittance used in the 2010 runs was significantly smaller than nominal [20, 21]. On the downside, this might cause an increased risk of instabilities induced by impedance. A study of this is left as future work.

Table 5: The minimum collimator setting achievable based on the analysis in previous sections and the minimum aperture in units of σ.

TCP IR7	TCS IR7	TCS IR6	TCT	aperture
5.70	8.50	9.30	11.80	14.10

It should be underlined that the linear sum of the errors gives a pessimistic estimate—it is very unlikely that they add up in the same direction. An alternative could be to consider the errors as independent random variables and add them in square. A confidence interval then has to be defined and the machine can be interlocked to protect against a violations.

A further gain in margins could be achieved through:

- More detailed aperture measurements, which are anyway needed to validate the scaling method.
- Adding errors in square instead of linearly in the margins.
- Reducing the crossing angle by either using a smaller-than-nominal emittance or going to a smaller beam-beam separation. This gains aperture, but may be possible or not depending on the filling scheme. More details will be given in Ref. [21].
- More margin could be gained if the large static offsets to the reference orbit, seen during stable beams in the experimental IRs, could be better corrected. This is true in particular for IR2.
- A more detailed analysis of the reduction in margin caused by orbit variations, taking into account the phase advance between collimators, could show that the margins can be decreased further.

REACH IN β^*

In addition to the new margins calculated here we consider also two other options, giving in total three different operational scenarios:

- *2010 settings*: Keeping the same margins as during the 2010 run.
- *2011 proposal*: Using the settings presented in Table 5.
- *Nominal*: Going to nominal collimator settings (see Fig. 1). For this to be possible an orbit stability of 0.1–0.2 σ is necessary, so these settings are clearly too tight to guarantee protection. We include calculations anyway for comparison.

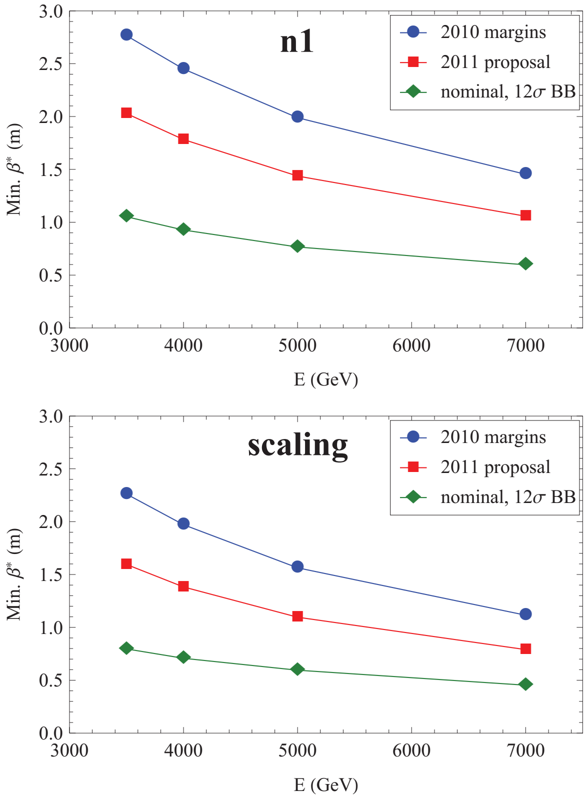

Figure 10: The minimum β^* as a function of beam energy for three different sets of margins between the collimators, with the aperture calculated with the *n1*-method (top) and aperture scaling (bottom).

For each scenario, the minimum aperture that can be protected is defined (see Table 5 and Fig. 1). The aperture was calculated, using aperture scaling and the *n1* method with a 10% β-beat and 2.3 mm orbit tolerance, for a range of β^*-values (with the crossing angle varied to keep a 12 σ beam-beam separation) and interpolated by a second degree polynomial as in Fig. 3. The intersection between the interpolated line and the minimum aperture that can be protected gives an estimate of β^*. The calculations were repeated also at 4 TeV, 5 TeV and 7 TeV. The resulting reach in β^* as a function of beam energy is shown in Fig. 10.

SUMMARY AND CONCLUSION

We have performed an evaluation of the reach in β^* based on data from 2010. Only limits from aperture were considered. We have reviewed first the triplet aperture itself and used scaling laws to extrapolate the measured injection aperture to top energy. We have also performed a detailed revision of the margins between different steps in the cleaning hierarchy.

Our operational proposals are:

- Reduce the separation at the IPs to its nominal value of 0.7 mm to gain aperture.
- Measure the triplet aperture locally.
- β-beating should be corrected to below 10% and with a reproducibility better than 5% with a bias at the TCT and triplets so that the beam size increases more at the TCT than at the triplet.
- The residual risk of magnet damage (estimated to $<$ 1 over 30000 years) or damage to the TCTs can be reduced further by interlocks or warnings when the orbit movements run out of defined margins.
- New settings have to be carefully verified with loss maps and asynchronous dump tests. If problems with the cleaning hierarchy are detected, relevant margins must be increased.
- The cleaning hierarchy has to be verified on a regular basis to monitor possible drifts. Regular beam dumps provide useful data on the leakage to the TCTs if uncaptured beam is present.

Based on data from the 2010 run, we have calculated new margins for 2011 presented in Table 6. The reach in β^*, calculated with aperture scaling, is presented in Table 7. With the *n1*-method, about 0.4 m is lost in β^*.

Table 6: Proposed margins based on data from the 2010 run in units of $\sigma$and mm. The margins in mm were calculated for $\beta^* = 3.5$ m, 3.5 TeV, for the 2010 case and for $\beta^* = 1.5$ m, 4 TeV, for the 2011 case. A range of values is given corresponding to different elements.

	2010		2011	
	(σ)	(mm)	(σ)	(mm)
triplet–TCT	2.5	0.9–2.1	2.3	1.1–2.7
TCT–TCSG IR6	5.7	3.5–4.4	2.5	1.3–1.8
TCSG IR7–TCP	2.8	0.6–1.6	2.8	0.5–1.5

Table 7: Calculated reach in β^* and corresponding half crossing angles when using aperture scaling and the 2010 margins with a 12 σbeam-beam separation. It is assumed that IP2 is not squeezed.

	3.5 TeV		4 TeV	
	β^* (m)	α (μrad)	β^* (m)	α (μrad)
2010 margins	2.3	125	2.0	125
2011 proposal	1.6	150	1.4	150

We propose to start with $\beta^* = 1.5$ m at 4 TeV, which is the closest matched optics point to the 1.4 m calculated with the scaling method. The collimation system has to be qualified before regular operation. In case of problems, the margins and maybe β^* must be increased. This proposal assumes that IP2 remains at a larger β^*.

The final choice of β^* has to be based on both machine protection and experimental requirements on luminosity. Higher luminosity can also be achieved through higher intensity [22] and a smaller emittance.

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INJECTION PROTECTION – ARE WE TAKING IT SERIOUSLY? HOW CAN WE MAKE IT SAFER?

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Abstract

The experience with the injection protection system during the 2010 run will be summarized, the setting-up times for the transfer line collimators and stability will be evaluated. Weak points of the protections system at injection which became apparent with first high intensity experience will be discussed and solutions for 2011 presented. Improvements for tools and procedures to be implemented during the shutdown will be mentioned.

INTRODUCTION

The LHC is protected against possible failures during the injection process by a dedicated injection protection system. Examples for possible failures are: LHC equipment not at injection settings while beam is injected, power converter failures during SPS extraction or in the transfer lines resulting in wrong injected trajectory, injection kicker (MKI) failures such as synchronisation issues due to timing problems, kicker flash-overs, erratics and missings.

Passive protection through collimators and absorbers and active protection in the form of interlock systems defining injection and SPS extraction permits is in place to cover the above mentioned failures. The “beam presence concept” protects e.g. against injecting high intensity into the LHC not at injection settings, the power converter interlocks in the SPS extraction region and the transfer lines disallow extraction from the SPS in case of power converter trips or wrong settings. There is a generic passive protection system, the transfer line collimation system (TCDI), located at the end of the lines to protect against any problem during the transfer. And the 4 m long absorbers, TDI, plus two auxiliary collimators downstream of the injection kicker cover injection kicker failures. More details on the injection protection system can be found in [1].

NEW IN 2010: INTERMEDIATE INTENSITY INJECTION

Injection of high intensity into the LHC is only permitted by the interlocking system if beam is already circulating. Only probe intensity (currently < 10^{10} charges) can be injected into an empty machine. This is the concept of “beam presence”. A number of so-called “safe machine parameters” (different flags derived from beam current measurements in the SPS and LHC and other quantities distributed across the machine) are combined in the permit equation in the master beam interlock controllers for the SPS extraction to guarantee this condition.

The LHC does not change settings when switching from probe beam to nominal beam (except sensitivity settings for some BI equipment). The injectors however are running at different settings and hence different cycles for the different beams. While the “beam presence concept” is vital for protection during the injection process at the moment the beam enters the LHC, it increases the complexity for the SPS to LHC transfer.

Trajectory Correction in the Transfer Lines

The trajectories in the transfer lines are drifting with time even in the absence of changes of magnetic settings. The settings in the transfer lines can therefore not be frozen. Trajectory correction is required every week or so triggered by too large injection oscillations or losses.

During the 2010 run it was noticed that with the same magnetic settings in the transfer lines, the trajectories for the probe beam and the nominal beam averaged over the bunches are significantly different (up to about 500 μm in trajectory). Structures of the kicker waveforms might play a role for the single bunch versus a batch, but also the different shape of the cycle (faster ramp) of the probe and hysteresis. Different BPM sensitivity etc might enter the game as well. Studies in 2011 will be conducted to identify the origin of the discrepancies.

Due to this effect the probe cycle could/can not be used for trajectory correction. Intermediate intensity batches were used for that purpose.

Fewer bunches per batch

In 2010 the LHC was filled with single batch injections from the booster into the PS, with the booster RF running on harmonic 2 (+1). The intermediate intensity batch was generated by injecting a single booster ring into the PS instead of three. The other two were disabled manually followed by adjusting the splitting in the PS. Intermediate intensity batches could not be generated in an automated way.

Following the recommendations of the External Machine Protection Review in September 2010, the physics filling schemes all contained an intermediate batch as first injection after the probe beam as final validation of the injection process. For 75 ns the intermediated intensity corresponded to 8 bunches, for 50 ns to 12 bunches and for 25 ns taking a single booster ring with one injection from the booster it would correspond to 24 bunches. The required manual intervention of the operations crew and the tuning of the splitting

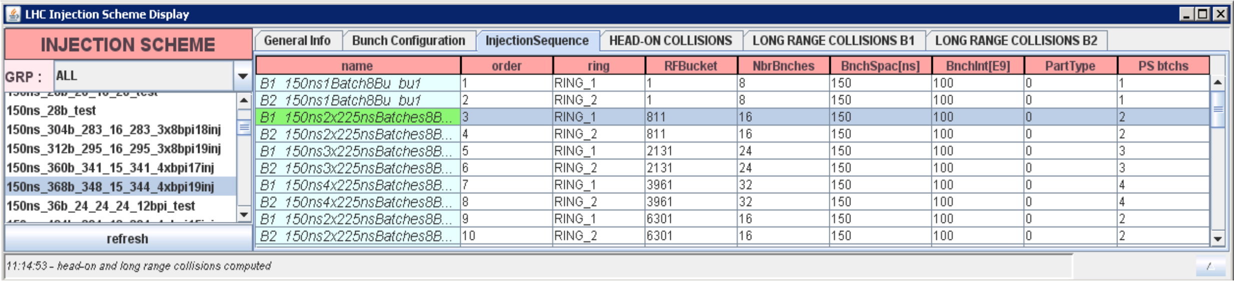

Figure 1: Current injection schemes: The current injection schemes consist of a number of injection requests. An injection request tells the injectors into which LHC ring and into which RF bucket the next injection should occur and how many PS batches should be injected into the SPS. The number of injections into SPS can be controlled on the fly. The same is not possible for the number of booster injections into the PS.

then in the PS before and after the intermediate batch injections caused some considerable holdup during the LHC filling. Improvements of the mechanism to switch to intermediate intensities will have to be put in place for the 2011 run.

Possibilities to speed up switching in and out intermediate batch injections

Two possibilities to make the switching to intermediate intensities more efficient are discussed:

1. Separate user for intermediate intensities
2. New type of LHC injection requests.

Separate user: this approach would not require any modifications of the existing way of controlling the LHC beams in the injectors. Nominal and intermediate intensity would be run on different cycles in the injectors. As the intermediate intensity cycle is used to steer the SPS to LHC transfer lines and to avoid the complication of having to copy the steering settings to the nominal cycle which risks to be forgotten, the same user in the SPS should be used for intermediate and nominal. Only the PS and the booster would run with different users. The drawbacks of the "separate user" solution are the larger number of users locked for the LHC beams, the potential issue of the copy of the transfer line steering in case of different SPS users and that the switching from intermediate to nominal and vice versa cannot be done through LHC injection requests. The timing system would have to be re-configured to play the other user. In this way intermediate intensities could only be used as first injection. Mixed filling schemes using nominal and intermediate intensity injections throughout the filling to optimise the luminosities at the different interaction points would not be possible.

New LHC injection requests: the drawbacks of the first possible solution could all be elegantly avoided by the introduction of more flexible LHC injection requests. An example of a filling scheme with the current type of injection requests is shown in Fig. 1. Note that the number of PS injections into the SPS can be piloted on the fly by the LHC injection request with today's Central Timing. This is not the case with the number of booster rings. However, the concept of different destinations for different booster rings exists. And different PS equipment settings can be associated with these different destinations (double PPM settings). These destinations are static today. The idea behind the "new LHC injection requests" is to use the fact of different settings for different booster ring destinations and upgrade the "LHC injection request" to also pilot the number of booster rings between 1 and 6 (2 x 3 rings for 2 batch injection from the booster).

Despite the obvious advantages for injection protection and overall flexibility of building injection schemes of this proposal, there are some drawbacks. The 2010/11 shutdown is short and this proposal would require a major, but technically feasible, modification of the LHC and Central Timing System. The bigger obstacle however comes from the fact that not all required systems in the PS are double PPM yet, a controls infrastructure upgrade and an efficient way of managing the settings in INCA would have to be organised. Possibilities to exploit the "separate users" proposal will be investigated for 2011. In addition we will study and prepare a new type of LHC injection requests in 2011 to be ready for implementation during the shutdown 2011/12.

TRANSFERLINE COLLIMATORS

The transfer line collimation system has been designed to provide full phase space coverage and protect therefore against any failure leading to large amplitude oscillations from upstream of the collimators. The TCDI collimators are at the end of the lines and due to optics and space constraints only three collimators per plane could be fitted into the lattice. The phase advance between two adjacent collimators is 60°. The settings of the collimators depend on the LHC aperture available for the injected beam, thus the aperture for the circulating beam minus a margin for sources of aperture reduction from injection like injection oscillations. The circulating beam aperture in the LHC at injection energy was measured to be 12.5 σ [2]. The settings of the transfer line collimators are chosen not to let amplitudes through larger than 7.5 σ. This is fulfilled with a setting of 5 σ. Currently the transfer line collimators are at 4.5 σ. The required protection level was validated for 5 σ settings. The results for the maximum amplitudes leaking through the system for different phases are shown in Fig. 2. In summary, the

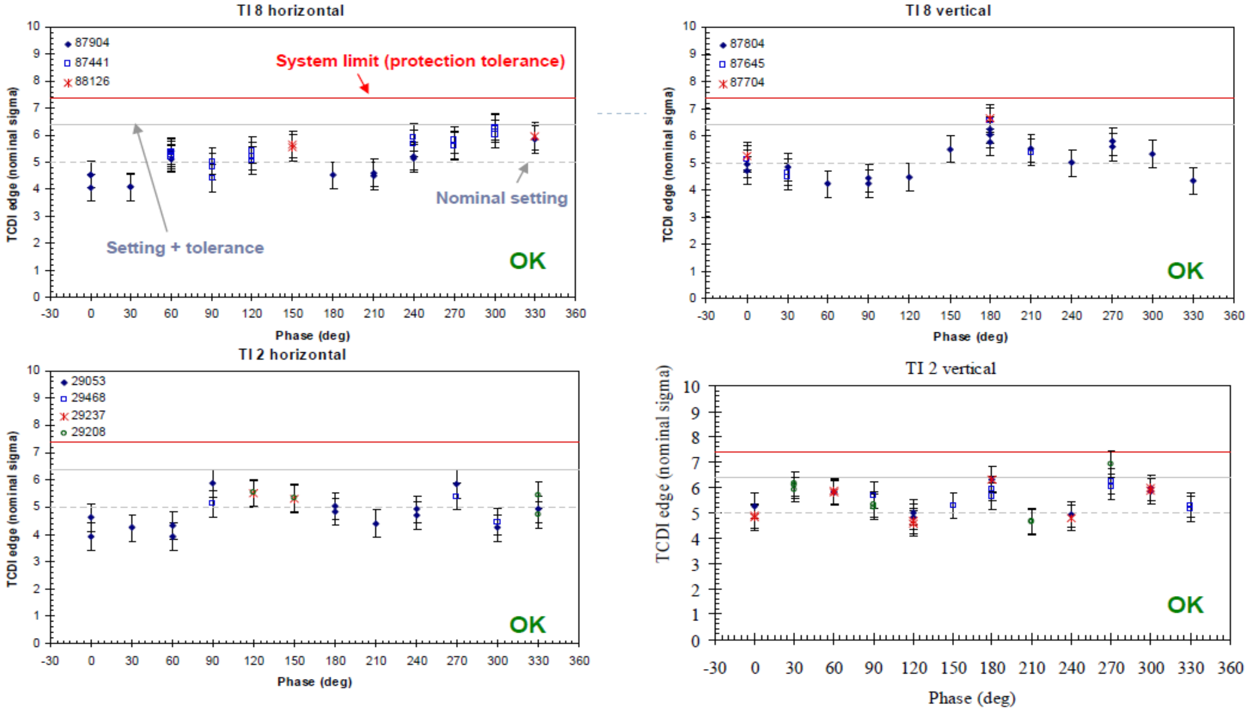

Figure 2: Results of the protection level measurements of the TCDIs for TI 2 and TI 8 on September 15, 2010: The phase space coverage was evaluated. The phase space is covered within the system limit protection tolerance

plots show that for 2010 the system achieved the required phase space coverage.

With the collimators at the end of the lines, close to the LHC, and the tight settings, any losses on the collimators are seen by the sensitive BLMs on the LHC superconducting magnets, see Fig. 3. This was one of the reasons for the partly poor operational efficiency during injection [3,4]. Frequently the showers from the collimators created signals above threshold in these BLMs.

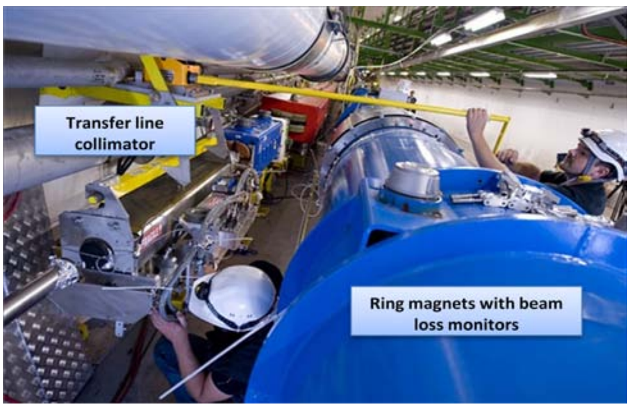

Figure 3: The transfer line collimators are close to the LHC superconducting magnets equipped with sensitive ring BLMs.

Setting-up frequency of the transfer line collimators

All TCDIs were set up middle of March using the old lengthy setting-up method as shown and described in Fig. 4. Until June, 1 to 2 TCDIs had to be adjusted a couple of times (maximum changes of centre positions were of 800 μm). Beginning of July 2010 all TCDIs were re-set up for higher intensities. This time the new method, scanning the jaw gap as described and shown in Fig. 5, was used. With this method the collimators for both lines can be set up within 1 shift.

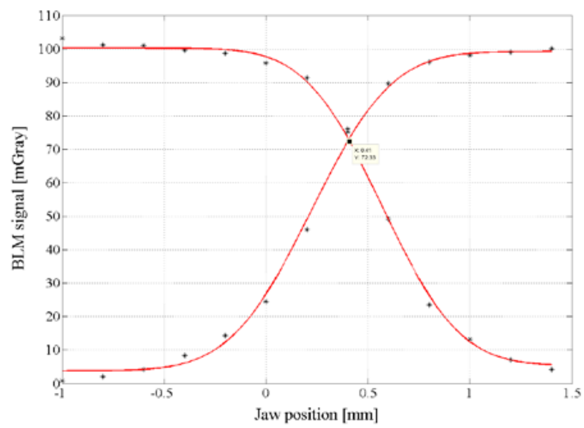

Figure 4: Response of BLM when moving each jaw individually through the beam during subsequent SPS extractions fitted with the error function to define beam size and centre position between the jaws.

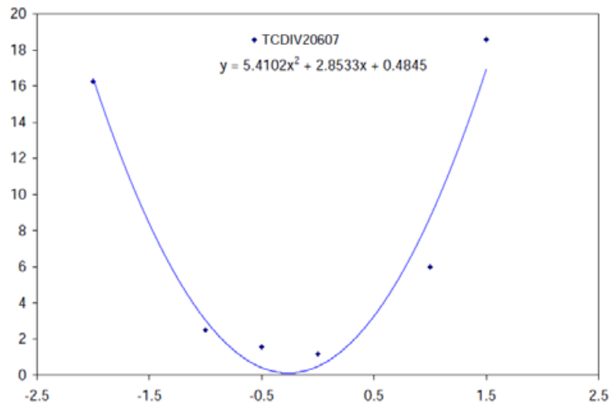

Figure 5: Response of transfer line BLM when moving gap and parabolic fit. This method quickly determines the optimum centre position for the two jaws.

From then on the collimators were only touched to reduce losses on the transfer line collimators when the injected intensities were increased or a new bunch pattern was introduced. Always the same collimators were affected, all of them in the horizontal plane: for beam 1 TCDIH.29050 and TCDIH.29205, for beam 2 TCDIH.87441. Per adjustment 1 to 2 TCDIs had to be touched, the typical changes of the centre position were between 200 to 300 μm. No change was required when switching to 150 ns and 50 ns running or ions.

The last big change of the TCDI jaw positions was caused by the re-steering of the injection of beam 1 due to an aperture bottleneck in the injection septum MSI with RF fingers buckling into the injected beam chamber. No scans for the optimum jaw position were necessary. The trajectory interpolations at the TCDI locations could be used directly to shift the gaps. The centre positions had to be changed by up to 1.2 mm.

Operational margin

It turned out in 2010 that the longitudinal and transverse parameters of the beam extracted from the SPS and the steering in the transfer lines had to be very well under control not to cause collimator losses above threshold on the LHC BLMs. Opening up the transfer line collimators beyond 5 σ was requested several times. The following will summarise the arguments for keeping the transfer line collimators as tight as possible. The TCDI settings contain margin for injection oscillations and LHC orbit.

Orbit bumps can be left in after MDs, be introduced by accident with steering algorithms or on purpose to compensate missing correctors. Currently the software interlock limit for orbit bumps is 1 mm which is frequently not enough in case of missing correctors. The correction of injection oscillations is problematic due to not understood systematic differences between different cycles in the SPS as already mentioned before and the tight collimator settings at the end of the line where the trajectory should not be changed. Injection oscillations are corrected with intermediate intensity. Also they can only be corrected after establishing a well corrected orbit in the LHC. Due to the differences in the orbit reading between high and low sensitivity settings of the BPMs, this is only fully done with nominal bunches in the LHC and not with probe. This is another argument for correcting injection oscillations with nominal bunches even though only a minor uncertainty well within any margin would be expected from this effect if correcting with probe. Depending on the bunch spacing intermediate intensity can already be above setup beam limit. To be pragmatic, trajectory correction in the lines therefore became expert intervention and was done as infrequently as possible in 2010. With the excellent performance of the LHC transverse damper [5] and the larger injection aperture and tight TCDI settings, injection oscillations of more than 1.5 mm were acceptable.

These values for orbit bumps and injection oscillations were comfortable values to work without having to spend too much time on optimisation, sophisticated algorithms and risking machine protection issues. Opening up the TCDIs will reduce these margins. Table 1 summarises the current situation.

Table 1: Tolerances for TCDI setting of 5 σ

	Tolerance [σ]
TCDI setting	5
TL tolreance	1.4
Real setting 1 col	6.4
Phase space coverage	**7.4**
Injection oscillations	2
Orbit	2
Dynamic beta-beat	0.6
Energy	0.5
Max. amplitude in LHC	**12.5**

Required correction during the 150 ns run

Trajectory correction was triggered by high loss levels at the transfer line collimators or significant injection oscillations (> 1.5 mm). The total correction applied in both lines reached about 1 σ at some of the collimators, see Fig.6 to 9.

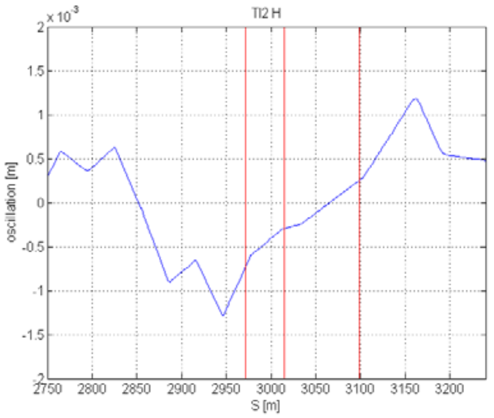

Figure 6: The sum of all corrections applied during the 150 ns proton run in 2010 in the horizontal plane end of TI 2. The red vertical lines indicated the locations of the transfer line collimators.

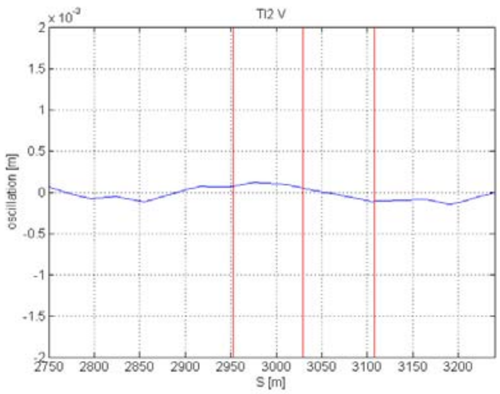

Figure 7: The sum of all corrections applied during the 150 ns proton run in 2010 in the vertical plane end of TI 2. The red vertical lines indicated the locations of the transfer line collimators.

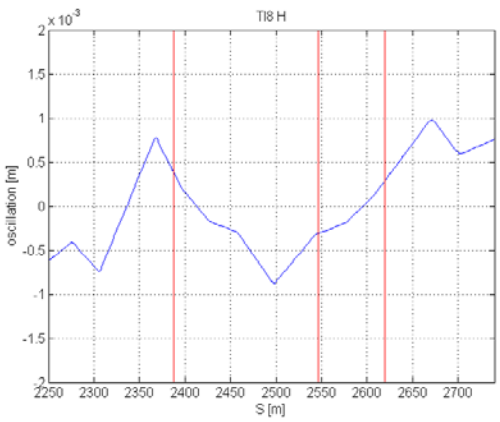

Figure 8: The sum of all corrections applied during the 150 ns proton run in 2010 in the horizontal plane end of TI 8. The red vertical lines indicated the locations of the transfer line collimators.

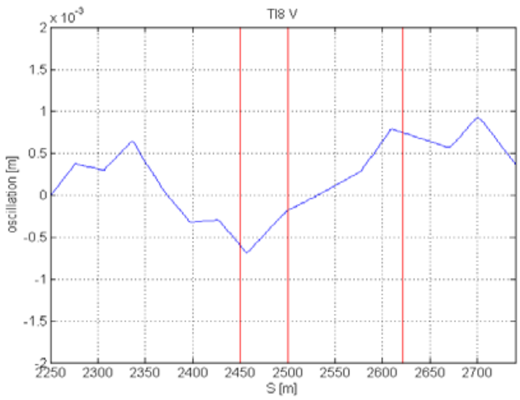

Figure 9: The sum of all corrections applied during the 150 ns proton run in 2010 in the vertical plane end of TI 8. The red vertical lines indicated the locations of the transfer line collimators.

NEW INJECTION SOFTWARE INTERLOCKS

Two new software interlocks will become active for the 2011 run. The software interlock system SIS will allow the injection of high intensity only if intermediate intensity is already circulating. In this way the injection of intermediate intensities will be enforced also through interlocking. Another flag will be introduced in the Injection Quality Check (IQC) [6] analysis checking the injection oscillations of the last injection. The new flag will also be picked up by the SIS. If the injection oscillations in the IQC have returned FALSE, the maximum intensity to be injected thereafter is intermediate intensity. This will be automatically reset, once the injection oscillations are within limits. (A special RBAC role will exist to overwrite the injection oscillation IQC result in case of data availability issues and for debugging.)

In 2011 operations will be responsible for correcting the trajectories in the transfer lines. Correction limits and safety of correction algorithms/tools will be investigated.

ANYTHING WE HAVE FORGOTTEN?

Accidental beam on TDI

At several occasions during 2010 a considerable amount of intensity, 24 to 32 bunches, ended up on the TDI. One failure type could have been avoided and was due to new filling schemes not respecting the abort gap keeper window for the last injected batch (abort gap keeper window: 3 μs abort gap + 8 μs). An automatic check will have to be implemented in the injection scheme editor (together with an unmaskable SIS check). A complication is coming from an unanticipated synchronisation issue. The abort gap keeper window had moved by about 50 RF buckets towards the end of the run. The reason is unclear.

Another unforeseen failure case was the complete loss of the synchronisation between SPS and LHC normally guaranteed through connecting both timing systems to the GPS. The GPS was off at one occasion and the injection pre-pulses had not been sent out at the correct moment with respect to the charging of the PFN voltages of the injection kickers. The whole injected beam was dumped onto the TDI. A surveillance system had been put in place already in 2010. For 2011 another upgrade of the timing system is planned where injection requests will be rejected by the timing system in case problems with the GPS are detected.

Circuits within the transfer line collimation section

The transfer line collimators can only protect against oscillations originating from circuits upstream the collimation section. A small number of circuits is within the collimation section or even afterwards. All have interlocked settings. The dipole chains are interlocked 0.1 to 0.2 % and dipole correctors at 10 μrad. Circuits with small time constants in case of a trip are protected in addition with FMCMs [1], not the dipole correctors or the three MCIAVs which are used as RBEND at the end of TI 8 (the MCIAVs are slow, time constant of 185 ms). Details are summarised in Table 2 and 3. Fig. 10 and 11 show the resulting oscillations in the LHC in case of wrong settings within the currently set interlock tolerances. The current thresholds are sufficient, but could be even further decreased depending on the power converter stability.

Table 2: Circuits within or upstream of the transferline collimation section in TI 2.

Circuit	
MBIBH	FMCM
MCIAV	-
MSI	FMCM

Table 3: Circuits within or upstream of the transferline collimation section in TI 8.

Circuit	
MBIAH	FMCM
3 x MCIAV	-
MCIAH, MCIAV	-
MSI	FMCM

IMPROVEMENTS TO COME

Threshold management of injection protection devices

The settings and threshold management of the injection protection collimators and dumps is implemented following the philosophy of the ring collimators. The ring collimators' motors block if the interlock thresholds are reached to avoid that the jaws accidently run into the circulating beam. The same logic is applied to the transfer line collimators and TDI plus TCLIs. As all these collimators are driven by stepping motors, a periodic cycling of the jaw positions is recommended to guarantee motor precision. Before each LHC fill all collimator positions are opened up and only then moved to their injection settings. Because of the blocking mechanism, the thresholds have to be opened up as well. Thus different sets of interlock thresholds have to be maintained in the control system. They can be loaded at any time with no guarantee for the correct ones to be resident at injection. An additional energy dependent gap interlock which does not have to be changed for cycling the motors, increases the reliability of the system.

In 2010 no energy gaps were implemented in the control system of the TDI. Also, relying on energy gaps only is not sufficient for the transfer line collimators. As the settings are tight and the collimators have to protect in single pass, the correct gap centre positions have to be ensured.

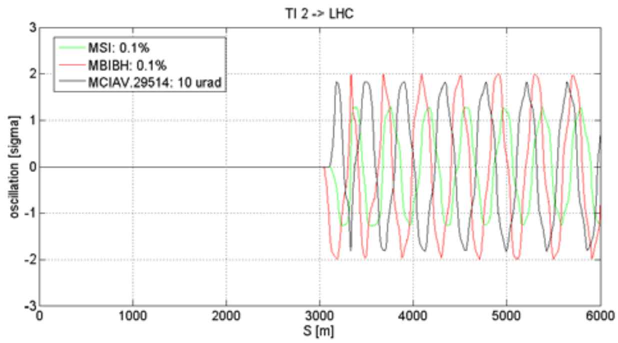

Figure 10: Resulting oscillations into the LHC for the large circuits within or upstream of the collimation section in TI 2 with current errors at the interlock limits.

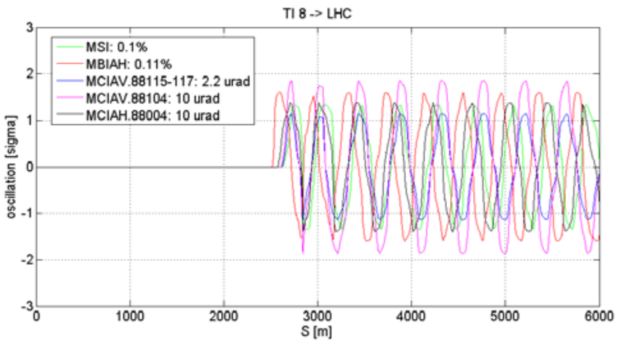

Figure 11: Resulting oscillations into the LHC for the large circuits within or upstream of the collimation section in TI 8 with current errors at the interlock limits.

Several improvements will be put in place during the 2010/11 shutdown. Running of collimator jaws into circulating beam is not an issue for transfer line collimators. It was therefore decided to remove the movement blocking mechanism for transfer line collimators for inner and outer thresholds and for the TDI for going across the outer threshold. The TDI will also be equipped with energy gap interlocks.

Over-injection

In 2010 the probe bunch required for beam presence was injected into RF bucket 1 and then over-injected onto the TDI with the first high intensity injection. If however no beam was extracted from the SPS during an over-injection attempt, the probe beam was kicked out, the beam presence condition was lost and therefore the possibility to resume the filling was lost as well. Cycles in the injectors had to be changed again to switch back to probe beam production etc. and a lot of time was lost.

For 2011 it is therefore planned to place the probe bunch at a better location around the LHC circumference such that over-injection does not occur during the first injection but later.

Keeping the probe bunch as part of the filling scheme as a witness bunch is another possibility.

SUMMARY

The LHC injection protection system is fully operational and is working well. All injection failures problems during the 2010 run were caught. The transfer line collimators could be kept at tight settings of 4.5 σ without any major efficiency problems. The LHC has already been saved several times from damage when high intensity batches of up to 32 bunches ended up on the TDI. The injection interlocking system has proved to be very reliable and available. Interlocks on injection oscillations not to compromise the available aperture will be implemented for the 2011 run. In 2010 the concept of injecting intermediate intensity before high intensity had been introduced and will be kept for 2011. Other improvements to tools e.g. the injection scheme editor, unmaskable SIS interlocks and upgrade of the timing system concerning the GPS issue should avoid accidently dumping high intensity beam onto the TDI. An increase of protection reliability will come from the new threshold management of the injection protection collimators. And an improved procedures concerning e.g. over-injection will help to make the restrictions of the injection protection system less cumbersome.

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LHC OPERATION: THE HUMAN RISK FACTOR

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Abstract

Issues associated with the human risk factor for the machine protection and operation of the LHC are discussed, with examples taken from the 2010 run. Emphasis is placed on risk factors that are present in the current modus operandi, and areas of improvement, both procedural and otherwise, are addressed. In addition, the The potential sources of human risk factors that lie outside the standard operations envelope and protective procedures are also considered.

INTRODUCTION

This paper takes a look at the human factors in LHC operation and discusses the human risk factors both for LHC operation and for machine protection. Given that at time of writing, the very successful 2010 run has only recently finished, the focus of this paper is on universal human risks factors and observations from the 2010 run rather than attempting to provide a list of operations errors from the first full a very year of running.

Human risk factors in LHC operation can take a variety of forms and can cause a wide range of issues ranging from weaknesses in the machine protection system to loss in operational efficiency through to risk oriented behaviour or operational mistakes. For machine protection the key issue with the human factor is whether the shift crew can damage the damage the machine. Clearly, for LHC operation, it is essential for the shift crew to exercise full control over the LHC and its systems, so by default, the possibility exists for the shift crew to drive the machine to a working point outside the machine protection envelope. However, the machine protection system, the operational procedures, the expertise of the shift crew, and the attention to the human factor greatly mitigate this risk.

HUMAN RISK ASSESSMENT CULTURE

When dealing with the human risk factors for LHC operation, the goal is not minimise risk by a post-problem reaction or pathological culture, but rather, by instilling a clear proactive risk assessment culture that respects, anticipates and responds to risks. This notion of a developing human risk assessment culture is one that is adopted in disciplines such as the nuclear and aeronautics industries, and can be defined in five broad categories[1]:

- GENERATIVE: Respects, anticipates and responds to risks. A just, learning, flexible, adaptive, prepared & informed culture. Strives for resilience.
- PROACTIVE: Aware that ‘latent pathogens’ and ‘error traps’ lurk in system. Seeks to eliminate them beforehand. Listens to ‘sharp enders’.
- CALCULATIVE: Systems to manage safety, often in response to external pressures. Data harvested rather than used. ‘By the book’.
- REACTIVE: Safety given attention after an event. Concern about adverse publicity. Establishes an incident reporting system.
- PATHOLOGICAL: Blame, denial and the blinkered pursuit of excellence (Vulnerable System Syndrome). Financial targets prevail: cheaper/faster.

The task for an effective human risk assessment culture is to evolve toward a Generative culture the promotes resilience, where resilience is defined as the ability of a system to adjust its functioning to sustain operations during expected conditions and in the face of escalating demands, disturbances, and unforeseen circumstances [1].

To assess the human risk factors associated with LHC Operation in 2010, a preliminary survey of the post mortem data and logbook statistics can be made. From approximately 500 global post mortem events that occurred over the last 4 months of running, 204 were with beams above injection energy. From these 204 events only 8 were classified as operational errors; a 4% rate of operational errors that led to beam dumps. These beam dumps were typically provoked either by hidden interlocks which were not cleared prior to the setup beam flag energy threshold being reached during the ramp, or the incorrect configuration of a setting during the commissioning with beam.

In addition to this, the logbook reveals a number of instances where operational irregularities also resulted in beam dumps. Examples from the logbook include accidentally switching off with the Equip State application and playing the wrong squeeze function in the squeeze.

What is clear is that in the 2010 run there were more operational errors than were documented, and a significant fraction could be associated with human risk factors. Unfortunately a significant number of the operational errors went untagged, thereby making it difficult to get a representative assessment of the human risk factor. However, it is reassuring that to date, the operational errors incurred have been caught by the machine protection system and dumped the beam immediately. This reduces the risk of damage to the machine but does not completely remove the risk of damage due to the risk from operational errors coupled with an asynchronous beam dump or an equipment failure. It is insufficient to rely solely on the hardwired machine protection system, and it is clear from the 2010 run that improvements can be made in the culture of human risk assessment.

NORMAL OPERATION

Normal LHC operation is defined in terms of a nominal operational procedure, which is mapped to a nominal LHC operational sequence. However, this is not a one-to-one mapping, as not all steps in the nominal procedure can be encapsulated in the nominal sequence. This then opened up several possibilities for human risk factors.

- Not all tasks are integrated into the sequencer, so there was the risk of tasks not being done. e.g. running through the collision beam process without switching off the tune and orbit feedbacks.
- Missing or skipping required steps in the nominal sequence.
- Playing an out of date sequence.
- Resorting to special procedures or workarounds that only have a limited duration validity or are not well documented.

In an attempt to curb these types of errors, an LHC State Machine (based on machine protection guidelines and the Beam Mode states) has been developed and is to be deployed for the 2011 run.This state machine will work in conjunction with the LHC sequencer and will help enforce that there is an adherence to the nominal procedure and that tasks are not performed out of order. Also, as part of the state machine, there is an incorporated checklist view that allows an overview of the performed task within a given state. This state machine should aid aid the shift crew in ensuring that all the required task have been performed before a state transition is performed.

Yet there is still the risk of that the wrong commands are sent or that a trim is too large and moves the working point outside the machine protection envelope. Such situations are difficult to catch automatically, as it is primarily an issue of operator competency. As seen from the 2010 run, the level of operator competency is extremely high, but that for whatever reason such errors have occasionally crept in. At present, the way to programmatically combat these errors is to implement settings checks and validation on operator initiated write commands. This can at best be only partially successful, as it is difficult to define a machine protection envelope that covers all the operational phases of the machine, without becoming so restrictive that the operations flexibility of the shift crew is compromised. The process of defining a machine protection envelope will continue in 2011.

NON-STANDARD OPERATION

The possibility for human risks in operation is naturally increased when there is need to move away from standard operational procedures. In particular, two specific cases were identified: the use of special interim procedures for the resolution of short term problems, and the use of low level applications at the operations level.

In 2010 the first case was highlighted with the case of bent RF fingers causing an obstacle in the beam pipe in at the end of the beam 1 injection. In order to avoid this obstacle steering was performed in the transfer line and the obstacle was successfully bypassed, but the steering induced significant injections oscillations. However over time the obstacle drifted and the steering had to be adapted, which resulted in unacceptable injection oscillations. For this case, there was no a clear definition of an operational envelope, and as the initial steering was set up at the limit of tolerable injection oscillations, the was no margin for fluctuations or for diagnostic probing of the problem by the shift crew.

As an example of the latter case, the use of the Equip State application is mentioned. Equip State is a low level application that allows the operator to directly set properties on the hardware, and the is not machine protection check on the settings being sent. This, coupled with the fact that some of the naming conventions for beam processes and setting are not always obvious or adhered to, means that there is a real risk of sending the wrong settings. It is only the vigilance of the operators that prevents such errors (e.g. when changing collimator settings during loss maps etc). In the 2011 run, when there is beam in the machine, the access of low-level applications such as Equip State is to be restricted or if possible, prohibited.

APPLICATIONS AND CONTROLS

Human risk factors in LHC operation are not solely linked to the LHC Operations team, but are also related to the LHC applications, controls interfaces and experts.

For the applications and controls interfaces, there is an obligation to present operational information at the top level in a clear and understandable way. In the 2010 run there were occasions where the information from an application was not clear yet was needed in order for the shift crew to react to a beam related problem. The loss of the tune feedback during the squeeze due to large coupling is a good example, as the tune feedback application gave significantly different coupling values depending on the tune fitter filter selected, leaving the shift crew unsure of the actual value of the coupling. This is an example of an extremely powerful application that sometimes failed to clearly deliver the information needed by the shift crew.

In addition to the presentation of monitoring data, there is also need for clarity in design and layout of setting controls in applications. Having a clear and responsive control interface is needed both for routine operation and for situations where immediate response is needed. For the risk from control interfaces in 2010, the proximity of the ON/OFF buttons in the Kicker application (normal operation) and the slow response and poor state selection of the tune feedback fixed display are examples where the interface can be improved.

From an operations point of view, it is clear that applications should provide an operations view, but they should also allow for an expert view. However, in order to reduce the risk of operator error the two view should remain separated, and where possible, both views should be documented. It is also crucial that after a commissioning or machine development session, equipment experts re-establish the operations view and do not leave unvalidated settings or configurations in the operator applications running in the CCC. When this happen in 2010, it only helped to complicate the diagnosis of problems.

Included in this issue of settings and configurations is the updating of front-end firmware, which at present is not controlled by the standard RBAC security checks[2]. Standardisation of firmware version tracking is not foreseen for 2011, and so the minimisation of risk from this source relies on clear communication between equipment teams and the operations team, and well prepared scheduling of updates.

As part of the issue of information transparency for the operations, one key issue is the presentation of alarm information through the LASER and DIAMON applications [3]. For the 2010 run the operations team did not have a clear picture of the alarms information and alarm flow from the LASER system simply because it was swamped with alarms. This made the monitoring of problems via LASER untenable, and as such greatly reduced the ability of the shift crew to respond to warnings an alarms flagged within the LASER system. For 2011 it is imperative that the alarm definitions be cleaned up and here the responsibility lies primarily with the equipment teams, but also with operations.

Similarly, the DIAMON application which is used to diagnose and monitor and front end servers, the 2010 run showed that the configuration of alarms within DIAMON is not yet optimised, and in addition that the operations monitoring view was not restricted to just the operational front-ends (i.e. it also included non-operational front-ends, which often showed alarms, and so made the monitoring of real alarms from operational front-ends difficult). Again the clean up of the DIAMON configuration lies primarily with the equipment teams.

COMMUNICATION

One of the primary areas for improvement that has been identified from the 2010 run is the area of communication and coordination. The lack of clear communication and coordination across the operations teams can and has resulted in a direct increase in the risks of human error and the potential for jeopardising the machine protection envelope. Lack of clear communication can create inconsistencies at the program level that can be consistent at the level of individual tasks, but may result in an overall working point that is outside the machine protection envelope.

In terms of communication, it is essential that a clear line of communication and chain of command be maintain between the machine coordinators, Engineers in Charge, and LHC operators, so that the programme is clear and the operational steps co-ordinated and well defined. As was seen in 2010 this line of communication needs to extend not only to the LHC but also to its injectors, the technical infrastructure, and the cryogenics shift crews, to avoid misunderstandings that unnecessarily stress the machine protection system.

As part of the communication issue there needs to be an improved passage of information and summary of decisions taken during the 8:30am meetings to the shift crews. Once the program is clear, it is also necessary that people in the LHC island respect the defined roles of the LHC operators and Engineers in Charge and permit them to carry out their functions, as it is the shift crew that is responsible for the safe an efficient running of the LHC during the shift.

OTHER FACTORS

In addition to all the above mentioned sources of human risk factors, there are other factors that can potentially affect machine protection, and these are the environmental factors. Environmental factors cover a wide range of topics ranging from:

- Working conditions in the CCC
- Operator fatigue
- Unbalanced work loads across the equipment and piquet teams
- Unnecessary pressure for fast turnaround times and rapid re-establishment of stable beams.
- Simple typing mistakes due to too many keyboards in the LHC Island.

For these environmental factors the responsibility to minimise there effect lies solely with the operations team, and as seen from the 2010 run, the influence of such environmental risk factors is being progressively reduced.

REDUCTION OF HUMAN RISK

The first step in reducing human risk factors is to realise that we are moving from a beam commissioning period into one of routine operation, and as such there is a need to tag instances of operational errors, in order to gather statistics and the analyse the manor and degree of the human risk factors. Implicit in this is the commitment from the operations team to tag any operation situations that involve error or risk, and also the support the management team in addressing operational errors so that a real human risk assessment culture can evolve.

As we move to routine operation, the robustness of the machine protection system is to provide the first line of defence against human error, such that deviations from normal operational procedure will initiate a beam dump. Beam conditions should then only be re-established once the reasons for the deviation are understood. In this way a more comprehensive machine protection envelope will be developed.

To aid in the reduction of operational errors, the operations team needs to build on the experience from the 2010 run, refine the machine protection envelope, and increase the degree of self assessment and evaluation of the operational procedure. This coupled with a balanced shift load, and clear lines of communication will help in reducing the operational errors as well as further help moving the LHC risk assessment culture from a Calculative level toward a fully Proactive and Generative human risk assessment culture.

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MULTI-TURN LOSSES AND CLEANING

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Abstract

In the LHC all multi-turn losses should occur at the collimators in the cleaning insertions. The cleaning inefficiency (leakage rate) is the figure of merit to describe the performance. In combination with the quench limit of the superconducting magnets and the instantaneous life time of the beam this defines the cleaning dependent beam intensity limit of the LHC. In addition, limits can arise from radiation-induced effects, like radiation damage and radiation to electronics. In this paper the used collimator settings, the required setup time, the reliability of collimation (all multi-turn losses at collimators), and the achieved proton/ion cleaning inefficiency are discussed. Observed and expected losses are compared. The performance evolution during the months of operation is reviewed. In addition, the peak losses during high intensity runs, losses caused by instabilities, and the resulting beam life times are discussed. Taking the observations into account the intensity reach with collimation at 3.5 and 4 TeV is reviewed.

INTRODUCTION

At nominal particle momentum (7 TeV/c) and intensity ($\sim\ 3 \times 10^{14}$ protons) the LHC has a stored energy of 362 MJ per beam. Uncontrolled losses of just a small fraction of beam at the superconducting magnets of the LHC can cause a loss of their superconducting state (quench limit at 7 TeV/c: $R_q = 7.6 \times 10^6\,\mathrm{ps^{-1}m^{-1}}$) [1, 2]. Therefore collimators are needed to intercept these unavoidable beam losses.

For installing the full LHC collimation system a phased approach has been taken. The collimators of the current phase-I system are mainly installed in two dedicated cleaning insertions. IR3 collimators are used for the cleaning of off-momentum particles and IR7 to intercept particles with too large betatron amplitudes. In addition the collimators provide a passive machine protection [3, 4, 5]. A sketch of the layout of the phase-I collimation system with 44 collimators per beam is shown in figure 1.

Figure 2 shows a simplified sketch of the gap opening arrangement of the different classes of collimators normalized to the beam size. The primary collimators (TCPs) are the ones closest to the beam and cut the primary beam halo. The secondaries (TCSGs) intercept the secondary halo, i.e. particles scattered by the primaries, and absorbers (TCLAs) catch showers produced by the other collimators at the end of each cleaning insertion. The dump protection collimators (TCSG-IR6, TCDQs) protect the superconducting arcs against mis-kicked beams. The tertiary

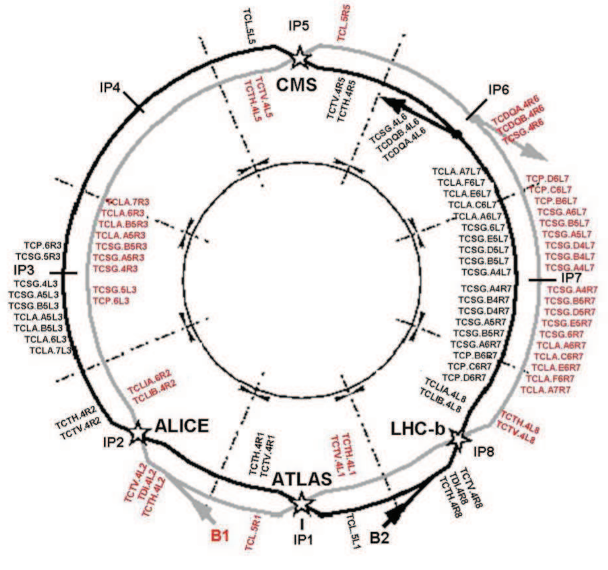

Figure 1: Sketch of the layout of the present phase-I collimation system. Beam 1 (beam 2) collimators are shown in red (black). [6].

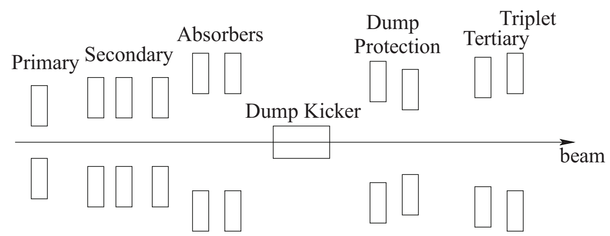

Figure 2: Simplified sketch of the gap opening arrangement of collimator classes normalized by beam size [9].

collimators (TCTs) are arranged around the experimental insertions, to protect the triplets locally [7, 8].

A measure for the performance of a collimation system is the local cleaning inefficiency

$$\eta_c = \frac{N_{local}}{N_{total}\Delta s}, \qquad (1)$$

with N_{local} the number of protons lost within an longitudinal aperture bin Δs and N_{total} the total number of lost particles. The calculated local cleaning inefficiency of the phase-I system with imperfections ($\eta_c = 5 \times 10^{-4}\,\mathrm{m^{-1}}$) was expected to limit the maximal possible beam intensity stored in the LHC at 7 TeV/c to 4% of the nominal [7, 6].

During the physics running period in 2010 the LHC was operated at 3.5 TeV/c with a maximum of 368 proton bunches per beam (i.e. $\sim 4.2\times10^{13}$ p) and a bunch spacing

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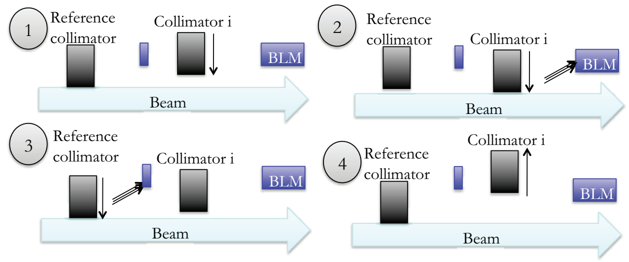

Figure 3: Simplified sketch of the beam-based setup procedure for one collimator [9]. Note: the sketch only shows one jaw per collimator whereas in reality the collimators in the LHC are in most cases double sided.

of 150 ns providing collisions to the particle physics experiments. During the last month of the 2010 operation the LHC was running with a maximum of 137 lead ion bunches per beam (i.e. $\sim 1.7 \times 10^{10}$ ions) at $3.5 \times Z$ TeV/c, with the atomic number $Z = 82$. The half gap openings used in 2010 for different families of collimators in units of beam sigma are given in table 1.

BEAM-BASED SETUP AND QUALIFICATION

To centre the collimator jaws around the beam and achieve the correct hierarchy of the collimation system a beam-based alignment procedure has been established during the LHC run in 2010 [9]. Figure 3 shows a simplified sketch of this procedure. A sharp edge is created in the beam halo by a reference collimator, which is usually a primary collimator (1). The jaws of collimator i are then moved to the edge of the beam halo and centered (2). After each centering of a collimator the reference collimator is re-centered around the beam (3). The measured beam size is therefore achieved as

$$\sigma_i = \frac{x_i^{L,m} - x_i^{R,m}}{(N_0^{k-1} + N_0^{k+1})/2}, \qquad (2)$$

with the measured positions of the centered collimator jaws $x_i^{L,m}$ and $x_i^{R,m}$ (L: left, R: right) and the half gap opening of the reference collimator in units of the local beam size before (N_0^{k-1}) and after (N_0^{k+1}) the centering of collimator i. Collimator i was then opened to its nominal settings using table 1 (4). At 450 GeV/c (injection) the full gap openings are relatively large (~ 12 mm) and therefore the influence of measurement errors on the achieved beam sizes value can be tolerated. At 3.5 TeV/c (smaller beam sizes) it turned out to be more precise to use the nominal beam sizes for the collimator settings [10].

The net setup time in 2010 was about 15-20 mins per collimator. In total two full setups (44 collimators per beam, B1 and B2 in parallel) were performed at 450 GeV/c and 3.5 TeV/c. One was performed for low ($\sim 1 \times 10^9$ p) and one for nominal bunch intensity ($\sim 1.15 \times 10^{11}$ p). The net beam time per setup was between 10 and 13 h. In addition several setups of all 16 tertiary collimators (TCTs) or a subset were performed due to changes in the beam crossing angles in the interaction points (IPs). To ensure the correct settings of the collimation system the centers of the collimators were partly re-checked when switching the LHC from proton to lead ion operation. With the reproducibility of the LHC orbit and collimator positioning achieved in 2010 the validity of a full setup was about 5 - 6 months.

The hierarchy and cleaning efficiency have to be qualified for each set of collimator settings and after each change in the collimation system or the LHC orbit. In addition the validity of the settings has to be regularly re-checked and the performance change of the system has to be monitored over time. For this purpose intentionally multi-turn losses are created. Over a time of 1-2 s 30-50 % of the beam (one nominal bunch) is lost. For betatron cleaning (IR7) the third integer tune resonance is crossed. This is performed for both planes and beams, i.e. B1-h, B1-v, B2-h and B2-v. For momentum cleaning (IR3) the RF frequency is increased (decreased) to qualify the system for negative (positive) off-momentum particles. The off-momentum qualification was done for both beams in parallel to reduce the number of measurements. One full set of measurements needs typically two dedicated LHC fills at top energy. The results of these measurements are plotted as so called loss maps.

CLEANING AND PASSIVE PROTECTION: PERFORMANCE AND PROBLEMS

Inefficiency measurements

Figure 4 shows, as example, vertical betatron losses in beam 1. To estimate the measured local cleaning inefficiency η^j_{meas} at element j signals S_j of the beam loss monitors (BLMs) were normalized to the highest loss signal S_{prim} at a primary collimator:

$$\eta^j_{meas} = \frac{S_j}{S_{prim}}. \qquad (3)$$

Note that this definition differs from the one mentioned in equation (1). The highest losses were found in the cleaning insertion and at primary collimators. The highest leakage to the cold aperture was found in the dispersion suppressor right of IR7 in a horizontal focusing (hf) quadrupole called Q8. Losses here are a factor ~ 5000 lower than at the primary collimator. This corresponds to a local cleaning inefficiency in the cold aperture of $\sim 2 \times 10^{-4}$, which is a typical value for betatron losses during the 2010 running period. The lower plot of figure 4 shows a zoom into the betatron cleaning insertion. The highest losses appear at the primary collimators and decline along the cleaning insertion exponentially to its end. Thus, the collimators in IR7 show the correct hierarchy for this case.

The measured global cleaning inefficiency to the cold

Table 1: Half gap openings in units of the beam sigma for different families of collimators and machine states.

	Injection optics	Injection optics	Squeezed optics
Energy [GeV/c]	450	3500	3500
Primary cut IR7 (H, V, S) [σ]	5.7	5.7	5.7
Secondary cut IR7 (H, V, S) [σ]	6.7	8.5	8.5
Quarternary cut IR7 (H, V, S) [σ]	10.0	17.7	17.7
Primary cut IR3 (H) [σ]	8.0	12	12(B1) / 10 (B2)
Secondary cut IR3 (H) [σ]	9.3	15.6	15.6
Quarternary cut IR3 (H, V) [σ]	10.0	17.6	17.6
Tertiary cut exp. (H, V) [σ]	15-25	40-70	15
TCSG/TCDQ IR6 (H) [σ]	7-8	9.3-10.6	9.3-10.6

aperture is defined as

$$\eta_g = \frac{\sum S_{cold}}{\sum S_{all}}, \tag{4}$$

where $\sum S_{cold}$ is the sum over all BLM signals at cold devices and $\sum S_{all}$ the sum over all BLM signals along the LHC ring. For the example in figure 4 the global cleaning inefficiency was $\eta_g = 2.3 \times 10^{-4}$, which translates to 99.98% of the losses appeared at collimators or warm magnets.

An example of the loss distribution of particles with a positive momentum offset is shown in figure 5. The measurement was performed at 3.5 TeV/c and after putting the beams into collision. The highest losses were found at the primary collimators of IR3. The highest leakage to the cold aperture was found in the dispersion suppressor left of IR3 in the horizontal focusing (hf) quadrupole called Q7. Losses here are a factor $\sim$ 330 lower than in the primary collimator. This corresponds to a local cleaning inefficiency in the cold aperture of $\sim 3 \times 10^{-3}$. The lower plot of figure 4 shows the zoom into the momentum cleaning insertion. The highest losses are found at primary collimators. In this measurement the two beams were not lost at the same time, which explains that the loss pattern is not symmetric between the two primary collimators but dominated by beam 1. The hierarchy seams to be correct for both beams. The global cleaning inefficiency to the cold aperture was $\eta_g = 1.1 \times 10^{-2}$.

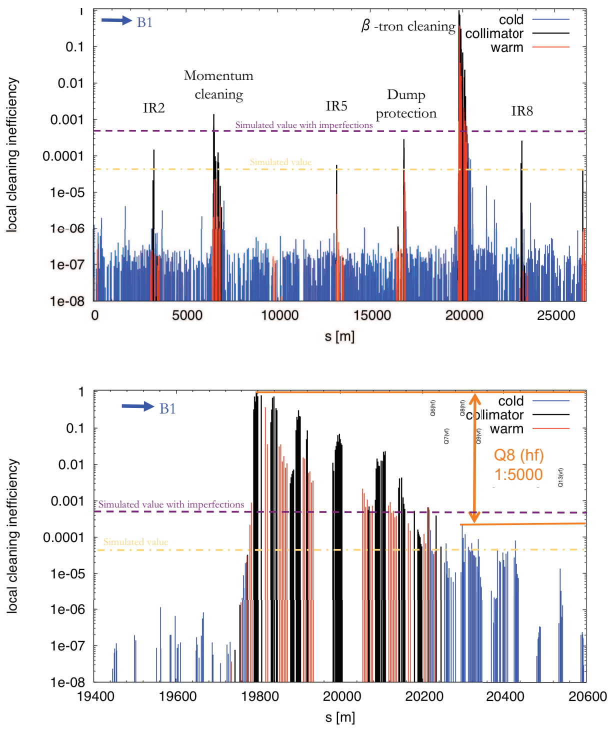

Figure 4: Cleaning with protons: Vertical betatron losses in B1 generated by crossing a 1/3 integer tune resonance. The measurement was performed at 3.5 TeV/c and collision optics. Blue/red/black bars indicate the local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators. The dashed purple (orange) line indicates the simulated maximum cleaning inefficiency into the cold aperture with (without) imperfections for the phase-I collimation system (for 7 TeV/c, nominal collimator settings). Top: Cleaning inefficiency along the whole LHC; Bottom: Zoom into the betatron cleaning insertion (IR7).

Comparison of Simulations with Measurements

Figure 6 shows a comparison of the measured betatron losses discussed above and results of a SixTrack [11] simulation with squeezed optics, at 3.5 TeV/c and the collimator gap openings of table 1. Note that the simulation was performed without imperfections. The measurements are in good agreement with the predictions: position and ratio of loss peaks are in general well reproduced. The measured leakage into the dump region in IR6 is one order of magnitude higher than expected. The reason for this behaviour is not understood yet. The plot at the bottom of figure 6 shows a zoom into the betatron cleaning insertion IR7. There are clear differences in the warm losses. This can be

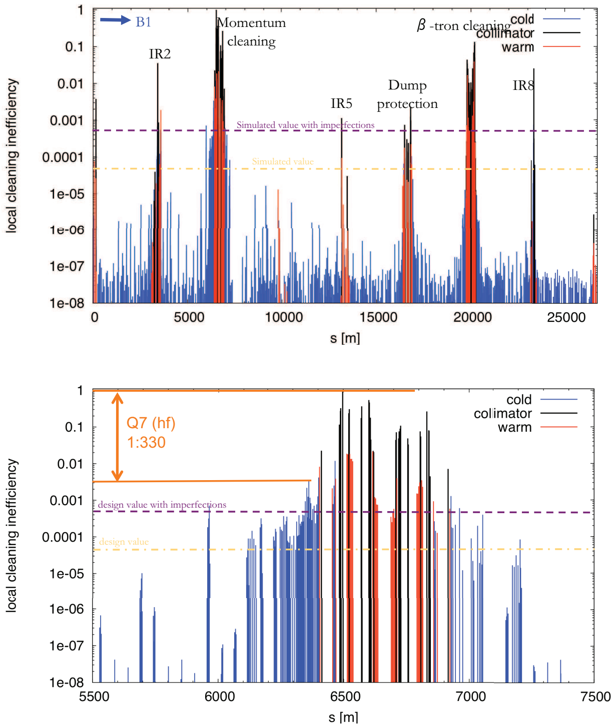

Figure 5: Losses of protons with a positive momentum offset. The measurement was performed at 3.5 TeV/c and collision optics with both beams. Blue/red/black bars indicate the local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators. The dashed purple (orange) line indicates the simulated maximum cleaning inefficiency into the cold aperture with (without) imperfections for the phase-I collimation system (for 7 TeV/c, nominal collimator settings). Top: Cleaning inefficiency along the whole LHC; Bottom: Zoom into the momentum cleaning insertion (IR3).

explained by particle showers which are measured by the BLMs but not taken into account in the simulations (only proton losses). As predicted in the simulations the highest leakage to the cold aperture is found in the Q8 of the dispersion suppressor. The different loss amplitude (1:7) can be explained by the influence of imperfections. Taking also other measurements into account this factor varies between 6 and 10, which is in good agreement with expectations presented in [6].

Problems

Figure 7 shows a breakdown of the collimation hierarchy in IR3 for positive off-momentum particles. The secondary collimator left of IR3 (TCSG.B5L3) experienced the highest losses, i.e. acted as primary collimator. This caused a non-conform radiation profile in the cleaning insertion and higher leakage into the cold aperture downstream of IR3. It was discovered about two months after a full collimation setup. The case of positive off-momentum particles had

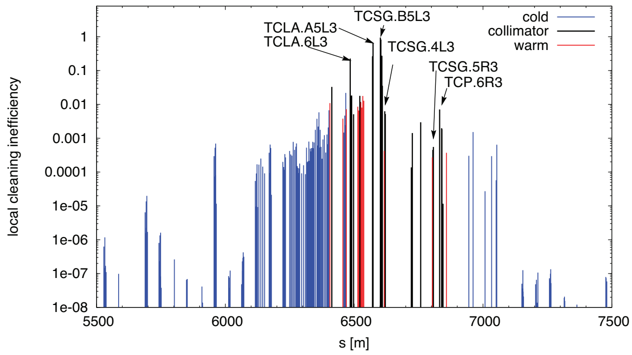

Figure 7: Breakdown of the collimation hierarchy for positive off-momentum protons in the momentum cleaning insertion (IR3) of beam 2. The measurement was performed at 3.5 TeV/c and collision optics by reducing the RF frequency. Blue/red/black bars indicate the local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators.

not been qualified for this setup. The hierarchy problem has been cured by a re-setup of the IR3 collimators and by further closing the primary collimator in beam 2 from 12 to 10 σ (see table 1). This shows that a full set of qualification measurements and a continuous monitoring has to be performed, to guarantee the performance and the provided passive protection of the collimation system.

Analyses of losses during high luminosity LHC runs showed a non-conform radiation profile in the betatron cleaning insertion of beam 2. The losses at secondary collimators were as high as at primary collimators. Hints of this behaviour have also been seen in beam 2 loss maps for horizontal betatron losses earlier. This did not cause a decrease in cleaning efficiency at this time. These types of non-conformities need to be addressed as the warm magnets in the cleaning insertions could otherwise be damaged by radiation in the long term.

Inefficiency for ions

Collimation for ions is known to be less efficient than for protons [12]. When ions hit a collimator, nuclear interactions and electromagnetic dissociation break up the nuclei in smaller fragments, which have different charge-to-mass ratios from the main beam. Because of the large cross sections of these processes, it is very likely that an ion will fragment before obtaining the required scattering angle from multiple Coulomb scattering to hit the secondary collimators. Instead the main fragments then pass through the whole cleaning insertion but may be lost locally further downstream where the dispersion is higher. The collimation system therefore works with one stage only. Each created isotope has a different effective momentum deviation and may be lost in localized spots around the ring [13].

Figure 8 shows horizontal betatron losses in beam 2 around the LHC ring. As for protons the main losses ap-

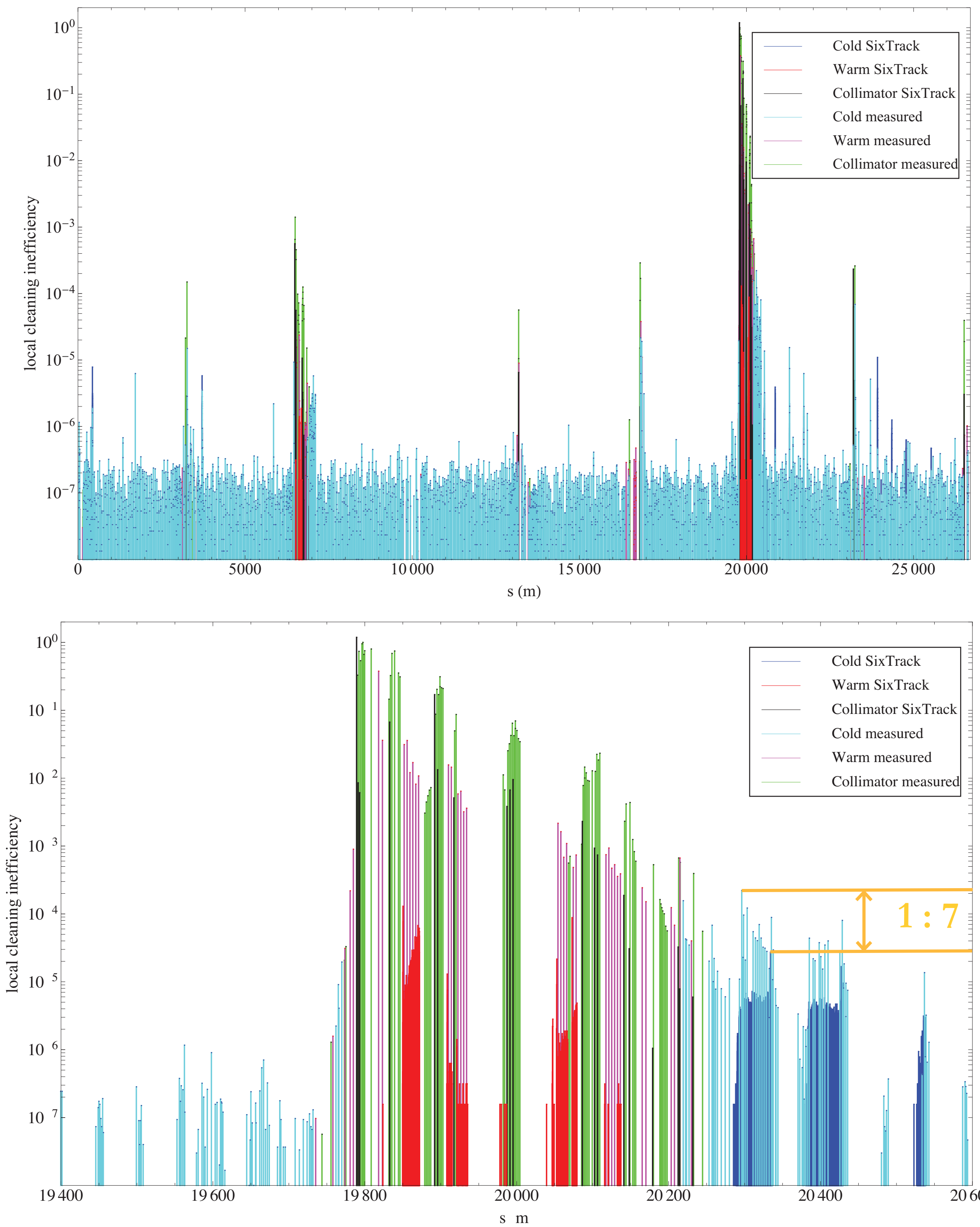

Figure 6: Comparison of simulated and measured proton losses. The measurements show vertical betatron losses in B1 generated by crossing a 1/3 integer tune resonance. The measurement was performed at 3.5 TeV/c and collision optics. The simulation was performed with SixTrack [11] for a vertical halo with squeezed optics, at 3.5 TeV/c and the collimator gap openings of table 1. Blue/red/black bars indicate the simulated local cleaning inefficiency η_c in units of 1/m in the cold aperture / warm aperture / collimators. Cyan/magenta/green bars indicate the measured local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators. Top: Cleaning inefficiency along the whole LHC; Bottom: Zoom into the betatron cleaning insertion (IR7).

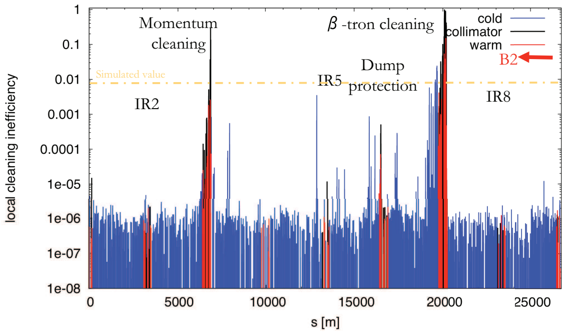

Figure 8: Cleaning with ions: Horizontal betatron losses in beam 2 generated by crossing a 1/3 integer tune resonance. The measurement was performed with lead ions at $3.5 \times Z\,\mathrm{TeV/c}$ and collision optics, with the atomic number $Z = 82$. Blue/red/black bars indicate the local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators. The dashed orange line indicates the highest simulated local cleaning inefficiency in the cold aperture without imperfections for the phase-I collimation system with lead ions.

Table 2: Highest leakage, in local cleaning inefficiency η_{meas}, of ions into specific regions (DS = dispersion suppressor, COLD= cold aperture excluding DS, TCT = tertiary collimators).

loss cases	DS	COLD	TCT
B1h	0.02	0.006	1.0e-4
B1v	0.027	0.005	0.001
B2h	0.03	0.011	8.0e-5
B2v	0.025	0.006	1.4e-4
B1+B2 pos. off momentum	0.045	8.0e-4	0.06
B1+B2 neg. off momentum	0.007	2.0e-4	0.005

pear in the two cleaning insertions. The highest leakage into the cold magnets of the IR7 dispersion suppressor is 3×10^{-2}, which is a factor 100 more than for protons. In addition there are localized loss spots in different parts of the machine with local cleaning inefficiencies in the order of 10^{-3} and 10^{-4}. Table 2 gives an overview of the highest leakage into specific regions of the LHC for the different betatron and momentum cleaning cases. The global cleaning inefficiency to the cold aperture for betatron cleaning with ions was below $\eta_g = 1.86 \times 10^{-2}$.

In figure 9 simulated (bars) and measured leakage (crosses) into the IR7 dispersion suppressor for horizontal betatron losses are compared. The simulations were performed with the code ICOSIM [12] without imperfections. ICOSIM combines optical tracking with a Monte-Carlo simulation of the particle-matter interaction in the collimators for heavy ions. Positions of the loss peaks in the disper-

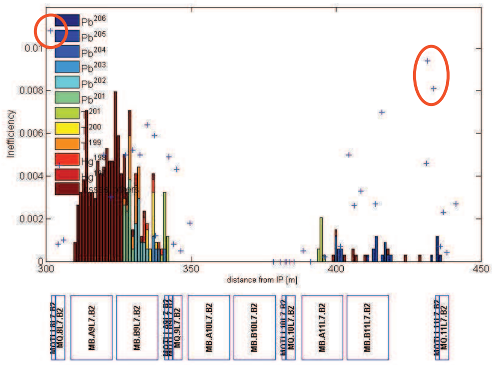

Figure 9: Comparison of simulated (bars) with the measured leakage (crosses) of ions into the IR7 dispersion suppressor expressed as local cleaning inefficiency. Measurement and simulation are shown for horizontal betatron losses in beam 2 at $3.5\times Z\,\mathrm{TeV/c}$ and collision optics, with the atomic number $Z = 82$. These preliminary simulations were performed with the code ICOSIM [12].

sion suppressor were reproduced in the measurements. The absolute level of the leakage differs. The measured leakage is significantly higher than predicted in simulations. The quantitative differences between measured and simulated losses with lead ions need to be further understood. Therefore, simulations with higher statistics are in preparation. Although using a state of the art simulation code there are uncertainties in the cross sections for hadronic fragmentation and electromagnetic dissociation with lead nuclei on carbon / tungsten.

Performance stability

After the full setup of the system for high bunch intensities in June 2010 the performance of the collimation system was continuosly monitored over the following 4 months until the end of the proton run. Figure 10 shows the evolution of leakage into the cold dispersion suppressor magnet called Q8 for betatron losses. As shown in figure 4 the highest local cleaning inefficiency in the cold aperture was found here. It had a value between between 1.3×10^{-4} and 6.1×10^{-4}. In one plane and beam the leakage varied up to a factor 3. The evolution of the leakage from the cleaning insertions into the tertiary collimators is shown in figure 11. The leakage is summed over all horizontal (vertical) collimators for each beam and plane. The maximum cleaning inefficiency for the horizontal (vertical) TCTs was 7×10^{-4} (1.25×10^{-3}). The leakage was varying in one plane and beam by less than a factor 4 (2.6). Together with the leakage into the Q8 these results show good stability of the collimation performance in this period of time.

The evolution of the leakage into the secondary collimators of the dump region (IR6) is shown in figure 12. The maximum cleaning inefficiency was found for horizontal

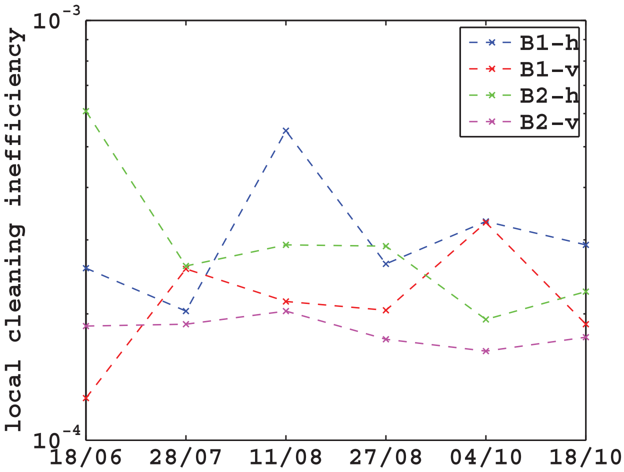

Figure 10: Evolution of the leakage from the cleaning insertions into the dispersion suppressor magnet Q8 over 4 months of LHC operation for betatron losses. Note: The loss response of beam loss monitors at collimators and cold magnets differs by about a factor of 2. This has not been taken into account here.

betatron losses in beam 2 with 5×10^{-3}. The maximum variation in one plane and beam was up to a factor 23. As shown in table 1 the margin between the secondary collimators in IR7 and the TCSGs in IR6 was $0.8\,\sigma$. The coupled orbit variations between these locations were found to be above this margin in certain fills[14]. This can explain the variation of the leakage to the IR6 collimators.

COLLIMATION BEAM LOSS EXPERIENCE 2010 AND OUTLOOK 2011

The collimation related total intensity limit is given by

$$N^q_{tot} = \frac{\tau_{min} R_q}{\eta_c}, \quad (5)$$

with the minimum instantaneous beam lifetime τ_{min}, the quench limit R_q and the local cleaning inefficiency η_c. The instantaneous beam lifetime is defined as

$$\tau(t) \approx \frac{N^q(t)}{R_{loss}(t)} \quad (6)$$

and depends therefore on the loss rate R_{loss} and the beam intensity N^q at the time t [15].

In beam halo scraping experiments the BLM signals at primary collimators in IR7 have been calibrated to the number of lost protons given by the beam current transformer (BCT) signals. Therefore the BLM signals can be directly converted into an instantanous proton loss rate [16]. The estimated error in the convertion of beam loss signals to loss rates was smaller than 20%. This calibration was used in all measurements presented below.

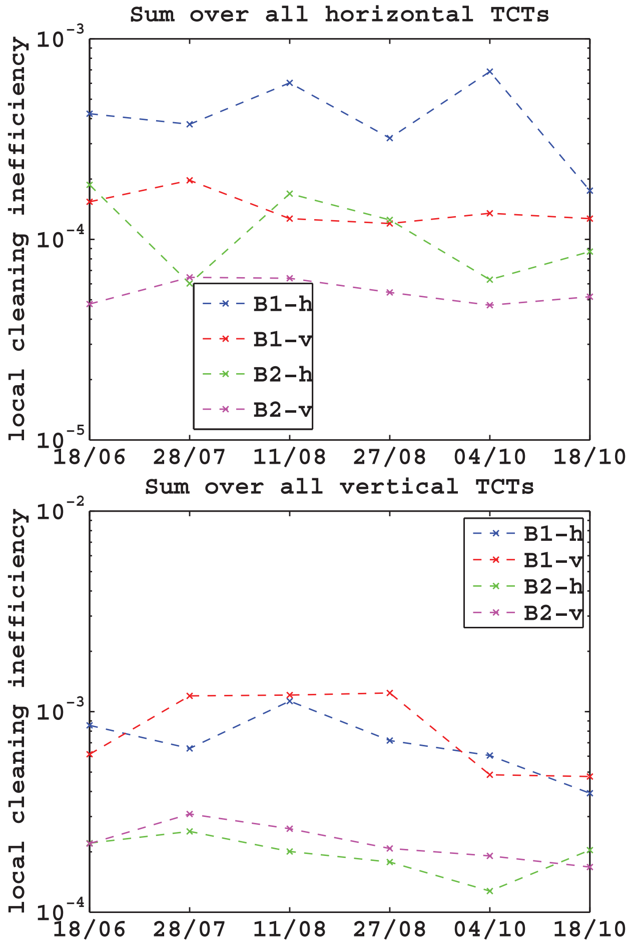

Figure 11: Evolution of the leakage from the cleaning insertions into the tertiary collimators (TCTs) over 4 months of LHC operation for betatron losses. Top: Sum over all horizontal TCTs; Bottom: Sum over all vertical TCTs. Note: The loss response of beam loss monitors at collimators and cold magnets differs by about a factor of 2. This has not been taken into account here.

Losses during high luminosity runs

Eight high luminosity fills have been analyzed: 3 runs with 312 bunches ($\sim 3.6 \times 10^{13}$ p) and 5 runs with 368 bunches ($\sim 4.2 \times 10^{13}$ p). The loss rates have been analyzed for four different integration times of the BLM signals: 80 μs, 640 μs, 10.24 ms and 1.3 s. Losses that appear only in the first two integration times can be assumed as transient losses, as these correspond to 1 - 7 LHC turns. Losses that appear also in the latter can be considered as steady state losses (115 - 14600 turns).

Figure 13 shows the calculated loss rates for BLM signals with different integration times at the horizontal primary collimator in the betatron cleaning insertion of beam 1 during a high luminosity run. In all integration times the loss rates showed a spike and the loss rate levels were significantly increased when the two beams were put into collision ($t > 1500$ s). They stayed at this levels until the

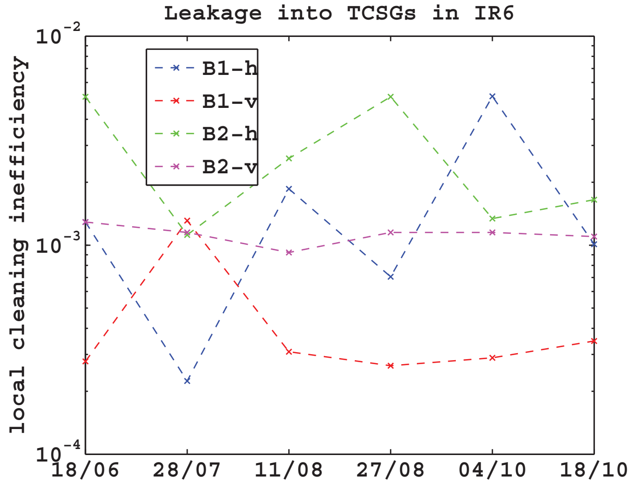

Figure 12: Evolution of the leakage from the cleaning insertions into the dump region (TCSG in IR6) over 4 months of LHC operation for betatron losses. Note: The loss response of beam loss monitors at collimators and cold magnets differs by about a factor of 2. This has not been taken into account here.

beams were dumped. This shows that the losses are mainly induced by beam-beam interactions. Additional loss spikes appeared for the different signals in most cases at the same time. Especially for the $80\,\mu$s integration time there were additional transient losses, which were nearly as high as the losses caused by bringing both beams into collision.

In figure 14 the highest measured loss rates are compared to the specified loss rate of 4.5×10^{11} p/s (nominal intensity, 7 TeV/c and $\tau = 0.2\,$h). It can be clearly seen that the loss rate for all integration times is below the specification. This still holds when the loss rate is linearly scaled to nominal intensity (dashed lines). Figure 15 shows that the lowest measured instantaneous life times of the high intensity runs are above the specified life time of $\tau = 0.2\,$h for all integration intervals. In addition figure 16 shows that the peak proton losses for the lowest two integration times are below the transient quench limit of the superconducting magnets (3.4×10^7 p at 7 TeV/c [2]).

Table 3 compares the 2009 predicted performance of the collimation system as presented in [17] and the resulting collimation related intensity limit with the measured performance 2010. Here it was assumed that the measured cleaning inefficiency is diluted over the length of one metre, i.e. $\eta_c = \frac{\eta_{meas}}{1\,\mathrm{m}}$. As the BLM responses on the same losses are different for a collimator and a superconducting magnet the measured cleaning inefficiency had to be corrected by a factor of 0.36. This factor was inferred from an aperture measurement experiment earlier. The assumed quench limits R_q were taken from [6]. The total intensity limit with the measured minimum life time for steady state losses was then calculated by changing equation (5) to

$$N_{tot}^{q} = \frac{\tau_{min} R_q}{\eta_{corr}} \cdot c_{blm} \cdot c_{fluka}. \qquad (7)$$

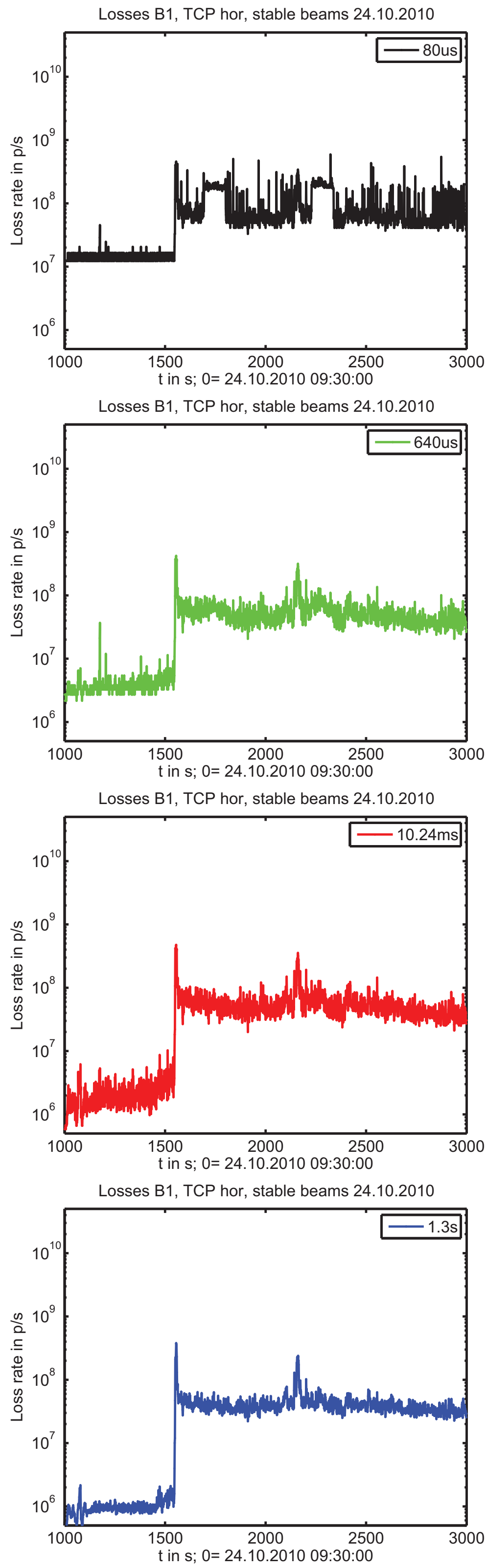

Figure 13: Loss rate at the horizontal primary collimator in the betatron cleaning insertion of beam 1 during 33 mins of a high luminosity LHC run. The different plots show the loss rates calculated from BLM signals with the different integration times: $80\,\mu$s, $640\,\mu$s, $10.24\,$ms and $1.3\,$s.

Table 3: Comparison of predicted and measured parameters for and the results of calculating the total intensity limit. For this analyses the high luminosity fill with the highest loss rate was used. This fill took place at the 26.10.2010 and had 368 bunches per beam with 150 ns bunch spacing.

	2009 prediction	2010 analysis	ratio
η_c [1/m]	2.16×10^{-4}	4×10^{-4}	1.9
BLM response	n.a.	0.36	-
η_{corr} [1/m]	2.16×10^{-4}	1.44×10^{-4}	0.66
τ_{min} [s]	500	4680	9.4
R_q [p/m/s] @3.5 TeV/c	2.4×10^7	-	-
R_q [p/m/s] @4 TeV/c	1.9×10^7	-	-
BLM factor	0.33	-	-
FLUKA factor	3.5	-	-
N^q_{tot} [p] @3.5 TeV/c	6.4×10^{13}	9.1×10^{14}	14.2
N^q_{tot} [p] @4 TeV/c	5.1×10^{13}	7.28×10^{14}	14.2

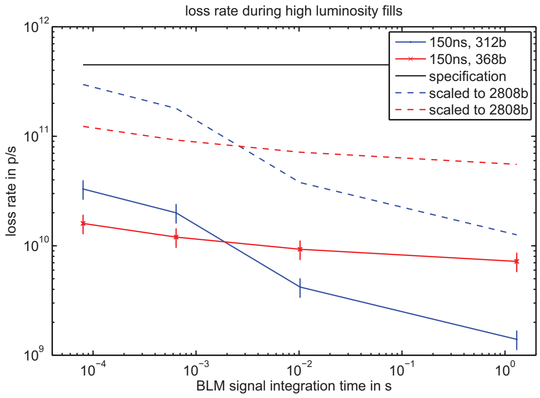

Figure 14: Highest instantaneous loss rates found in the high luminosity LHC runs with 312 and 368 bunches for different integration times of the BLM signals compared to the specified loss rate (4.5×10^{11} p/s at nominal intensity, 7 TeV/c and $\tau = 0.2$ h). The dashed lines show the linear scaling of the measured loss rates to the nominal number of bunches (2808).

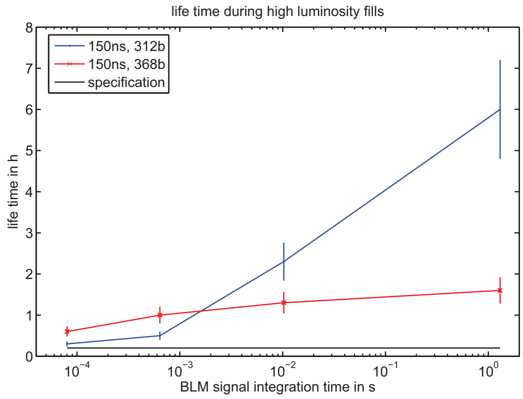

Figure 15: Lowest instantaneous life times found in the high luminosity LHC runs with 312 and 368 bunches for different integration times of the BLM signals compared to the specified life time (0.2 h at nominal intensity and 7 TeV/c).

The BLM factor c_{blm} reflects the fact that the dump limit of the BLMs is set to 1/3 of the quench limit of the superconducting magnets they should protect. The FLUKA factor c_{fluka} was introduced as a dilution factor for the assumed quench limit [17]. The calculation shows that in 2010 the total intensity limit exceeded the expectations from 2009 by a factor 14. This is mainly due to a life time which was significantly better than expected. Also the corrected cleaning inefficiency was slightly better, which could be explained by a lower influence of imperfections due to a good orbit stability. For 3.5 TeV/c this means that the intensity could be increased by a factor 22 from $\sim 4.2 \times 10^{13}$ p to $\sim 9.1 \times 10^{14}$ p, which would be above nominal intensity. At 4 TeV/c the total intensity would be limited to $\sim 7.28 \times 10^{14}$ p.

Losses due to instabilities

Two runs with high losses due to instabilities, which finally caused a beam dump, have been analyzed. Both runs had 108 bunches per beam with a bunch spacing of 50 ns. In the first the beam became unstable at the end of the so-called squeeze, when the beta functions in the interaction points (IPs) are reduced to collision values. The second fill showed high losses before the squeeze, when the transverse damper was turned off.

Figure 17 compares the highest instantaneous loss rates found during these two runs with the specified loss rate. In both cases the loss rates for all integration times were below the specifications. This does not hold any longer, if the loss rates are linearly scaled to nominal intensity. Figure 18 shows that the life time in both cases was significantly below the specifications, whereas the transient losses (see figure 19) were below the transient quench limit. If these were scaled linearly to nominal intensity the transient losses could get close to the quench limit.

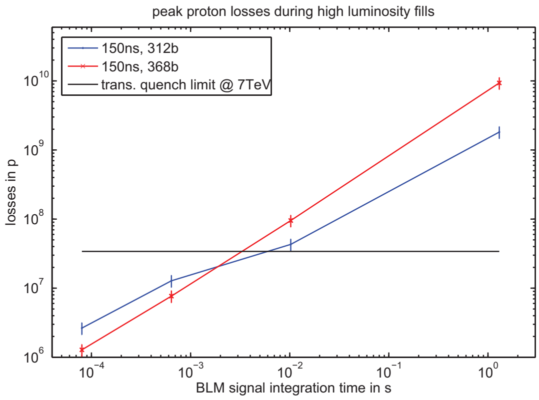

Figure 16: Peak losses found in the high luminosity LHC runs with 312 and 368 bunches for different integration times of the BLM signals compared to the transient quench limit of the superconducting magnets at 7 TeV/c: 3.4e7 p [2]. Note: losses that appear only in the two lowest integration times of the BLM signal, i.e. $80\,\mu$s and $640\,\mu$s, can be consideres as transient losses.

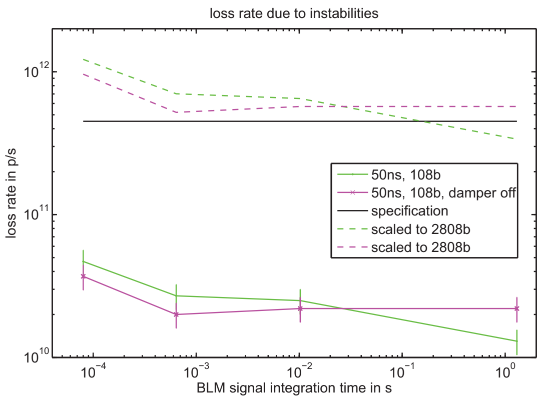

Figure 17: Highest instantaneous loss rates found in LHC runs with instabilities. The first fill with 108 bunches and 50 ns bunch spacing became instable at the end of he squeeze, the second due to turning of the tranverse damper. Different integration times of the BLM signals are compared to the specified loss rate (4.5×10^{11} p/s at nominal intensity, 7 TeV/c and $\tau = 0.2$ h). The dashed lines show the linear scaling of the measured loss rates to the nominal number of bunches (2808).

Applying equation (5) with the minimum instantaneous life time for steady state losses found in these two cases of $\tau_{min} = 468$ s gives a limit of the total intensity per beam at 3.5 TeV (4 TeV) of $N^q_{tot} = 9.1 \times 10^{13}$ p ($N^q_{tot} = 7.2 \times 10^{13}$ p), which is a factor ~ 3.3 (~ 4.2) below nominal intensity. This analysis shows that instabilities can cause a collimation indicated limitation of the achievable intensity in the LHC.

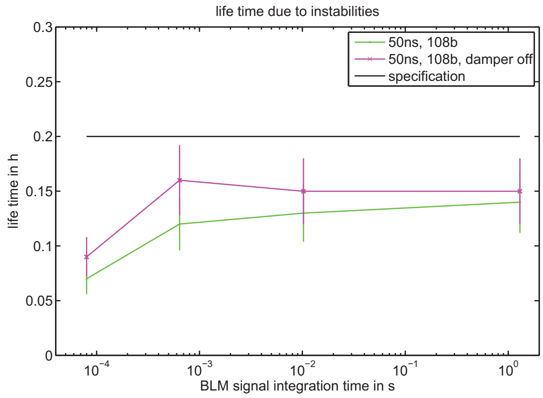

Figure 18: Lowest instantaneous life times found in LHC runs with instabilities. The first fill with 108 bunches and 50 ns bunch spacing became instable at the end of he squeeze, the second due to turning of the tranverse damper. Different integration times of the BLM signals are compared to the specified life time (0.2 h at nominal intensity and 7 TeV/c).

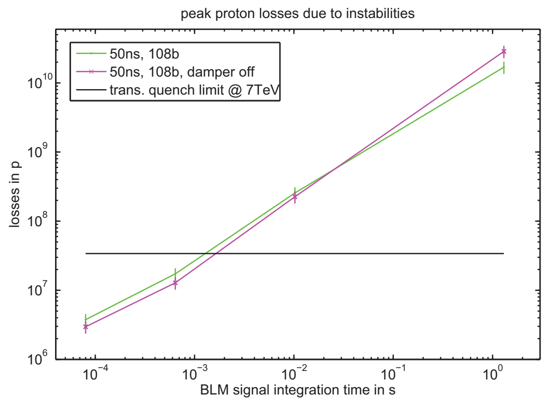

Figure 19: Peak losses found in LHC runs with instabilities. The first fill with 108 bunches and 50 ns bunch spacing became instable at the end of he squeeze, the second due to turning of the tranverse damper. Different integration times of the BLM signals are compared to the transient quench limit of the superconducting magnets at 7 TeV/c: 3.4e7 p [2]. Note: losses that appear only in the two lowest integration times of the BLM signal, i.e. $80\,\mu$s and $640\,\mu$s, can be consideres as transient losses.

Losses due to un-captured beam

Particles which are not captured correctly in the RF bucket, or moved out of it due to an RF failure, will get lost in the momentum cleaning insertion (IR3) as soon as the particle energy is ramped up from 450 GeV/c. In a run with 368 bunches 1.3×10^{12} un-captured protons were lost in beam 1 within 6 s at the beginning of the ramp. This was equivalent to about 2.8 % of the total beam intensity. Figure 20 shows the instantaneous loss rate compared to the specified loss rate. For all integration times this was

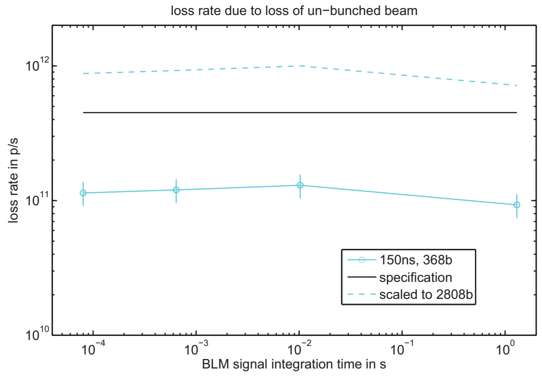

Figure 20: Highest instantaneous loss rates found during the loss of un-bunched beam at the beginning of the ramp on 27th of October 2010. Within about 6s 2.8% ($\sim 1.3 \times 10^{13}$ p) of beam 1 were lost in the momentum cleaning insertion (IR3). The fill had 368 bunches with 150 ns bunch spacing. Different integration times of the BLM signals are compared to the specified loss rate (4.5×10^{11} p/s at nominal intensity, 7 TeV/c and $\tau = 0.2$ h). The dashed lines show the linear scaling of the measured loss rates to the nominal number of bunches (2808).

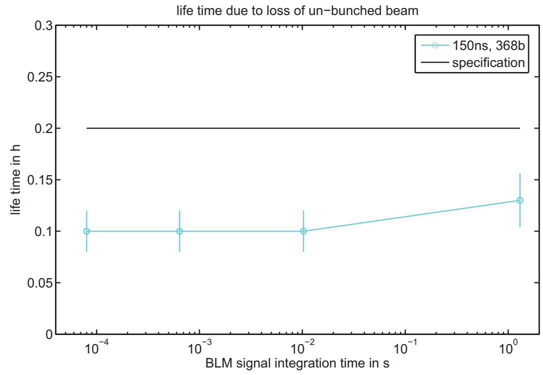

Figure 21: Lowest instantaneous life times found during the loss of un-bunched beam at the beginning of the ramp on 27th of October 2010. Within about 6s 2.8% ($\sim 1.3 \times 10^{13}$ p) of beam 1 were lost in the momentum cleaning insertion (IR3). The fill had 368 bunches with 150 ns bunch spacing. Different integration times of the BLM signals are compared to the specified life time (0.2 h at nominal intensity and 7 TeV/c).

below the specifications. Scaling the measured loss rate linearly to nominal intensity shows that this would exceed the specifications. Figure 21 depicts that the instantaneous life time stayed clearly below the specifications for all integration times. These two results indicate that losses due to un-captured beam could limit the total intensity in the LHC. As shown in figure 22 transient losses were far below the transient quench limit at 450 GeV/c. Scaling to nominal intensity this result still holds. The minimum instantaneous life time for steady state losses in this example was $\tau_{min} = 360$ s. Using this in equation (5) together with the quench limit at 450 GeV/c, $R_q = 7.0 \times 10^8 \frac{\mathrm{p}}{\mathrm{sm}}$, this results in a total intensity limit of $N_{tot}^q = 2.7 \times 10^{14}$ p, which is slightly below nominal intensity.

Note that for the above discussed intensity limits other possible limitations due to collimation like radiation to electronics (R2E) were not taken into account. It was also assumed that the stability of the beam would stay constant for higher beam intensities, which may not be true. It was not considered that the performance reach of the collimation system will be worse for higher particle momentum (cleaning inefficiency, lower margins at superconducting magnets, lower quench limits). On the other hand cleaning efficiency can be improved by using nominal collimation settings. With the orbit stability achieved in 2010 this is not possible. Finally it needs to be considered that the analysis is based on a limited number of fills.

CONCLUSION

The phase-I LHC collimation system delivered the expected collimation efficiency during the 2010 LHC operation. The impact of imperfections on cleaning was about a factor 2 smaller than predicted. This was mainly due to a better control of the orbit in the dispersion suppressor regions. The measured global cleaning inefficiency to the cold aperture was $\eta_g \sim 2.3 \times 10^{-4}$.

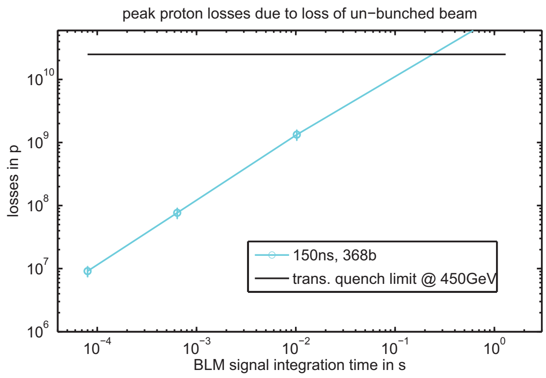

Figure 22: Peak losses found for the loss of un-bunched beam at the beginning of the ramp on 27th of October 2010. Within about 6s 2.8% ($\sim 1.3 \times 10^{13}$ p) of beam 1 were lost in the momentum cleaning insertion (IR3). The fill had 368 bunches with 150 ns bunch spacing. Different integration times of the BLM signals are compared to the transient quench limit of the superconducting magnets at 450 GeV/c: 2.5×10^{10} p [2]. Note: losses that appear only in the two lowest integration times of the BLM signal, i.e. 80 μs and 640 μs, can be consideres as transient losses.

The setup procedures of the collimation system have been refined and optimized. During each setup 15 to 20 minutes net beam time per collimator was needed. The validity of collimation setups has been around 5-6 months. After this time the radiation profile started to be non-conform. Assuming a 10 months running period in 2011 two full setups of the collimation system should be expected.

The instantaneous life time during high luminosity LHC runs in 2010 was found to be a factor 9 higher than specified. The intensity limits calculated from the measured life time was 9.1×10^{14} p (7.28×10^{14} p) at 3.5 TeV/c (4 TeV/c). This means that in terms of cleaning collimation should be ready for nominal intensity at 3.5 and 4 TeV/c. Note that other issues such as radiation to electronics (R2E) have not been considered here.

As seen in several runs 2010 instabilities can decrease the life time significantly. The collimation induced intensity limit with instabilities was found to be 9.1×10^{13} p (7.28×10^{13} p) at 3.5 TeV/c (4 TeV/c). As instabilities are possible for higher intensities and particle momenta these limitations need to be taken into account. Losses due to uncaptured beam, as experienced in the 2010, could limit the intensity to 2.7×10^{14} p, which is slightly below nominal. Note that these intensity limits are no hard limits, as they will cause at first beam dumps. The frequency of instability induced beam dumps could then decrease the performance of the LHC.

As expected cleaning with lead ions was much less efficient than for protons. The leakage into the superconducting dispersion suppressor magnets and the tertiary collimators was in the order of percents. The global cleaning inefficiency to the cold aperture was below $\eta_g = 1.86 \times 10^{-2}$.

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LHC INJECTION AND EXTRACTION LOSSES

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Abstract

Single pass losses at injection into LHC and extraction to the beam dump are distinguished regarding their origin. Potential mitigations as local shielding, injection gap cleaning or temporarily blinding the BLM system at injection are discussed. The limits for injecting higher intensities in 2011 due to losses above BLM thresholds together with the risk for quenching magnets are extrapolated from observed loss levels in 2010 operation.

OBSERVED LOSS LEVELS AT INJECTION

Injection is the main contributor in the turn-around time as shown in [1]. Beam loss levels close to the BLM dump thresholds can lead to significan delays in preparing the machine for stable beams. In Table 1 the main reasons for injection losses are listed. Collimators (TCDI) in the transfer lines TI 2 and TI 8 create particle showers which are detected by ring BLMs in the common parts of LHC and transfer line tunnels. These showers coming from the outside do not present any harm to LHC magnets since they are protected by the cryostats, however, a beam dump is triggered if the loss level exceeds the BLM thresholds. Monitors on the elements Q6, Q7, Q8 and the MSI are most affected. Another loss reason is uncaptured beam from both, the SPS and the LHC, which does not see the full MKI kick and therefore gets spread onto the upper (uncaptured beam SPS) or lower (uncaptured LHC beam) TDI jaws. Particle showers are created and detected mainly by the monitors of TCTVB, MQX, MBX, TCLI and the experiments ALICE and LHCb.

Table 1: List of injection losses by cause and main elements affected.

Loss reason	Loss position
TCDI cutting transv. beam tails	Loss shower on cold elements: Q6, Q7, Q8, MSI
Uncaptured beam SPS	TDI upper jaw with shower on: TCTVB, MX,MBX, TCLI
Uncaptured beam LHC	TDI lower jaw, TCTVB, MQX, MBX, TCLI
Overinjection	TDI lower jaw, TCTVB, MQX, MBX,...
MKI failure	TDI upper jaw,...

The lower TDI jaw is also used as a beam stopper when over-injecting a high-intensity bunch onto the low-intensity probe beam.

In case of a missing MKI kick the whole injected beam is dumped on the upper TDI jaw. Figures 1-4 show measured loss levels from bunch train injections with 8, 16, 24 and 48 bunches. In Fig. 1, a bad injection with 16 bunches (magenta curve) sticks out with 10% of the dump threshold at the MSIB and 6% at Q8 and Q5. The 24 bunch injection (yellow curve) gives 12% at the MBX and 3% at the MSIB. For B2, Fig. 2, losses from the TCDI shower

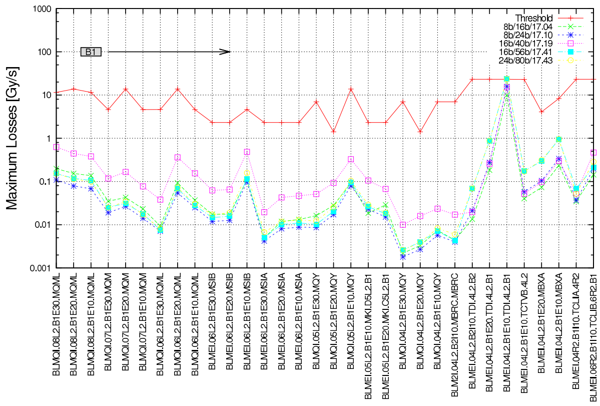

Figure 1: B1 injection losses with bunch train injections of 8, 16 and 24 bunches. 8b/16b/17.04 denotes 8 bunches injected at 17:04 with 16 bunches circulating. Data from 23rd, October 2010.

reach 5% of the dump threshold at Q7 and losses from the TDI shower 4% at MBX, otherwise the loss level is less than 1% . Figure 3 shows the loss level for the firs 48

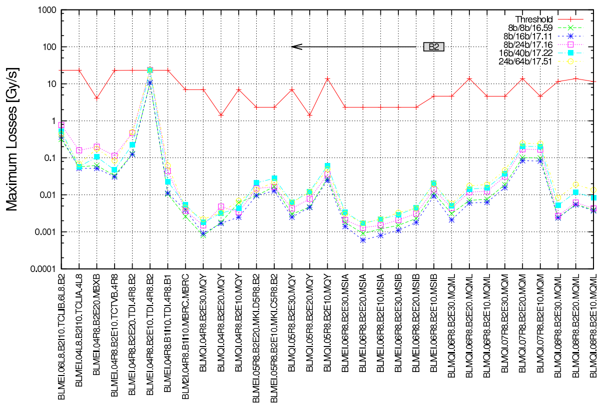

Figure 2: B2 injection losses with bunch train injections of 8, 16 and 24 bunches. Data from 23rd, October 2010.

bunch train injection. The loss peaks reach 23% at MSIB, 20% at MBX and 15% at Q8. These values have to be taken with caution though, since there was not much time spent in optimising beams or injection. For B2, Fig. 4, the loss level amounts to 24% at Q7, 8% at TCLIB and 5% at the MKI. Figure 5 shows the Post Mortem analysis of an

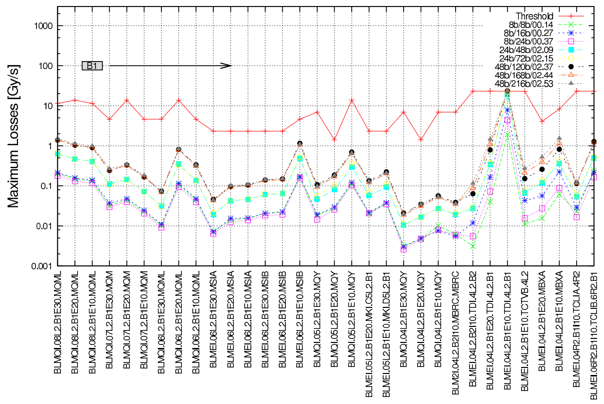

Figure 3: B1 injection losses with bunch train injections of 8, 24 and 48 bunches. There was not much time spent in optimising the injection. Data from 18$^{\mathrm{th}}$, November 2010 .

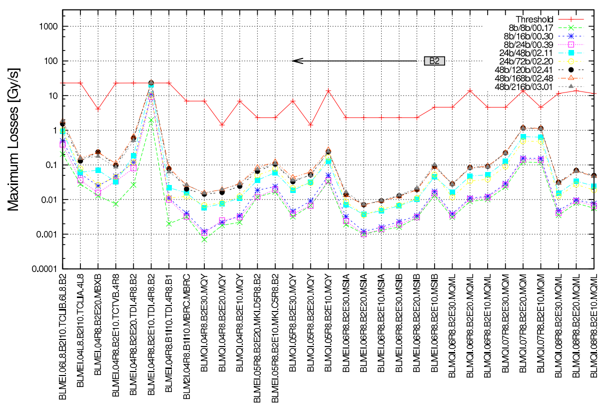

Figure 4: B2 injection losses with bunch train injections of 8, 24 and 48 bunches. There was not much time spent in optimising the injection. Data from 18$^{\mathrm{th}}$, November 2010

attempt to inject 32 bunches into the abort gap. The abort gap keeper prevented the MKI from f ring and thus, the train of 32 bunches was directly dumped on the upper TDI jaw in P2 which is designed to withstand a full SPS batch of 288 bunches with nominal intensity. ALICE is prepared for the full batch impacting the TDI and could conf rm their simulations with losses from TDI grazing tests.

EXPECTATIONS ON LOSS EVOLUTION

As injected beam intensity progression for 2011 are assumed 96 or 108 bunches for operation, possibly 144 bunches with 50 ns spacing for injection tests and maybe 25 ns bunch spacing injections for electron cloud studies. Another ingredient in the loss evolution is the intensity dependency of the uncaptured beam in the LHC. The present threshold of triggering the dump by BLMs has been measured on 30$^{\mathrm{th}}$, September 2010 and was found to be $1 \cdot 10^{10}$ protons per injection which corresponds to $3.3 \cdot 10^{6}$ protons per m [2]. The limit was originally assumed to be $2.6 \cdot 10^{8}$, thus the situation is expected to be worse by a factor 100 for the nominal bunch scheme.

Figure 5: Post mortem analysis of dumping 32 bunches on the upper TDI jaw in P2.

The shower from TCDIs is assumed to increase linearly with the intensity increase per injection. In Table 2 the loss levels shown in Figures 1-4 are summarised in percent of the BLM dump threshold. The values shown in *italic* are expectations for future loss levels. The losses for 48 bunch injections do not follow the trend which is due to not optimising these injections. How do these injection losses limit

Table 2: Measured losses in % of dump theshold for B1/B2 up to 48 bunches per train, expected loss levels for 96 and 144 bunches are shown in *italic*.

Loss type	**8b**	**16b**	**24b**	**48b**	***96b***	***144b***
TCDI shower	1/2	3/5	4/6	23/24	*< 50?*	*< 75?*
Uncapt. beam	4/2	12/3	12/5	20/8	*< 40?*	*< 60?*

the performance reach? MKI failure and overinjection need interlocking and a good procedure. Transverse losses coming from the TCDIs and detected by LHC BLMs will increase by roughly a factor 2 and should therefore not limit 2011 operation. The factor 6 intensity increase - when going to the nominal scheme - needs loss reduction. The situation is more severe for the uncaptured beam in the LHC. Already for 2011 operation injection cleaning is probably needed. The factor 100 loss increase for the full nominal injection scheme will demand several mitigation techniques which are presented in the following section.

MITIGATION TECHNIQUES

Following mitigation techniques are considered to overcome transverse losses from the TCDI collimators:

- Local shielding between TCDIs and LHC
- Beam scraping in the SPS
- Opening TCDIs (discussed in detail in [3])
- BLM sunglasses (temporal inhibit of BLM channels)

Losses due to uncaptured beam shall be counteracted by:

- Local shielding downstream of TDI
- Minimisation of capture losses
- Injection and abort gap cleaning
- Carefully monitoring beam quality in injectors (transverse beam size and shape, bunch length, satellites)
- BLM sunglasses

Local shielding of TCDI collimators

Three problematic TCDIs have been spotted, in TI 2 the vertical collimator TCDIV.29234 and the horizontal one TCDIH.29205 and in TI 8 the horizontal collimator TCDIH.87904. Figure 6 shows the shielding concept for TI2 based on results from FLUKA simulations and Fig. 7 shows the shielding blocks installed at the technical stop in the end of 2010.

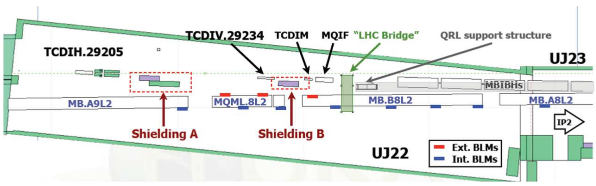

Figure 6: Shielding concept for TI 2 based on FLUKA simulations.

Figure 7: Shielding blocks installed in UJ22. On the right the incoming TI 2 line, upstream view.

Figure 8 illustrates the spatial constraints for shielding installations. From simulations the loss reduction by shielding is expected to be a factor 8 at TCDIV.29234, a factor 5 at TCDIH.29205 and a factor 4 at TCDIH.87904.

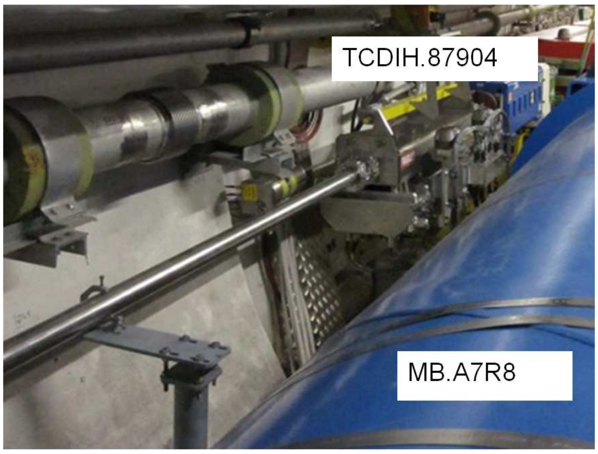

Figure 8: Limited space for shielding at TCDIH.87904.

Beam scraping in the SPS

Figures 9 and 10 show measurements of the transverse beam distribution in the transfer lines with blue lines indicating the collimator jaw position. The measurement without scraping in the SPS, Fig. 9, results in a beam interception of up to 2% of the total intensity. The number of particles lost on the TCDIs can be reduced using scraping

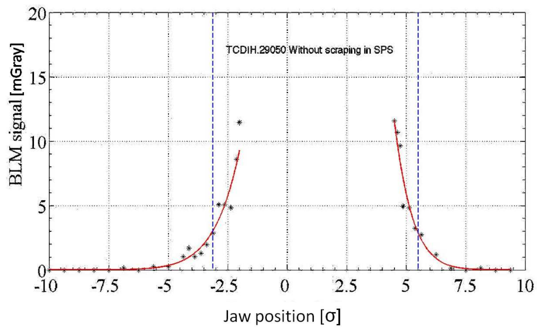

Figure 9: Transverse beam tails at TCDIH.29050 without scraping in the SPS, the blue lines indicate the position of the collimator jaws.

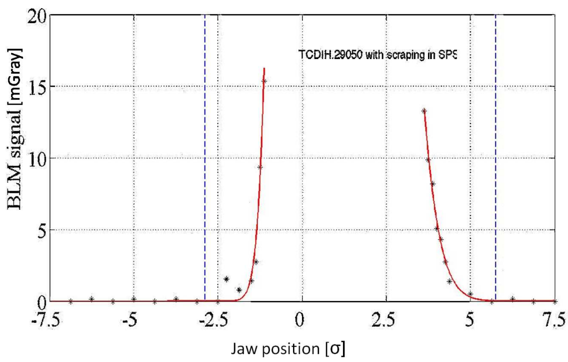

Figure 10: Transverse beam tails at TCDIH.29050 with scraping in the SPS, the blue lines indicate the position of the collimator jaws.

in the SPS by a factor ~ 1000, Fig. 10.

BLM sunglasses

Since the major part of the BLM loss levels described above are caused by particle showers from outside the cryostat, and thus not harmful to LHC magnets, it is considered to investigate possible changes of the BLM system itself. Adding complexity to the BLM system or its input to the interlock system has to be carefully evaluated regarding consequences to machine protection. The term "‘sunglasses"’ might allude to a signal attenuation but should be rather understood as a temporal inhibit of BLM channels. Following options are considered:

1. Update of all LHC BLMs with new functionality, but only BLMs in injection regions to receive triggers $\rightarrow$ **impact on all LHC BLMs**
2. Add/separate new BLM system with new functionality, keep all old monitors for acquisition (increase/disable thresholds at 450 GeV) $\rightarrow$ **additional new BLM system**
3. Rearrange/add new BLM system to enter a new BIC with masking capability, with masking of interlock signal triggered by pre-pulse $\rightarrow$ **additional new BIC system**
4. Reroute affected BLMs to BIC channel, and introduce a timing system triggered blank of the signal for these channels only $\rightarrow$ **best compromise, no changes to BLM or BIC systems (at FPGA levels)**

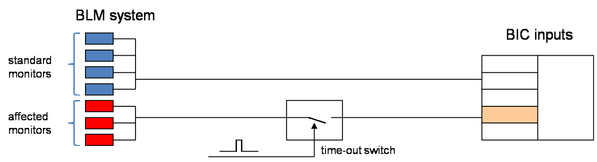

Figure 11: Sketch of option 4 for the BLM sunglasses with a time-out switch.

Local shielding downstream of TDI

Simulation show that a 2 m concrete block downstream of the TDI gives a loss reduction by a factor 3 for the triplet monitors while only a 30% reduction is reached for the TCTVB collimator. Here, either more sophisticated shielding or increasing the BLM threshold is required.

Minimisation of capture losses

It is not expected to improve the capture losses in the injectors. An RF voltage reduction as used for ions was found to create signif cant satellite population and it is not planned to be used for protons.

Injection gap cleaning

In analogon to abort gap cleaning it is foreseen to resonantly excite and thereby remove the unbunched particles in the injection kicker gap [4]. One method uses an excitation pulse after the last injected bunch train. This pulse together with the pulse from the abort gap cleaning conf nes the debunching particles and is therefore called *barrier method*. Here, the cleaning should be kept as long as possible while the injection part length is not important. Figure 12 shows results from measurements with abort and injection gap cleaning. For later injections the losses mea-

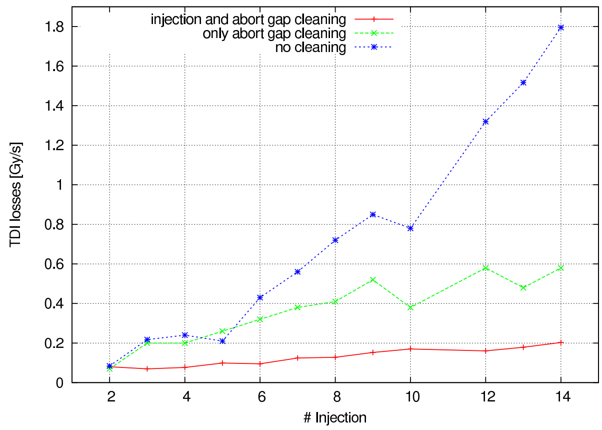

Figure 12: Reduction of losses at the TDI for a series of injections without cleaning (blue), with only abort gap cleaning (green) and with abort and injection gap cleaning (red).

sured on the TDI can be reduced by a factor 3 with abort gap cleaning only and a factor 9 with both cleaning pulses. Another method, called injection *gap* cleaning, uses a pulse located at the position of the next injected bunch train. For operational reasons this method will be used for commissioning in 2011.

Monitoring beam quality of injectors

In order to more sensitively detect satellites coming from the SPS, the according BQM thresholds have been tightened from 20% to 3-4% where 100% are given by the bunch with the highest wall current monitor signal. The diagnostics of the 800 MHz RF system in the SPS and the 80 MHz system in the PS is being improved [5]. Diagnostics is also installed to monitor the SPS scraping. At SPS extraction and LHC injection it is foreseen to install fast BLMs to distinguish between uncaptured beam coming from the SPS or LHC.

EXTRACTION LOSSES

The most critical situation extractionwise are asynchronous dumps with the risk to quench Q4 and Q5 in P6. Debunched beam dumps at 450 GeV show low losses with a factor 3 above the dump threshold for Q4. These were carefully tested with different bump heights and frequency offsets. Figure 13 shows the loss pattern in P6 for a dump after 90 s debunching time with collisions in P1 and P5 at 3.5 TeV. The beam was intentionally steered away from the TCDQ to simulate the worst case scenario orbitwise. The losses on Q4 and Q5 are a factor 180 and 30, respectively, above the BLM dump threshold. These losses are mainly showers from TCDQ which does not allow to draw conclusions on the quench limit. The BLM thresholds are set to 1/3 of the assumed quench limit. From simulations a loss level of 50 % of the dump threshold is expected on Q4 and Q5. Figure 14 shows a similar loss pattern for a debunched

Figure 13: Post mortem analysis of debunched beam dump with collision settings.

dump (90 s) with end of ramp settings, energy 3.5 TeV, crossing angle of 170 μrad, β^* of 11.0/10.0 m (P1/P5). The losses are a factor 230 and 40 above the dump threshold for Q4 and Q5, also losses on the dump septum MSD. The leakage to the TCT in P5 for all dumps is $\sim 1 \cdot 10^{-3}$.

Figure 14: Post mortem analysis of debunched beam dump with end of ramp settings.

INJECTION COMMISSIONING

The following time line is assumed to commission the injection systems in 2011:

- Injection set-up
  - **2 shifts**
- First injection protection set-up with validation
  - **1 shift** for TCDI set-up
  - **0.5 shifts** for TDI/TCLI set-up
  - **1 shift** for TCDI validation checks
  - **0.5 shifts** for MKI failure validation checks
- Protection Maintainence
  - **1 shift every 2-4 weeks** for TL steering or TCDI re-centering after trajectory change or increased TL loss levels
- Injection cleaning to be operational
  - **2-3 shifts**
- Analysis of regular operational data

CONCLUSION

The foreseen increase of a factor 2 in number of bunches per injection for 2011 operation looks feasible regarding injection losses. Injection tests with higher intensities (144 bunches per injection) might need mitigation of TL shower and capture losses. Extraction losses are dominated by the shower from TCDQ and thus do not allow to draw conclusions on the quench limit. Loss mitigation at injection is necessary to go beyond the operational intensity scope. Techniques already deployed are scraping in the SPS and partially shielding in TI 2. There is heavier shielding installed in TI 2 which has not seen beam yet and further shielding planned for TI 8 and the TDIs in P2 and P8. There is more diagnostics being added in the injectors to monitor the beam quality. Injection gap cleaning needs to be commissioned to be operational in 2011 and BLM sunglasses are in the design phase.

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LOSSES AWAY FROM COLLIMATORS: STATISTICS AND EXTRAPOLATION

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Abstract

This paper focuses on beam losses in the LHC arcs. The main task of the approximately 2200 (out of a total of about 3600 ring monitors) is quench prevention. The arcs are generally very well protected by the collimators. The aim of this work is to search for possible holes in the arc protection, and to present the impact of short (single turn to several turn) and/or highly localized losses on the arcs. The paper first extensively addresses millisecond time scale losses ('UFO' type losses). A detailed analysis of these events is presented and the changes in the threshold settings for cold magnets are discussed and summarized. Subsequently, other losses in the arcs are studied with the help of betatron and momentum cleaning collimator loss maps and data from periodic scraping of the beam halo. The impact of few-turn-losses is briefly discussed. To conclude, the hardware interventions and intervention times for the 2010 run are summarized and the requirements for BLM system tests at the 2011 start-up are outlined.

MILLISECOND TIME SCALE LOSSES (UFOS)

Ten beam dumps due to fast (ms scale) beam losses (less than 1% of beam intensity) have been observed. They have been called UFOs (Unidentified Falling Objects). The current hypothesis is that some sort of 'dust' particle intercepts the beam. None of these events lead to a magnet quench. As a consequence, cold magnet thresholds have been increased by a factor of three on 01 October 2010 and by a factor of five on 26 October 2010—both with respect to the original applied thresholds, i. e. 0.3 times the 'best to our knowledge' quench level—by changing the monitor factor (MF) from 0.1 to 0.3 and 0.5. With the thresholds after the last MF increase, none of the UFOs would have dumped the beam. For the start-up of 2011 the cold magnet thresholds are adapted empirically (based on quench tests, wire scanner tests, 2010 signals and UFO signals). In the millisecond range they are set similar to the thresholds at the end of 2010, above all 2010 measured UFO losses. The losses are always detected by more than six local monitors, at least three of them getting close to (or above) the abort threshold (in the 2.5 ms integration window), confirming the redundancy in the system. Furthermore, the losses from these events are seen at the aperture limits (collimation regions). Figure 1 shows the local longitudinal pattern of one of these events and the signal for the different integration times for the monitor with the highest loss, compared to the applied thresholds. Comparison with loss patterns during a wire scan confirms the similarity in shape and timescale of the loss patterns. Additional BLMs at aperture limits with a bunch-to-bunch resolution have been installed, using diamond detectors and ACEMs (Aluminum Cathode Electron Multiplier). The BLM logging data were scanned for events with the same signature, which did not trigger a beam abort (sub-threshold UFOs). The conditions for the scan were: Firstly a signal in a TCP BLM above $6 \cdot 10^{-4}$ Gy/s in the 2.5 ms integration interval; secondly three local BLMs (within 40 m distance to each other), which all have a signal above $6 \cdot 10^{-4}$ Gy/s in the 2.5 ms integration interval; and thirdly a calculated (from the signals of all integration times) loss duration in the ms range.

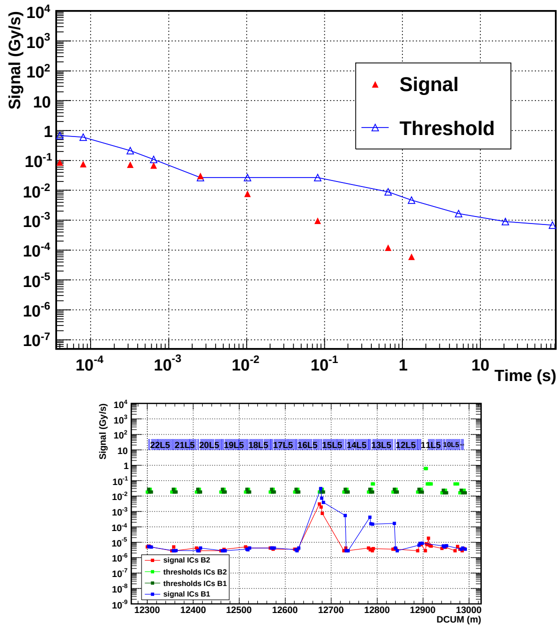

Figure 1: Longitudinal pattern of a fast loss event (top) and signal in the different integration times for the monitor with the highest loss (bottom). The beam abort was triggered on the 2.5 ms integration time.

During approximately 380 hours of stable proton beams at 3.5 TeV, 111 UFOs were identified, most of them far below the BLM beam abort threshold. The rate of UFOs was found to increase linearly with the number of bunches in the machine at a rate of $(1.35 \pm 0.17) \cdot 10^{-3}$ UFOs per bunch per hour per beam (see Figure 2). For 2000 bunches in the machine this leads to about 5.2 UFOs per hour. As the (high end of) the distribution of the magnitude of the UFO induced signal in the BLMs is poorly defined by the current statistics, no estimate can be given on what percentage will be above BLM threshold.

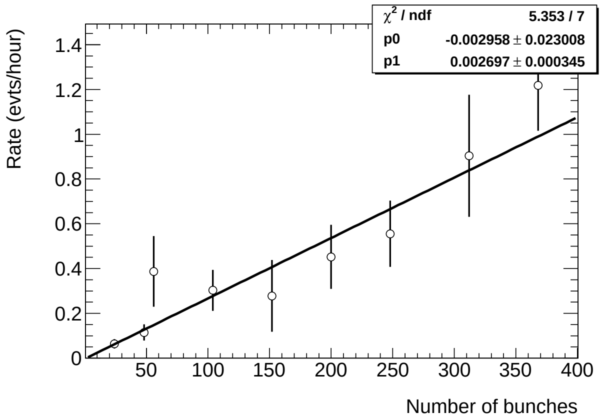

Figure 2: UFO rate (for both beams) as a function of the number of bunches (per beam)

At 450 GeV one sub-threshold UFO was detected over 88 hours of beam with mostly very few bunches in the machine. To combine measurement periods with different number of bunches the assumption is made that, at 450 GeV too, the number of UFOs is proportional to the number of bunches. The measured rate of UFOs per bunch per hour per beam is $(7.9 \pm 7.9) \cdot 10^{-5}$ at 450 GeV.

Table 1: UFO rates (measured vs. scaled) at injection and 3.5 TeV

Beam energy	**UFOs per bunch per hour per beam**
3.5 TeV, measured	$(1.35 \pm 0.17) \cdot 10^{-3}$
scaled down to 450 GeV	$(2.4 \pm 1.7) \cdot 10^{-5}$
450 GeV, measured	$(7.9 \pm 7.9) \cdot 10^{-5}$

As can be seen in Table 1, the measured rate of number of UFOs per bunch per hour per beam is significantly lower at 450 GeV. To be able to compare these numbers, however, it has to be taken into account that a particle intercepting a 450 GeV beam gives a lower signal in the BLMs than the same object interception a 3.5 TeV beam. The size of this effect can be measured with the help of the wire-scanners. There, a quadratic dependence of the BLM signal on the beam energy was found. The ratio between the signals at 3.5 TeV and 450 GeV is about 32. Scaling the BLM signals of UFOs at 3.5 TeV down with this factor, only two UFO would have passed the BLM detection limit from above (taking into account that three BLMs above detection threshold are required, and the third highest BLM is typically a factor of five lower than the highest BLM). The measured number of UFOs per bunch per hour per beam at 450 GeV is consistent with the scaled-down observation at 3.5 TeV.

No clear dependency of the average UFO signal on the beam intensity has been observed while the loss duration has been found to decrease with intensity (Figure 3).

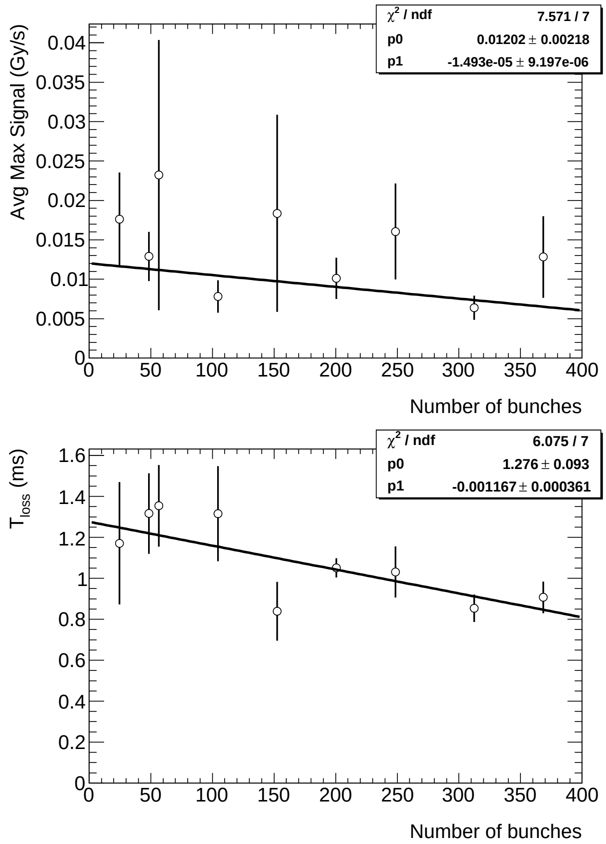

Figure 3: Average maximum UFO signal (top) and loss duration (bottom) as function of the number of bunches

The UFOs are not equally distributed along the ring. Hot spots and cold regions can be seen in Figure 4. Statistically significant hot spots are the injection kicker MKI right of IP8 (7 UFOs) and half-cells 30–31 right of IP7 (6 UFOs). The probability of measuring six UFOs within any of the 270 100 m bins is 0.13%. The probability to have three or more sections without UFO that are longer than 1400 m has been simulated [1] and calculated to less than $4 \cdot 10^{-3}$. There are three sections with lengths between 1400 m and 1700 m without any UFO. These cold regions are right of IP4, left of IP6, and left of IP7.

In a further analysis of 155 hours of ion beams no UFOs were found.

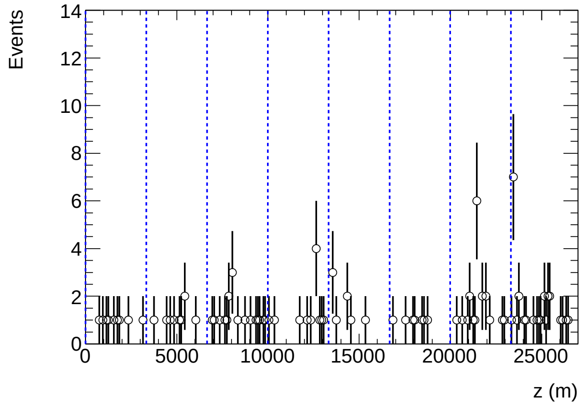

Figure 4: UFO events in 100 m bins along the LHC ring

OTHER LOSSES IN THE ARCS

Collimation Loss Maps

Leakage (signal in the arc BLM divided by the signal in the primary collimator, TCP) from collimators into the arc was analyzed with the help of betatron and momentum cleaning collimator loss maps at 3.5 TeV, for proton and ion beams. The results are compiled in Table 2. The proton leakage rate is very low ($3 \cdot 10^{-4}$ for momentum cleaning and $2 \cdot 10^{-5}$ for betatron cleaning respectively). An ion leakage rate of $2 \cdot 10^{-2}$ was measured. Preliminary comparisons of loss maps with simulations show a good agreement of magnitude and certain positions for beam 2, while for beam 1 hardly any losses are seen in the simulations.

Table 2: Collimation leakage into the arcs for 3.5 TeV protons and ions

Test data		Collimation	Detection limit	Maximum measured
Loss maps	p	betatron	$> 7 \cdot 10^{-6}$	$\approx 2 \cdot 10^{-5}$
		momentum	$> 3 \cdot 10^{-6}$	$\approx 3 \cdot 10^{-4}$
	Pb	betatron	$> 2 \cdot 10^{-5}$	$\approx 2 \cdot 10^{-2}$
		momentum	$> 4 \cdot 10^{-5}$	$\approx 2 \cdot 10^{-2}$
Periodic halo scraping	p	betatron	$> 3 \cdot 10^{-5}$	none
		momentum	$> 1 \cdot 10^{-5}$	$\approx 4 \cdot 10^{-3}$

Halo Scraping

Leakage out of the collimation region was further studied by using data from periodic scraping of the beam halo with the primary collimator. This leads to a modulated BLM signal on the TCP and at 'leakage' locations which can be identified using a Fourier transform. Figure 5 shows the leakage for ion betatron scraping for all LHC monitors (including the collimator regions). For ions, the sensitivity of this method is similar to the procedure using loss maps. It identifies, however, only about half of the monitors with a few additional ones. The observed leakage rate is about five times smaller than in the loss map method.

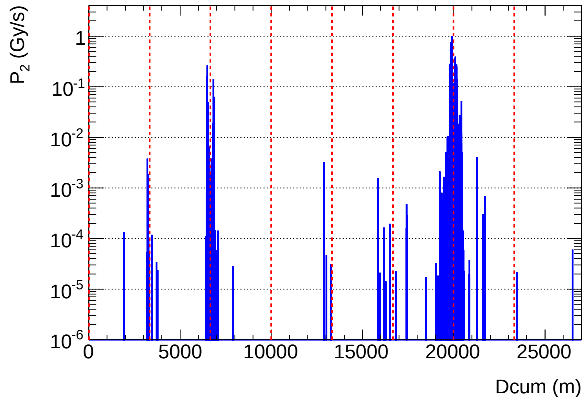

Figure 5: Leakage for ion betatron scraping for all LHC monitors (including the collimator regions)

The sensitivity for proton beams was significantly lower, no leakage into arc monitors could be identified. The slower TCP movement for ion beams (every 8 seconds) compared to the proton beam (every 3 seconds) yields better separated peaks in the Fourier transform and thus a higher sensitivity. The results are summarized in Table 2.

The data from halo scraping of the proton beam was also analyzed for luminosity induced losses, of which none where found in the arcs.

Few Turn Losses After Injection

Two loss events have been analyzed to determine whether they could be potentially dangerous to arc magnets. A three-turn loss of the proton beam on 10 December 2009 lead to a small signal in only one monitor ($1.8 \cdot 10^{12}$ Gy/s in 40 μs integration time), which was probably noise related. Even if not attributed to noise, the signal, if scaled to nominal injection intensity, corresponds to less than 20 % of the damage level.

A loss of the ion beam on 15 November 2010, which occurred 10–20 seconds after injection was due wrong beam chromaticity. It turned out to be a 2–3 seconds loss ($9 \cdot 10^{11}$ Gy/s in 1.3 s integration time). It was not fast enough to cause a problem for the magnets.

COLD MAGNET THRESHOLDS FOR 2011 START-UP

For the 2011 start-up the cold magnet thresholds are changed empirically based on 2010 measurements and quench tests. Table 3 compiles their typical evolution from the 2010 start-up to the 2010 end-of-run and to the 2011-start-up.

During the 2010 run the thresholds have already been raised via the monitor factors to avoid dumping on UFOs. Still, this has not lead to any magnet quenches. Therefore,

Table 3: Typical evolution of the cold magnet thresholds over time; the applied thresholds are master thresholds × monitor factor

Integration time	Date	Monitor factor	Change factor with respect to 2010 start-up Master threshold	Applied thresholds
40–80 μs	2010 start-up	0.1	1	1
	2010 end-of-run	0.5	1	5
	2011 start-up	0.1	3	3
0.3–2.5 ms	2010 start-up	0.1	1	1
	2010 end-of-run	0.5	1	5
	2011 start-up	0.1	5	5
10 ms	2010 start-up	0.1	1	1
	2010 end-of-run	0.5	1	5
	2011 start-up	0.1	1	1
80 ms–84 s	2010 start-up	0.1	1	1
	2010 end-of-run	0.5	1	5
	2011 start-up	0.1	1 (triplets) 0.33 (others)	1 (triplets) 0.33 (others)

this increase has been kept in the applied thresholds for the millisecond range integration intervals, which are the only ones sensitive to UFOs. Similarly, for microsecond range integration intervals the applied thresholds have been raised to accommodate for losses measured during the high luminosity proton runs. For the long integration intervals, preliminary results of the quench tests from 2010 showed that already the 2010 start-up thresholds were a factor of 2–3 to high. Hence, these applied thresholds have been lowered with the exception of the triplet magnets (to accommodate for luminosity losses). As the monitor factors have now been consistently lowered to 0.1 again, they allow for operational increases of up to a factor of ten.

SYSTEM PERFORMANCE

Hardware Interventions and Intervention Times

Table 4 summarizes the hardware interventions of February to December 2010. Most of the interventions were prompted by the onset of system degradation detected by regular offline checks. Hence, the component was replaced before malfunctioning. Some interventions became necessary because a failure was detected by one of the automatic internal system tests, preventing beam injection. Interventions mostly took place during scheduled technical stops or in the shadow of other interventions. The availability of the LHC was not seriously compromised by BLM system failures and repairs.

With respect to the intervention times, no changes are expected in 2011. Changes of monitor factors take approximately half an hour and master threshold changes take about one hour. For hardware interventions approximately one hour is required (plus the time for tunnel access, if necessary).

System Tests 2011

Before releasing the new firmware for the 2011 start-up it is tested on the vertical slice test system. Tests cover, among others, linearity, response to predefined patterns of input signals and tests of the XPOC and PM buffers. The exhaustive threshold triggering test of the ring monitors, covering every channel, every threshold and selected energy levels, will take about six days without beam. The system tests with pilot beams will need about six hours of beam time. They consist of a global test (injecting pilot beams, de-bunching them and initiating a beam dump) and of threshold triggering tests, for which one collimator jaw of a TCP is closed and pilot beams are injected a few times. As in 2010, the signal reception and the system status will be assessed continuously during the run.

CONCLUDING REMARKS

Until today the machine protection by the BLM system has been fully reliable. No avoidable quench occurred. There is no evidence of a single beam loss event having been missed. Hardware issues never caused a degradation of the reliability. The number of false beam aborts due to hardware failures are as expected and within requirements. Noise events never caused beam aborts. The initial thresholds (even though set conservatively) proved mostly adequate 2010 operation. No big deviation has been detected between the protection thresholds and the magnet quench levels. Losses were always seen by several local monitors and at the aperture limits, showing a certain protection redundancy.

This paper has summarized the analysis concerning losses in the arcs. It revealed that the arcs have been well protected at all times. The study on millisecond loss events (UFOs) showed that such events are frequent. Their rate increases with the beam intensity. The induced signals are

Table 4: Hardware interventions due to channel degradation or failure since february 2010

Element	**Details**	**Number**	**Out of total installed**
IC	bad soldering	12	3600
tunnel electronics	noisy analogue component (CFC)	7	359
tunnel electronics	bad soldering	2	720
tunnel electronics	low power optical transmitter (GOH)	9	1500
tunnel electronics	damaged connector	1	1500
surface electronics	weak optical receiver	12	1500
surface electronics	failed SRAM	2	350
VME64x Crate	failed CPU RIO3	3	25
VME64x Crate	failed power supply	1	25

mostly below the BLM thresholds. During the 2010 run the thresholds have already been raised via the monitor factors. Still, this has not lead to any magnet quenches. Therefore the shape of the master thresholds was changed for the 2011 start-up based on the 2010 measurements .

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BEAM LOSSES AND LIMITING LOCATIONS

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Abstract

About 4000 Beam Loss Monitors (BLMs) are installed along the LHC ring to detect critical beam losses which could quench the superconducting magnets or damage the components of the accelerator. In 2009 and 2010 the LHC BLM system detected all critical beam losses, so that no damage or unscheduled quench occurred. However a further fine-tuning of the beam abort thresholds is needed, especially for the high luminosity and high beam intensity runs planned for 2011. Possible sources of an increased ratio of beam loss to abort threshold will be addressed for the upcoming 2011 run. It will be verified whether the specified beam loss rates can be achieved in 2011, at what locations there are possible limiting thresholds and to what extent an increase of the thresholds at specific elements might be needed. In a second step the locations with the highest beam loss rates will be determined using the integrated dose as a function of integrated luminosity. This is useful in order to define the expected increase in dose for the 2011 operation. A special focus will be given on beam losses at and around collimators.

POSSIBLE CRITICAL BLM BEAM ABORT THRESHOLDS AT 3.5 TEV

The identification of elements with possible critical beam abort thresholds for the upcoming 2011 run has been performed using the ratios of the maximum measured beam loss to the beam abort threshold for five high luminosity proton physics fills and five high luminosity ion physics fills.

Introduction

The scan was done for all monitors being connected to the Beam Interlock System (BIS) for nine different integration time windows: for the running sums (RS) RS01 up to RS09, i.e. for integration time windows ranging from 40 µs to 1.3 s. The BLM system is using twelve different RS in total; however the loss data from RS10 and RS11 are not logged in the LHC Measurement and LHC Logging databases (DBs). An overview of the different RS and their integration time window is given in table 1.

The monitors not being connected to the BIS are not taken into account in this analysis since they cannot initiate a beam dump. It is not planned to increase or decrease the number of BLMs being connected to BIS for the 2011 run and therefore this analysis should give a reasonable overview of the monitors having a threshold for a specific running sum (or several running sums) that should be re-considered.

In case the ratio of the maximum measured loss to the threshold:

$$r_{l/t} = \frac{Max(Beam\ loss)\,|_{start\ of\ fill}^{end\ of\ fill}}{Applied\ Threshold\ (E = 3.5\ TeV)}$$

is $r_{l/t} \geq 0.1$, the monitor is considered having a threshold possibly too low for the 2011 run, due to the fact that beam losses are increasing with the number of bunches per beam and with luminosity. A margin of a factor of 10 between a maximum beam loss and the applied beam dump threshold is considered to be sufficient for the operation in 2011, since the product of number of bunches per beam and the luminosity will be increased compared to the settings in 2010.

The thresholds are decreasing with beam energy; therefore the thresholds for the beam energy of 3.5 TeV were the lowest being loaded to the BLM system in 2010, since this was the highest beam energy in 2010. The scan concerns only the thresholds at 3.5 TeV since it will most probably be the beam energy chosen for the 2011 run. In case the beam energy will be higher than 3.5 TeV in 2011, even lower thresholds have to be considered.

Analysis method

Two essential beam operation periods were selected during which the beam energy was at 3.5 TeV: the time before the stable beams condition was declared, usually with a duration of around 50 minutes. This period includes the beam modes ‘flattop’, ‘squeeze’ and ‘adjust’. The second operation period being investigated is the period during stable beams, usually with duration of 3 - 12 hours. The start and end times for the two main periods at 3.5 TeV were defined using the following three different timestamps:

- the beam presence flag for both beams (defining the time during which there was beam in the machine or not),
- the loaded BLM threshold settings at the beam energy of 3.5 TeV (defining the 3.5 TeV operational period)
- the stable beam mode flag (defining the stable beam operational period)

The start time for the first period was defined using the BLM threshold settings at 3.5 TeV and the end time was defined using the start time of stable beams. The start time of the second period was defined using the start time of stable beams and the end time was defined using the BLM thresholds settings at 3.5 TeV and the beam presence flag, where the end time taken at 10 -20 s before the BLM thresholds at 3.5 TeV changed or before the beam presence flag changed. The reason is that one has to avoid misleading beam dump losses in this analysis, since the focus is given on thresholds and losses at 3.5 TeV.

The beam presence flag for both beams was used in order to bypass the problem of a not yet automated timing of the stable beams mode flag, that is set manually by the machine operators at the moment (while the switch of the beam presence flag is triggered by hardware, i.e. by beam current transformers). The BLM threshold settings are changed according to the beam energy which is transmitted to the BLM electronics through the Safe Machine Parameters (SMP). The combination of the three flags originating from different sources assures a proper timestamp selection for the two main time periods at 3.5 TeV.

Table 1: An overview of the different integration time windows as used by the BLM system is presented in this table.

Running Sum	Integration time window	Logging of BLM loss data
RS01	40 µs	Yes
RS02	80 µs	Yes
RS03	320 µs	Yes
RS04	640 µs	Yes
RS05	2.56 ms	Yes
RS06	10.24 ms	Yes
RS07	81.92 ms	Yes
RS08	655.36 ms	Yes
RS09	1.31 s	Yes
RS10	5.24 s	No
RS11	20.97 s	No
RS12	83.89 s	Yes

Several BLM thresholds changes for specific monitors were applied during the operation in 2010, some of them concerning the LSA MASTER Thresholds tables and some of them concerning the monitor factor only. The main changes for the LSA Master Tables are summarized in the next chapter. For each physics fill being analysed the actual applied thresholds for each monitor and each running sum were downloaded from the LHC Logging database specifically, in order to avoid an unrecognized threshold change as it would have been the case when assuming fixed thresholds for all monitors for the fills analysed.

To give the most reasonable indication of possibly low thresholds at specific elements for the 2011 operation, the proton (and ion) fills with the highest number of bunches per beam in 2010, i.e. 368b/beam (121b/beam for ions) and the highest integrated luminosity during the stable beam condition have been selected for this analysis, i.e. proton fill numbers 1440, 1443, 1444, 1450 and 1453 (1520, 1521, 1522, 1525 and 1526 for ions). The same bunch spacing of 150 ns (500 ns for ions) and the same filling scheme was applied for these fills.

Results: possibly critical dump thresholds

The ratio of maximum loss to beam dump threshold $r_{l/t}$ for each monitor connected to BIS as measured during the proton fills 1440, 1443, 1444, 1450, 1453 for RS01 - RS09 for the beam energy of 3.5 TeV during the stable beams period is shown in fig.1. Note that there are in total ~ 3×10^5 values given in fig. 1 which were calculated out of a dataset of ~ 3×10^8 values. The same data are presented in fig. 2 but as a scatter plot, i.e. the maximum losses are plotted versus the corresponding applied thresholds for each monitor. In such a plot it is possible to recognize whether a high ratio $r_{l/t}$ is originating from high beam losses or from low thresholds (or from the combination of the two).

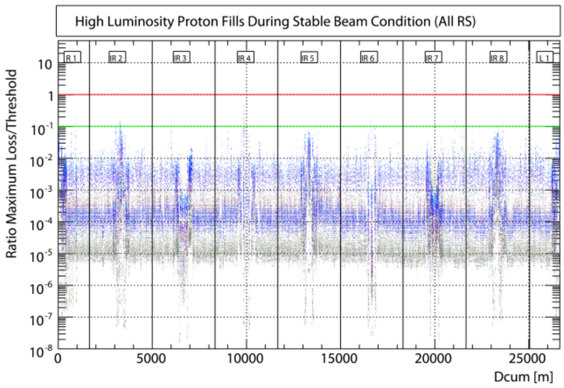

Figure 1: Shown is the ratio of the maximum measured loss to threshold $r_{l/t}$ for RS01 - RS09 for each monitor as measured during the fills 1440, 1443, 1444, 1450 and 1453 for the beam energy of 3.5 TeV during the stable beams period. The monitors are sorted by their dcum [m] and the different IR's 1 - 8 are indicated with a black line. The ratio $r_{l/t} = 0.1$ is indicated in green and $r_{l/t} = 1.0$ in red.

Fig. 3 and 4 show the results of this scan for the period where the beam energy was 3.5 TeV, but before the stable beam condition was declared. A summary of the statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the analyzed proton and ion fills is given in tables 2 - 5. Statistically significant means that the ratio $r_{l/t} \geq 0.1$ for a specific monitor was observed at least during two fills out of the five protons and ion physics fills.

Statistically significant monitors were exceeding $r_{l/t} \geq 0.1$ only in the LSS for both, proton and ion fills. The following monitors fulfil $r_{l/t} \geq 0.1$ during the five selected proton fills: five triplet monitors in 01L2, 02L2 and 03L2, one monitor in 04L6 (TCDSA) and one monitor in 04R6 (TCDQA) (during the stable beam period). During the period before stable beam was declared the following

monitors were observed having a ratio $r_{l/t} \geq 0.1$: one monitor in 04R8 (MQY), one monitor in 07R8 (MQM) and one monitor in 04R8 being installed next to the TCTH collimator.
Note that the triplet monitors are exceeding $r_{l/t} \geq 0.1$ only for RS01.

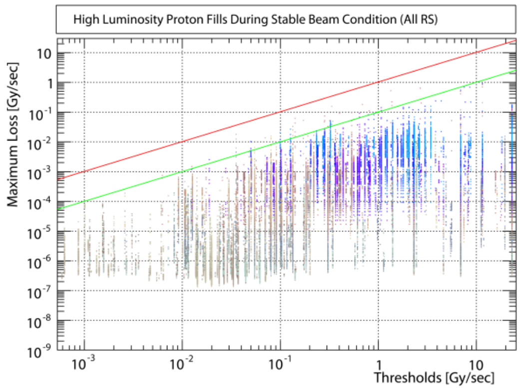

Figure 2: Shown is the maximum measured loss versus applied threshold in Gy/s for RS01- RS09 for each monitor as measured during the fills 1440, 1443, 1444, 1450 and 1453 for the beam energy of 3.5 TeV during the stable beams period. The ratio $r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red.

In total three out of the ten monitors mentioned have a RC signal reduction filter installed (so called filter monitors). For more details on RC signal reduction filters see next chapter where a summary about the "Modification of monitors in the injection and dump lines" is given. The TCDSA and TCDQA monitors have a filter installed with R = 150 kΩ, C = 47 nF and the MQM monitor with R = 150 kΩ, C = 2.2 nF. As it can be seen in fig.5 the applied thresholds for the TCDSA monitor are not dependent on the different integration time windows. The signal is reduced by a factor of 180 (for RS01) due to the installed filter, i.e. the measured loss without a filter would have been 180 times higher than shown in fig.5.

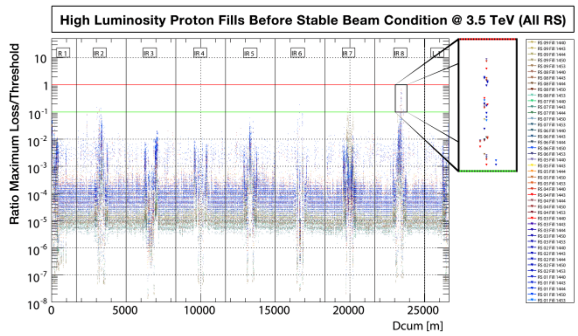

Figure 3: Shown is the ratio of the maximum measured loss to threshold $r_{l/t}$ for each monitor as measured during the proton fills 1440, 1443, 1444, 1450 and 1453 for RS01 - RS09 for the beam energy of 3.5 TeV before the stable beams period. The monitors are sorted by their dcum [m] and the different IR's 1 - 8 are indicated with a black line. The ratio $r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red. Higher ratios, i.e. $r_{l/t} \geq 0.1$ for IR 8 are shown as a zoomed plot on the right side.

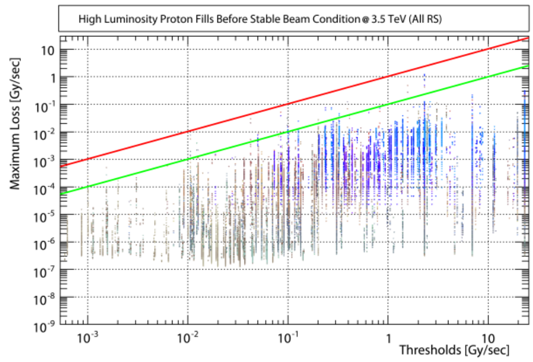

Figure 4: Shown is the maximum measured loss versus applied threshold in Gy/s for each monitor as measured during the fills 1440, 1443, 1444, 1450 and 1453 for RS01- RS09 for the beam energy of 3.5 TeV during the stable beams period. The ratio $r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red.

The same holds for the TCDQA monitor. Both monitors are in the same 'LSA threshold family', i.e. they are protecting the same elements. The 'LSA family name' is THRI_TCD_RC.

Monitors being affected during the five ion fills are: nine triplet monitors in 01L2, 02L2, 03L2 and 01R2 (stable beam condition) and three triplet monitors in 03L2 and 01R2 (before stable beam). The main difference compared to the proton fills is that for the triplet monitors the ratio $r_{l/t} \geq 0.1$ has been observed during the longer running sums as well and not only during RS01 (see tables 4, 5).

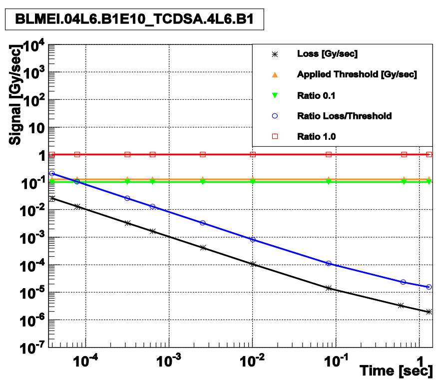

Figure 5: Shown are the losses (in black) for one filter monitor (BLMEI.04L6.B1E10_TCDSA.4L6.B1) and the corresponding applied thresholds at 3.5 TeV (in orange) for the proton fill 1444 (during the period of stable beams) for RS01 – 09. The maximum loss was found for RS01. The ratio of loss to threshold is shown in blue and it is greater than 0.1 for RS01 and RS02 ($r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red).

Note that the LSA MASTER Table thresholds were not changed for the ion run compared to the proton run, even though the loss scenarios are different for proton physics and ion physics.

In fig. 6 the losses for all running sums (RS01 - RS09) are shown for one of the mentioned triplet monitors for the ion fill 1522 (during the period where the stable beam condition was fulfilled). The ratio of loss to threshold was higher than 0.1 for RS01 - 05.

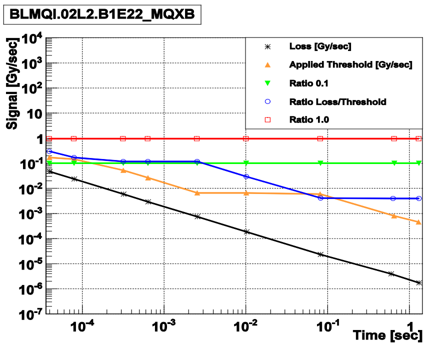

Figure 6: Shown are the losses (in black) for one monitor (BLMQI.02L2.B1E22_MQXB) and the corresponding applied thresholds at 3.5 TeV (in orange) for the ion fill 1522 (stable beam) for RS01 - 09, where the maximum loss was found for RS01. The ratio of loss to threshold is shown in blue and it is greater than 0.1 for RS01 - RS05 ($r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red).

Table 2: Summary of statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the proton fills 1440, 1443, 1444, 1450 and 1450 for RS01 - 09 at 3.5 TeV during the stable beam condition.

Monitor Expertname	**Running Sum**	**Highest Ratio**
BLMQI.01L2.B2I30_MQXA	01	0.14
BLMQI.02L2.B2I21_MQXB	01	0.14
BLMQI.02L2.B1E22_MQXB	01	0.12
BLMQI.02L2.B1E23_MQXB	01	0.16
BLMQI.03L2.B1E30_MQXA	01	0.14
BLMEI.04L6.B1E10_TCDSA.4L6.B1	01-02	0.21
BLMEI.04R6.B1E10_TCDQA.B4R6.B1	01	0.10

Table 3: Summary of statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the proton fills 1440, 1443, 1444, 1450 and 1450 for RS01 - 09 at 3.5 TeV before the stable beam condition was declared.

Monitor Expertname	**Running Sum**	**Highest Ratio**
BLMQI.04R8.B2E20_MQY	01-06	0.71
BLMEI.04R8.B2E10_TCTH.4R8.B2	01 - 09	0.52
BLMQI.07R8.B2E20_MQM	01-02	0.12

Table 4: Summary of statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the ion fills 1520, 1521, 1522, 1525 and 1526 for RS01 - 09 at 3.5 TeV during the stable beam condition.

Monitor Expertname	**Running Sum**	**Highest Ratio**
BLMQI.01L2.B2I30_MQXA	01-02	0.23
BLMQI.02L2.B1E22_MQXB	01 - 05	0.29
BLMQI.02L2.B1E23_MQXB	01 - 05	0.30
BLMQI.02L2.B2I21_MQXB	01 - 05	0.30
BLMQI.02L2.B2I22_MQXB	01 - 02	0.20
BLMQI.02L2.B2I23_MQXB	01 - 05	0.27
BLMQI.03L2.B1E30_MQXA	01 - 02	0.16
BLMQI.01R2.B2E20_MQXA	01	0.13
BLMQI.01R2.B1I20_MQXA	01	0.13

Table 5: Summary of statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the ion fills 1520, 1521, 1522, 1525 and 1526 for RS01 - 09 at 3.5 TeV before the stable beam condition was declared.

Monitor Expertname	**Running Sum**	**Highest Ratio**
BLMQI.03L2.B1E30_MQXA	01 - 05	0.26
BLMQI.01R2.B2E20_MQXA	01	0.12
BLMQI.01R2.B1I20_MQXA	01	0.11

Attempt to establish a scaling factor for the maximum beam losses as function of luminosity

In a second step of the analysis an effort has been made to establish the increase in maximum beam loss per second with luminosity in order to scale the expected maximum loss rates for the 2011 run. A complication comes from the fact that this analysis was performed using the BLM loss data from the LHC Logging DB, which are 'filtered' compared to BLM loss data from the LHC Measurement DB. Note that the beam loss data are stored on the LHC Measurement DB for only 7 days with a frequency of 1 Hz and during the transfer for long term storage in the LHC Logging DB are reduced using a fixed interval filter of 1 minute values (e.g. 5.43 x 10^{-3} Gy/s for RS01, see table 6). The fixed interval filter values are different for each RS and have been introduced in order to reduce the amount of stored data. It is important to mention that only the last value within a minute is stored, not the maximum or average measured value. Therefore it is not possible to define the maximum loss within a minute for losses being below the filter value. To be able to define the increase in maximum beam losses for all monitors as a function of luminosity it is needed to use the loss data from LHC Measurement DB and the author strongly suggests to repeat the analysis in 2011 using the higher frequency data from the LHC Measurement DB. However it is partially possible to determine the increase in loss using data from LHC Logging DB for cases when the losses were logged with a 1 Hz frequency, i.e. high losses. In such cases it turns out that the maximum measured beam losses increase on average (for all monitors available) with a factor of about 0.3 - 0.6 with luminosity, depending on the integration time window (see table 6). Such conclusion was made assuming a linear increase:

$$f = \langle a * x \rangle, \qquad \text{with } x = \frac{Max.loss\ (high\ lumi\ fill)}{Max.loss\ (low\ lumi\ fill)}$$

The slope a was defined for all available monitors during the highest and the lowest luminosity fill and the losses had to be higher than the filter interval values for both fills. But it has to be underlined that the factor of 0.3 - 0.6 is certainly biased and varies in addition with the IR and the element. Maximum losses on triplet and collimator monitors are increasing much more with luminosity than on monitors in ARC regions and on cold magnets (where the slope was almost not measurable, i.e. a=0). A better way for defining the increase in beam loss as a function of luminosity is by using longer integrated dose values as described later in the section "Definition of the most critical BLM locations".

Table 6: A summary of factors for the increase in maximum beam loss with luminosity per RS is given in this table as well as the number of monitors that were taken into account for this calculation.

RS	Slope	# monitors	DB Filter [Gy/s]
01	0.27	414	5.43×10^{-3}
02	0.29	367	2.96×10^{-3}
03	0.36	302	8.8×10^{-4}
04	0.41	265	4.8×10^{-4}
05	0.44	241	1.43×10^{-4}
06	0.43	314	4.24×10^{-5}
07	0.51	300	6.88×10^{-6}
08	0.55	130	3.75×10^{-6}
09	0.50	154	2.23×10^{-6}

Conclusions

The need of a threshold change at 3.5 TeV for the monitor findings of this report (see tables 2 – 5) probably requires additional measurements in 2011 for a final confirmation of the criticality. Also the respective quench limits for the elements concerned need to be checked before changes can be applied. A final decision will be taken by the responsible machine protection representatives.

BLM LSA MASTER TABLE THRESHOLD CHANGES IN 2010 IN IR2, 3, 6, 7 AND 8

Following a brief description on the 'applied BLM beam abort threshold settings', the LSA Master Table threshold changes for monitors in IR2, 3, 6, 7 and 8 as well as the major hardware changes being applied in 2010 will be summarized in this section.

The beam abort threshold settings for each running sum (RS01 - RS12) and 32 different beam energy levels for each BLM are managed and controlled by using the LHC Software Architecture (LSA) [1]. LSA depends on an on-line database and its software is based on Oracle. BLM LSA Master Table threshold changes can be performed only by a restricted group of people who have been assigned the necessary privileges in the Role Based Access Control (RBAC) system. Any changes are confirmed by a before-after comparison that must be equal to the pre-defined settings as described in an approved Engineering Change Request (ECR). The values on the LSA MASTER Tables are the maximum allowed values and they are set generally above the quench level (for cold elements) and below the damage level (for all elements). The LSA MASTER Table thresholds are multiplied with the so called monitor factor, ranging from 1×10^{-3} to 1.0. Both, the LSA Master Table settings and the corresponding monitor factor are (can be) set separately for each monitor and are sent to the BLM electronics. The product of the two values defines the so called 'applied threshold' for each monitor, initiating a beam dump in case a loss is measured being equal or higher than the applied threshold. The monitor factor can be changed without changing the LSA Master Table settings but such changes are as well restricted to a small group of people who have been assigned another RBAC role. The LSA Master Table thresholds changes generally need a longer time than a monitor factor change, due to the fact that such changes must be verified within an ECR, the need of a longer calculation time and because the LSA tables have to be updated.

LSA MASTER Table threshold changes were applied in 2010 for the following monitors and monitor families (BLM monitor families are groups of monitors that share the same values since they are protecting the same type of element from identical topology).

- <u>Modification of monitors in the injection and dump lines</u>: in total 68 BLMs were modified in 2010 and RC signal reduction filters (called filter for simplification) were added to the signal readout chain since injection and dump line losses at specific monitors were above and/or equal the applied beam dump threshold, being already set to the maximum possible value of a measurable loss of 23 Gy/s at which the BLM electronics saturates. In order to overcome the electronics saturation issue two different types of RC signal reduction filters have been installed: a) R = 150 kΩ, C = 47 nF and b) R = 150 kΩ, C = 2.2 nF, depending on the losses being expected at these locations. A filter of type a) (b)) reduces the amplitude in RS01 by a factor of 180 (8) for an instantaneous loss and stretches the length of the signal by the same factor. For longer integration times the reduction in maximum measured amplitude of the signal is decreasing with integration time. The rise time of such modified monitors is higher than for the non-modified ionization chambers, i.e. the time needed to collect 95% of all charges is longer by a factor of ~ 1.5 – 2.5, depending on the type of filter [2]. The charge collection time for a non-modified monitor for injection losses, i. e. instantaneous losses, is 80 - 120 µs. Also BLMs around collimators (close to the injection lines) were modified by adding a filter. The thresholds for these filter monitors were adapted according to the different signal shape by applying the formula:

$$T = \mathrm{T}' \left(1 - \mathrm{e}^{(-\mathrm{RS}/\tau)}\right) ,$$

where T is the corrected threshold per RS and beam energy, T' the initial threshold per RS and beam energy, RS describes the length of the integration time window and τ is the RC time constant. The RC time constant τ describes the time required to charge a capacitor to 63 % of full charge and is given in theory via the product of capacitance and resistance. Taking into account the additional resistance from the signal cables in the tunnel and the signal cable length, the time constant for filter monitors is increased in reality and strongly dependent on the cable length [2]. The monitor families with filter monitors are MSD, TCD, TDI, TCTVB, MSI, MQM and MQML with monitors in IR 2, 6, 7 and 8. In addition BLM threshold changes were applied for monitors that see injection losses but no RC signal reduction filters have been installed. These changes affected basically the injection energies and were done mostly according to the measured loss distributions. Since injection losses are ultra-fast or instantaneous losses, basically the thresholds for RS01 - RS03 had to be adapted only.

- Other regions: The LSA Master Table thresholds for MQW families were corrected since the initial thresholds (from 2009) did not have an energy dependency, i.e. they were equal for the energies between 450GeV and 5.0 TeV. The energy dependency between 450GeV and 5.0 TeV has been introduced in 2010.
- TCLA: In IP7 the thresholds were changed for cell 6 in position A and B. These monitors sit in the shower of the TCP losses and thresholds were changed in a way that the TCLA's in cell 6 in position C and D protect them now. Thresholds in cell 7 in position A and B were changed and increased. The thresholds for TCLA's in IR 3 were increased as well.

For a more detailed description of the applied changes in 2010 see [3].

DEFINITION OF THE MOST CRITICAL BLM LOSS LOCATIONS

For the determination of the most critical locations along the LHC ring in terms of beam losses, the integrated BLM dose has been calculated for the stable beams condition for 23 different proton fills and 17 different ions fills. The dose is determined as the sum of the RS12 BLM signal.

Since a permanent offset current is applied to each BLM in order to check continuously the availability of the electronic channel and in order to avoid lockups due to noise and radiation deposited in the electronics, this offset must be subtracted in order to calculate the integrated dose being deposited in a monitor due to beam losses.

In the following subsection the offset level will be described in more detail in order to show the importance of a properly calculated offset level for the dose determination. Afterwards a description of the calculation of the BLM integrated dose as well as the results of this analysis will be presented.

The offset level

The offset current is varying for each of the monitors around the ring between 5 – 30 pA in an optimum case, leading to an apparent dose of 1.5 - 5 x 10^{-7} Gy/s (RS09 with an integration time of 1.3 s).

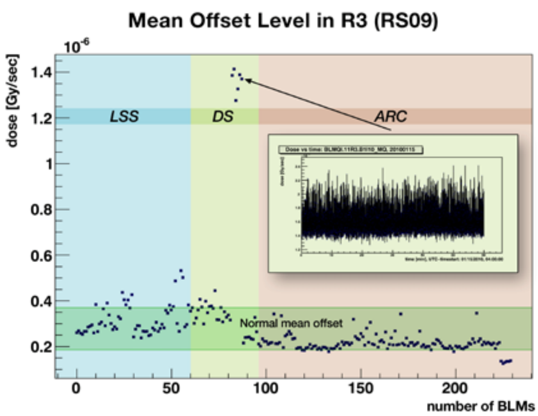

Figure 7: Example for the variation of the mean offset level in units of Gy/s for the Long Straight Section (LSS), the Dispersion Suppressor (DS) and the ARC region for all monitors in R3, being calculated by using the RS09 data (with an integration time of 1.3 s). No beam was in the machine at this time. The mean offset level is higher

and fluctuating more in the LSS and DS than in the ARC (see text).

A mean offset level of 5 – 40 pA for all monitors in the LHC ring being connected to BIS has been assured during the LHC operational periods in 2010. In fig.7 the mean offset level is presented in Gy/s as measured by the RS09 for all monitors in R3. The average offset level is taken from an one hour dataset and the smaller plot indicated in fig. 7 is showing the RS09 data per second over this period of one hour, for one specific monitor having a high offset level, i.e. higher than 30 pA, here 80 pA (~ 1.3 x 10^{-6} Gy/s).

The plot indicates also 6 monitors, which are connected to one tunnel card, where the mean offset level exceeds the operational allowed level of 30 pA and a tunnel card reset was needed in order to set the offset level back to the operational level. The reset was done before the LHC started operating.

The offset level is increasing over time by about 2 - 5% during a time period of 2 weeks without beam in the machine. In fig. 8 such time variation is indicated using again the example of all monitors in R3. In this example the mean offset level was determined four times a day over a period of one hour using the RS09 data from LHC Measurement DB during 14 days when there was no beam in the machine.

The origin of the different levels in offset fluctuations over region and over time are summarized in the following:

- One of the main contributors in the change of the offset level of one monitor is the noise that is introduced into the acquisition input.
- A charge balance integrator is used in order to construct the Current to Frequency Converter (CFC) and it can end up in a locked-up state in case the current flows in the opposite direction. In such a situation a protection circuit is adding a constant current of 1 pA every 20 - 25 s until the CFC exits the locked-up state. The different noise levels depend on the monitor's position within LSS, DS and ARC due to the different length of signal cables and the quality of the cabling [4].
- A slightly increased offset level of around 30 - 40 pA on all channels of several cards has been observed and can be explained with a difference in the temperature at which the CFC cards have been calibrated. The CFC tunnel cards (with a maximum of 8 connected monitors) are calibrated in the laboratory at a temperature of 20 - 30 °C before they are installed in the LHC tunnel. The average temperature in the tunnel is slightly lower with 15 - 20 °C [5].
- On a regular basis the so called BLM sanity checks for all BLM monitors are performed. The checks are systematically executed (at least once every 24 hours) by the machine operators, testing the electrical part of all monitors, their cable connections to the front-end electronics, further connections to the back-end electronics and their ability to request a beam abort [6]. Due to the connectivity check, being one part of the sanity checks, the offset level can be slightly increased, but with a maximum increase of 1 % (compared to the level before the check).
- In total there are three VME crates (right, centre, left) installed within one rack for IR1 - 6 and IR8; in IR7 four crates are installed. The right VME crate controls the HV supplies for the full rack. In case the right VME crate has a breakdown, the HV supply will trip to zero Volt what will induce a negative current into the CFC cards. Therefore the charge balance integrator is entering a locked up state and a constant current of 1 pA is added every 20 - 25 s until the CFC exits the locked-up state. In such a failure case, a CFC card reset is needed.

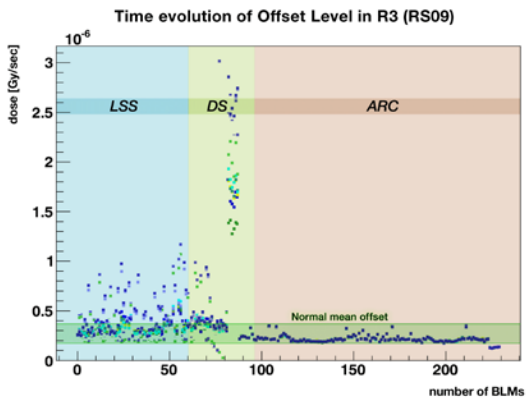

Figure 8: Example for the variation of the mean offset level with time for each monitor in R3, calculated using the RS09 in Gy/s. A time period of 2 weeks was taken into account during which the mean offset level has been defined four times a day using a time interval of one hour. Deviations are higher in the LSS and DS than in the ARC, where the mean offset level is constant (see text).

It has to be mentioned that the increase of the mean offset level seems to be higher than 2 - 5% during operational periods due to additional beam induced losses. A more detailed analysis on the effect of beam induced losses on the increase in offset level over time is ongoing and the final conclusions cannot be presented in this paper.

On a regular basis a CFC card reset of the system is performed in order to avoid an increase of the offset level over time (at least once per technical stop) and in order to assure the operational offset level for all monitors along the ring.

Calculation of the offset level and integrated dose per monitor

Because of the variations mentioned it is important to define the offset level for each monitor and each fill that has been analyzed, separately. The offset for the integrated dose analysis presented here is defined as an average value (using RS09) over a time interval of at least 10 min, several times during the day when the fill took place, but only when there was no beam in the machine. This has been done in order to achieve a statistically relevant data set for the mean offset level per monitor. Also the standard deviation of the mean offset has been calculated for each monitor and each fill separately. The times of having no beam in the machine were defined using the beam presence flag and the timestamps from the sanity checks since the beam presence flag can be at zero even though beam injections are ongoing or while injection tests are performed. The BLM sanity checks however can only be performed if there is no beam at all in the machine.

The criteria for the physics fill selection and for the quality of the data will be summarized in the following:

- Only fills with 2 beams in the machine, fill duration of at least 1 hour and only fills where both beams were dumped within a minute were selected. This has been done using the beam presence flags for beam 1 and 2. In case beam 1 was injected first, this timestamp is chosen as the start time and vice versa.
- The stable beam mode flag was used for the definition of the start time for each fill's stable beam period.
- In order to define the mean offset level (to be subtracted from the integrated dose values) for each monitor separately, a very precise check was made concerning the condition whether there was any beam in the machine or not, using the beam presence flag, the BLM threshold settings and the BLM HV modulation timestamps.

Several data quality checks have been implemented in the analysis:

- The offset fluctuations (i.e. the standard deviation of the mean offset level) should not exceed 10 %. In case offset instabilities over time with more than a 10 % deviation (comparing 2 - 3 sets of 10 minutes per day) were observed, the data quality of the integrated dose cannot be ensured and such results are excluded from this analysis.
- The quality of the logging of the RS12 was investigated and in case an entry was not recorded every 84 s in the LHC Logging DB, the correctness of the integrated dose value cannot be ensured for the monitor concerned, but only in case data are missing by more than 1 % out of the total. The reason of such data loss is still under investigation.
- A check concerning the monitor's noise (RS01 with an integration time window of 40µs) has been implemented, since in case of an increased noise level the signal in RS09 and RS12 are higher as well (see reasons for offset level fluctuations). Therefore a subtraction of the mean offset level from RS12 can lead to a negative integrated dose, because the offset level is overestimated. Higher fluctuations in RS01 introduce higher fluctuations in RS12 and in this case the 'spikes' originating from noise would be interpreted as beam induced losses.
- Furthermore it has been investigated whether the HV modulation (i.e. the BLM connectivity check as part of the BLM sanity checks), being performed at least once a day, has any influence on the offset level (a maximum increase of the mean offset level of 1 % can be introduced). In such cases, the offset level was not calculated for this time period and another time for the offset level determination was selected.

The integrated dose was calculated for physics fills with a different integrated luminosities and a different number of bunches following the formula:

$$D = \sum_{start\ of\ fill}^{end\ of\ fill} (\mathrm{RS12} - \langle 4 * \langle \mathrm{RS09}\ |_0^{600\ \mathrm{s}} \rangle\rangle) * 83.89\ \mathrm{s}$$

RS12 and RS09 are given in Gy/s.

In a first approach it has been tried to define the increase in integrated dose per monitor depending on the number of bunches per beam. The dose was not normalized to integrated luminosity in a first step but defined in mGy per hour.

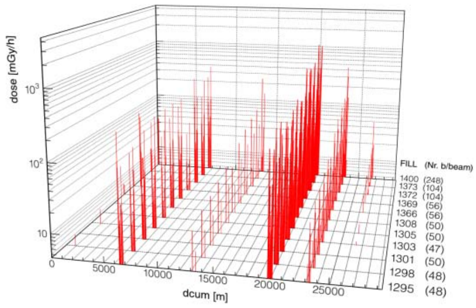

Figure 9: Shown is the integrated dose in mGy/h per monitor versus their position within the ring in metres. Only monitors are shown at which the integrated dose was higher than 5.0 mGy/h. The integrated dose was calculated for several physics proton fills with a different number of bunches per beam in the machine. Note: the dose is not given per integrated luminosity unit in this example, but per hour.

As an example fig. 9 shows the dose in mGy/h for physics proton fills with a different number of bunches per beam.

In a second step it has been tried to decouple the effect of number of bunches from integrated luminosity in order to see the contribution from the number of bunches only. The dose was normalized to integrated luminosity and the increase in dose was determined assuming a linear increase with the number of bunches. The physics proton fill 1400 with 248b/beam was compared to the physics proton fill 1295 with 48b/beam.

$$f = \langle a * x \rangle, \qquad \text{with } x = \frac{Dose/h\ (248b/beam)}{Dose/h\ (48b/beam)}$$

As a general result it turned out that the slope a is ranging between 0.3 and 0.6, strongly depending on the IR and on the specific element. Triplet monitors and collimation regions are affected much more by the number of bunches than ARC regions and cold magnets (where the slope was almost not measurable, i.e. zero).

Table 7: Summary of the integrated luminosity per fill.

Fill Nr.	**Int. Luminosity [nb^{-1}]**
1440	6015
1443	1493
1444	4025
1450	6375
1453	2658
1520	337
1521	240
1522	487
1525	545
1526	329

In a second approach the effect of luminosity on beam losses at different locations/elements has been investigated more detailed using the increase of integrated dose per integrated luminosity. Only high luminosity fills being equal in number of bunches (368b/beam) were investigated. The ratio in dose (mGy/nb^{-1}) for high luminosity fills compared to lower luminosity fills was defined for several combinations of the fills summarized in table 7 (proton and ion fills were treated seperately).

$$Ratio = \frac{D_{high\,\mathcal{L}} / \int \mathcal{L}_{high}}{D_{low\,\mathcal{L}} / \int \mathcal{L}_{low}}$$

However fluctuations were observed from fill to fill, so that the only reasonable solution involves the use of the ratio between highest and lowest luminosity from fills 1450/1443 for protons and 1525/1521 for ions respectively. In an ideal case the ratio should be 1.0, i.e. the integrated doses should increase linearly with integrated luminosity. In case the ratio is greater than 1.0, it means that the losses increase more with luminosity than expected.

Results

Table 8 summarizes the average increase in integrated dose per integrated luminosity unit in nb^{-1} per left and right side of an IR and it's LSS, DS and ARC excluding the TCP's, TCSG's, tertiary collimators, TDI's, MSI's, MKI's and triplet monitors for the fills 1450/1443 with a bunch spacing of 150 ns and 368 bunches per beam.

The tables 9, 10 and 11 give an overview of the increase for the collimator regions, the injection regions and on triplet monitors. It should be mentioned that only 3 TCP collimators are installed in L7 and R7, but 4 monitors on each side and all monitors have been taken into account here.

Table 8: Summary of the average ratios in dose in mGy per luminosity in nb^{-1} for proton fills 1450/1443 for LSS, DS and ARC monitors of each IR.

IR	**LSS (#monitors)**	**DS (#monitors)**	**ARC (#monitors)**
L1	0.82 (27)	1.05 (36)	1.95 (103)
R1	0.77 (27)	0.58 (22)	1.09 (109)
L2	0.92 (27)	3.54 (41)	0.64 (103)
R2	1.56 (20)	4.37 (25)	4.69 (118)
L3	4.81 (24)	2.51 (32)	0.75 (100)
R3	4.58 (22)	1.48 (26)	1.90 (122)
L4	0.79 (23)	1.31 (12)	6.40 (111)
R4	0.95 (23)	0.59 (16)	1.21 (112)
L5	1.65 (28)	1.13 (32)	0.96 (100)
R5	1.18 (28)	1.08 (34)	1.48 (111)
L6	0.75 (28)	1.81 (24)	0.78 (97)
R6	1.28 (27)	2.60 (12)	1.43 (111)
L7	0.69 (28)	5.29 (35)	1.05 (107)
R7	0.83 (28)	0.72 (40)	0.67 (102)
L8	1.03 (24)	1.14 (34)	1.56 (97)
R8	1.06 (25)	1.64 (31)	1.42 (111)

The results for the ion fills 1525/1521 with 121b/beam are summarized in table 12, 13, 14 and 15 respectively. The highest ratios have been observed in the LSS of R1, DS of L2, R2, L7 and R8 and in the DS of L7 and ARC of L8.

Table 9: Summary of the average ratios in dose in mGy per luminosity in nb^{-1} for proton fills 1450/1443 for collimator monitors.

IR	**TCP (#monitors)**	**TCSG (#monitors)**	**TCL & TCT (#monitors)**
L1	-	-	0.93 (2)
R1	-	-	1.33 (2)
L2	-	-	0.80 (2)
R2	-	-	3.07 (2)
L3	6.64 (1)	5.21 (4)	-

R3	3.82 (1)	4.36 (4)	-
L5	-	-	1.30 (2)
R5	-	-	1.02 (2)
L6	-	0.04 (1)	-
R6	-	1.20 (2)	-
L7	0.58 (4)	0.71 (11)	-
R7	1.47 (4)	0.95 (13)	-
L8	-	-	1.00 (2)
R8	-	-	0.99 (1)

Table 10: Summary of the average ratios in dose in mGy per luminosity in nb^{-1} for proton fills 1450/1443 for TDI, MSI and MKI monitors in L2 and R8.

IR	TDI (#monitors)	MKI (#monitors)	MSI (#monitors)
L2	0.79 (3)	0.72 (2)	1.12 (6)
R8	0.92 (3)	0.47 (2)	1.21 (6)

Table 11: Summary of the average ratios in dose in mGy per luminosity in nb^{-1} for proton fills 1450/1443 for triplet monitors.

IR	Triplets (#monitors)
L1	0.74 (18)
R1	0.78 (8)
L2	0.73 (18)
R2	0.77 (12)
L5	0.69 (18)
R5	0.89 (18)
L8	0.89 (18)
R8	0.95 (18)

During the ion fills the monitors on triplets show an asymmetry between the left and right side in IR2 and 5, what was not observed during the proton fills. The beam intensity was 1 e11p/bunch and the filling scheme was 150ns_368_348_15_344. In most of the regions around the ring the dose scales linearly with luminosity (i.e. the ratio is close to 1.0), except in the DS of L2 and R2, the ARC of R2, the LSS of L3 and R3, the ARC of L4 and the DS of R6 and L7.

Table 12: Summary of the average ratios in dose in mGy per luminosity in nb^{-1} for ion fills 1525/1521 for for LSS, DS and ARC monitors of each IR.

IR	LSS (#monitors)	DS (#monitors)	ARC (#monitors)
L1	0.61 (17)	0.86 (34)	1.65 (109)
R1	3.94 (19)	1.68 (21)	1.85 (101)
L2	27.87 (13)	0.76 (36)	0.73 (100)
R2	3.34 (9)	0.79 (33)	0.71 (101)
L3	1.66 (24)	1.26 (29)	2.72 (97)
R3	1.33 (24)	1.25 (30)	1.84 (105)
L4	0.40 (9)	0.74 (10)	1.85 (93)
R4	1.24 (15)	0.93 (13)	0.44 (103)
L5	0.90 (22)	1.26 (30)	1.21 (96)
R5	0.98 (13)	0.94 (31)	0.63 (108)
L6	0.52 (27)	1.06 (23)	1.22 (84)
R6	0.70 (23)	0.75 (18)	0.67 (104)
L7	10.24 (25)	3.14 (36)	0.71 (95)
R7	1.51 (21)	1.10 (31)	0.62 (115)
L8	1.36 (10)	0.92 (26)	4.64 (94)
R8	60.50 (20)	1.68 (28)	0.88 (99)

Table 13: Summary of the average ratios in dose in mGy per luminosity in nb^{-1} for ion fills 1525/ 1521 for collimator monitors.

IR	TCP (#monitors)	TCSG (#monitors)	TCL & TCT (#monitors)
L1	-	-	0.72 (2)
R1	-	-	1.79 (2)
L2	-	-	0.68 (2)
R2	-	-	1.01 (1)
L3	1.35 (1)	1.79 (4)	-
R3	1.26 (1)	1.70 (3)	-
L5	-	-	1.61 (2)
R6	-	1.13 (2)	-
L7	0.73 (4)	1.14 (11)	-
R7	0.56 (4)	0.74 (13)	-

Table 14: Summary of the average ratios in dose in mGy per luminosity in nb^{-1} for ion fills 1525/1521 for TDI, MSI and MKI monitors in L2 and R8.

IR	**TDI (#monitors)**	**MKI (#monitors)**	**MSI (#monitors)**
L2	0.93 (2)	-	0.55 (6)
R8	2.01 (3)	-	3.45 (3)

Table 15: Summary of the average ratios in dose in mGy per luminosity in nb^{-1} for ion fills 1525/1521 for triplet monitors.

IR	**Triplets (#monitors)**
L1	0.79 (11)
R1	0.93 (8)
L2	0.41 (8)
R2	2.25 (5)
L5	0.44 (11)
R5	2.10 (10)
L8	0.77 (4)
R8	1.69 (8)

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EMITTANCE PRESERVATION

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Abstract

The preservation of the transverse emittance is crucial for luminosity performance. At the LHC design stage the total allowed emittance increase was set to 7% throughout the LHC cycle. The injection process is particularly critical in this respect. Results of an analysis trying to quantify the emittance increase from injection to stable beams will be presented. The luminosity goals of the 2010 proton run could be achieved with fewer bunches than initially foreseen. This is due to the excellent performance of the injectors concerning the higher than nominal number of protons per bunch and also the smaller than nominal emittances. Recommendations for required instrumentation and emittance preservation goals for next year's run will be given.

INTRODUCTION

It is well-known from the formula for the luminosity, Eq. 1, that smaller beam sizes at the interaction point and hence smaller emittances are advantageous for luminosity performance.

$$L \approx \frac{f_{rev} \cdot n_b}{4 \cdot \pi} \cdot \frac{N_1 \cdot N_2}{\sigma_1 \cdot \sigma_2} \qquad (1)$$

with n_b the number of bunches, N_1 and N_2 the number of particles per bunch for the two beams and σ_1 and σ_2 the beam sizes of the beams. In proton machines, such as the LHC, without strong damping, preservation of the emittance throughout the different stages in the operational cycle is very important. The design values for allowed emittance increase from injection to collisions is $\varepsilon/\varepsilon_0 < 1.07$, allocating $\varepsilon/\varepsilon_0 < 1.05$ for injection. The obtained emittance increase values during the injection process are detailed in [1]. A summary of the findings will be given in this paper, that will also report on a first attempt at quantifying the emittance increase from injection to stable beams for the 150 ns proton period. Ions will be mentioned briefly towards the end when discussing possible explanations for the observed emittance growth during the period of collisions.

LIMITATIONS

At LHC injection currents reliable emittance measurements could be obtained with the wire scanners. They were systematically used up to an intensity of 2×10^{13}, above which a software interlock forbids their operation to avoid either wire damage (at 450 GeV) or quenching the downstream magnets (at 3.5 TeV). Unfortunately the synchrotron light monitors and ionisation gas monitors have not reached the operational state yet. Because of a lack of reliable, continuous emittance measurements for beam 1 and beam 2 and horizontal and vertical plane, emittances at flat-top were derived from the luminosity or the luminous region measurements. This approach has clear limitations. From the luminosity data no conclusion on the single beam behaviour can be drawn. Also, any possible offset between beam 1 and beam 2 at the IP is neglected in this paper for deriving the emittances. The results above injection and numbers for emittance growth from injection to collisions are therefore of a more qualitative nature.

In addition the nominal beta functions were assumed to convert beam sizes to emittances.

EMITTANCE PRESERVATION AT INJECTION

SPS and LHC wire scanner data for beam 1 and beam 2 and horizontal and vertical plane is plotted in Fig. 1 and Fig. 2.

Throughout this period, the SPS as the last machine of the LHC injectors delivered emittances well below nominal emittance of 3.5 μm. The SPS delivered about 2.5 μm until roughly fill 1400, and afterwards the injected emittances were even partly below 2 μm. These small emittances are a result of how the beam with the larger bunch spacing is produced. With 25 ns bunch spacing nominal emittances can be expected.

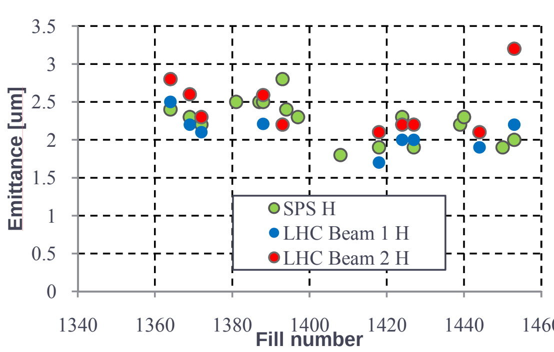

Figure 1: Horizontal emittances measured in the SPS at flat-top and in the LHC at injection for beam 1 and beam 2. The emittances for beam 2 are systematically larger than for beam 1.

The results in the LHC consistently indicate larger emittances for beam 2 in both planes, more pronounced however in the vertical plane. There are no shot-by-shot emittance measurements in the SPS. The emittances are measured as part of the preparation some time before the actual filling starts. This could be the reason why for beam 1 the wire scanners show partly even smaller emittances than measured in the SPS. To exclude nevertheless issues with cross-calibration between machines and LHC beams, cross-checks with other instruments (e.g. turn-by-turn screens) should be carried out in 2011.

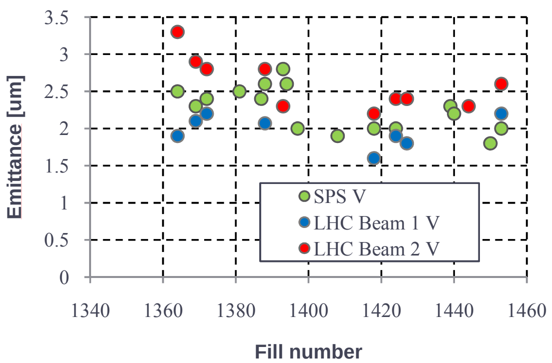

Figure 2: Vertical emittances measured in the SPS at flat-top and in the LHC at injection for beam 1 and beam 2. The emittances for beam 2 are systematically larger than for beam 1.

Also, the emittances in the LHC were not measured directly after injection, but rather either at the end of filling or after the first injections. Emittance growth from errors during the injection process can therefore not be easily disentangled from other effects like the hump. Taking nevertheless the values from Fig. 1 and 2 for beam 2, the difference on average between the LHC and the SPS values is 10 % in H and about 15 % in V. The emittance growth from the injection process itself is estimated to be lower by at least a factor 2, as described in the following.

Beam stability, kicker ripple, betatron, dispersion and coupling mismatch at the LHC injection point all lead to emittance increase at injection (details can found in [1]). The betatron mismatch to the nominal injection optics was evaluated during the transfer line setting up periods using the OTR screens. The measurements for TI 2 are shown in Fig. 3. The measured mismatch factors are λ = 1.05 to λ = 1.1, corresponding to an emittance increase in the order of 3 % for λ = 1.1 (the measured small beta beating in the LHC was not taken into account). More precise values will be obtainable with a turn-by-turn matching monitor in the LHC. Such an instrument might be available for 2011. The tools for the transfer line screen matching, as shown in Fig. 4, will have to be upgraded to also deal with the LHC matching monitor.

Due to the constraints of the transfer line collimators and the limited possibility to correct, we partly allowed for large injection oscillations. Amplitudes of 1.5 mm were tolerated. The LHC transverse feedback system took care of the emittance preservation. The excellent performance is demonstrated in Fig. 5 with a typical example of the damping times reached. Damping times were as low as 40 turns.

There is also a rotation angle between the reference frame of the transfer lines and the LHC. This 'tilt mismatch' leads to a phase dependent coupling, see [3], and emittance increase following

$$\frac{\varepsilon_x}{\varepsilon_{0x}} = 1 + \frac{1}{2}\cdot\left(\beta_x\gamma_y + \beta_y\gamma_x - 2\alpha_x\alpha_y - 2\right)\cdot\sin\theta^2 \quad (2)$$

The emittance increase due to this effect is 1.3 % for TI 8 (tilt angle of 54 mrad) and 0.3 % for TI 2 (tilt angle of 20 mrad) and is presently uncorrectable, although correction schemes using skew quadrupoles are under study.

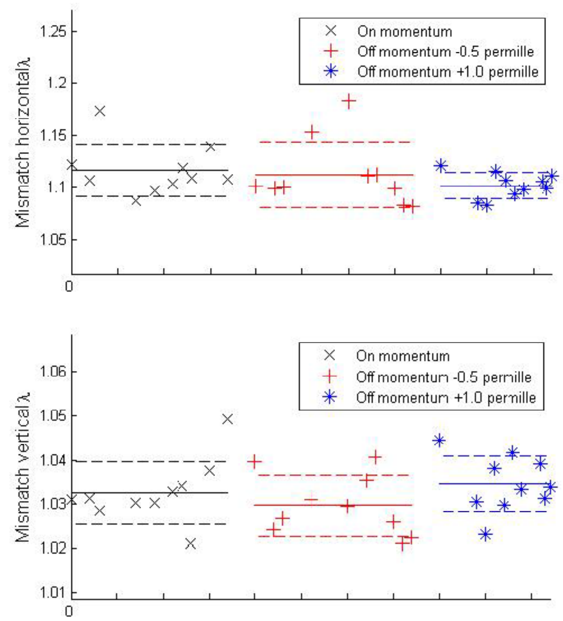

Figure 3: No measurable change of the betatron mismatch factor (to the nominal optics at the injection point) was measured for the transfer lines, also looking at possible momentum dependence. The betatron mismatch can be assumed to be in the order of 5 % for both lines. (The results in the horizontal plane show a larger mismatch due to using the nominal dispersion instead of the measured and not including the variation of the bunch length hence momentum spread). The LHC beta beating was found to be maximum 20 %, [4].

EMITTANCE INCREASE UNTIL COLLISION

Fig. 6 and 7 compare the emittances at injection for beam 1 and beam 2 with the data from the ATLAS luminous region at the moment of first collisions in the horizontal and vertical plane for all fills which made it into stable beams (wire scanner data does not exist for all analysed fills).

The achieved emittances at the moment of declaration of stable beams were still below nominal, with values on average below 2.5 µm at the beginning of the 150 ns period and below 2.5 µm for later fills.

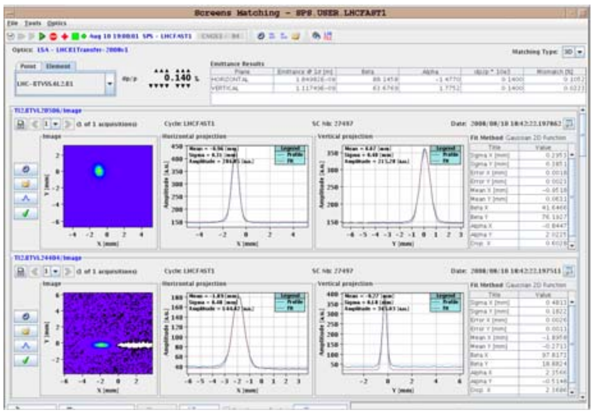

Figure 4: The screen matching application of the transfer line will have to be adapted for the LHC turn-by-turn matching screens. Instead of using several screens, several turns of one screen will be combined in the analysis.

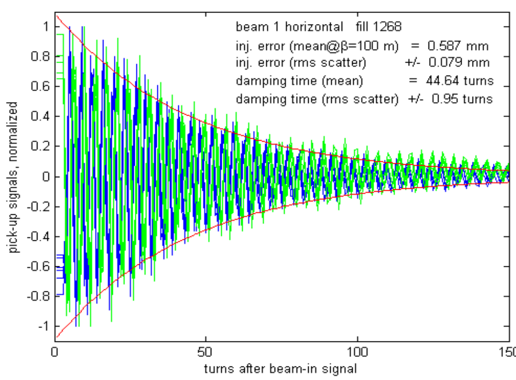

Figure 5: Horizontal injection oscillations of beam 1 for fill 1268, pick-ups Q7 (green) and Q9 (blue) as well as exponential fit from averages of the reconstructed data

.

Because of the lack of consistent data throughout the LHC cycle, an indication of the emittance increase from injection to the start of collisions is derived from comparing the achievable beam size of the luminous region with the emittances at injection with the measured luminous region data from ATLAS. To calculate the convoluted beam sizes formula (3) was used.

$$\sigma_L = \left(\frac{1}{{\sigma_1}^2} + \frac{1}{{\sigma_2}^2}\right)^{-\frac{1}{2}} \qquad (3)$$

The results are shown in Fig. 8 and 9 indicating about 30 % emittance growth in both planes on average for the different fills, or about 15 % on average in convoluted beam size. Further studies are planned for 2011 with the aim of using the BSRT to disentangle contributions from beam 1 and beam 2.

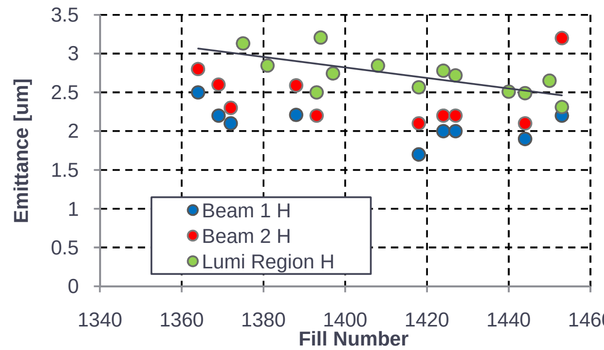

Figure 6: Horizontal emittances of beam 1 and beam 2 at injection and from the luminous region data from ATLAS at the beginning of physics for different fills.

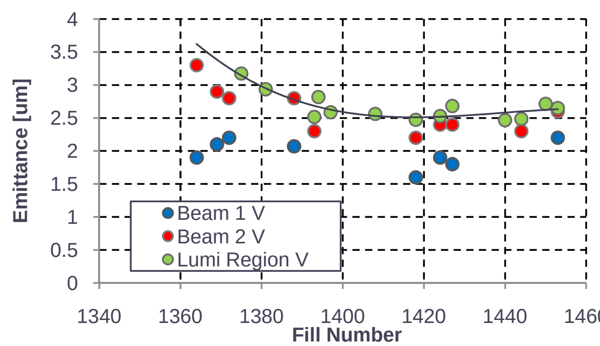

Figure 7: Vertical emittances of beam 1 and beam 2 at injection and from the luminous region data from ATLAS at the beginning of physics for different fills.

EMITTANCE INCREASE DURING PHYSICS

Fig. 10 shows the evolution of the luminosity during the 2010 record luminosity fill with a peak luminosity of 2.08×10^{32} cm^{-2}s^{-1}. The measured beam current data is used to plot the expected evolution of the luminosity assuming only current decay and the emittance as at the beginning of physics. The discrepancy between the expected and the real evolution of the luminosity is due to emittance growth during physics.

The emittance growth times were calculated by smoothing and differentiating the luminous region data using

$$\frac{\varepsilon}{\tau} = \frac{d\varepsilon}{dt} \qquad (4)$$

An example of the evolution of the growth time during fill 1440 is shown in Fig. 11.

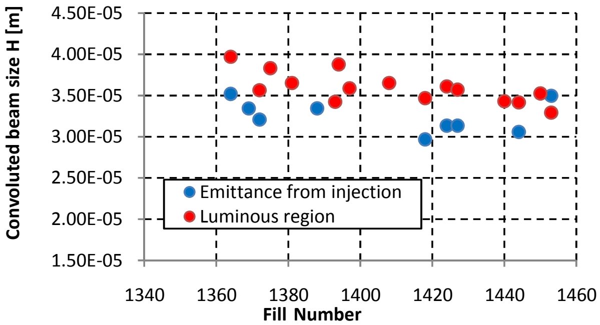

Figure 8: Horizontal convoluted beam size assuming the emittances at injection in blue and the beam size from the luminous region data of ATLAS in red. The beam sizes from the measured ATLAS are on average about 15 % larger.

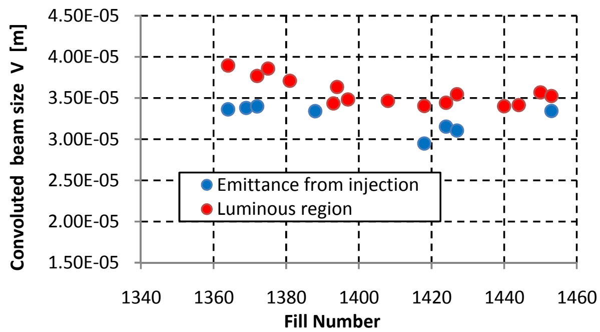

Figure 9: Vertical convoluted beam size assuming the emittances at injection in blue and the beam size from the luminous region data of ATLAS in red. The beam sizes from the measured ATLAS are on average about 15 % larger.

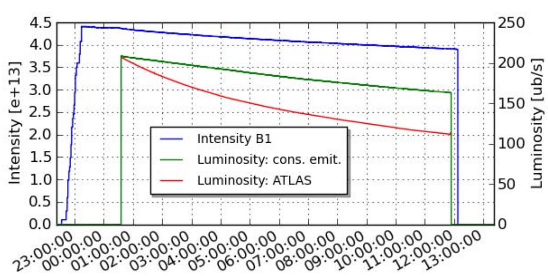

Figure 10: Evolution of the luminosity (data from ATLAS) during the record luminosity fill 1440 in red. The beam current during the duration of this fill is shown in blue. In green the expected evolution of the luminosity is plotted assuming no emittance increase, only beam current decay.

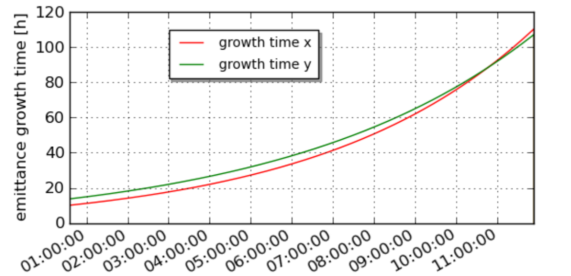

Figure 11: Emittance growth time in H and V by smoothing and differentiating the ATLAS luminous region data for fill 1440.

Fig. 12 shows the emittance growth times at the beginning of the physics period for different fills during the 150 ns run where data with sufficient quality was available. A trend to shorter growth times towards the end of the proton run from around 20 h to below 10 h is apparent.

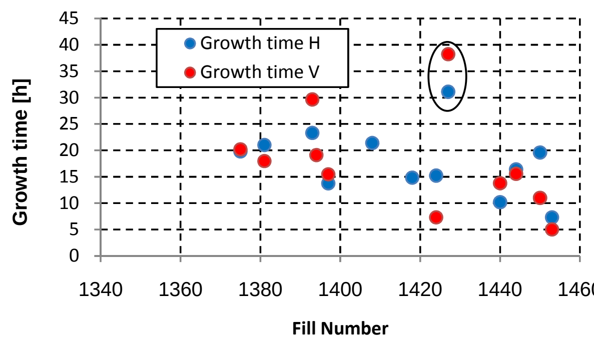

Figure 12: Emittance growth times for different fills during the 150 ns proton run period at the beginning of the collisions phase. Data quality did not allow to calculate growth times for all fills. The encircled data set corresponds to a fill with smaller bunch intensity.

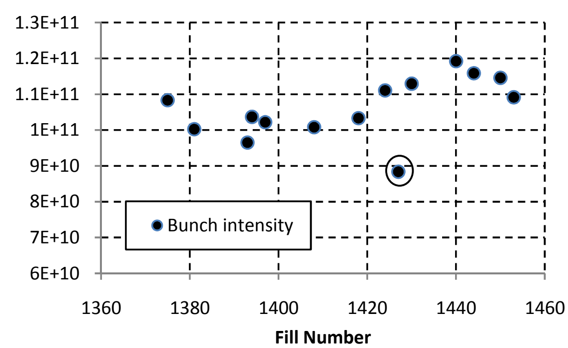

Figure 13: Towards the end of the 150 ns run period the bunch intensities were further and further increased from the injectors.

This coincides with the hunt for 50 pb^{-1} integrated luminosity where emittances were further and further reduced in the injectors and bunch intensities increased, see Fig. 13. One data set, fill 1427, does not follow the overall trend. This might be explained by the much reduced bunch intensity during this fill, see encircled data points in Fig. 12 and 13. The dependence of the emittance growth times on bunch intensity and initial emittance indicates beam-beam effects and IBS as main cause for the emittance increase. External noise such as the hump might be the driving source for the beam-beam related emittance growth. IBS alone does not explain the measured data. Whereas longitudinally the emittance growth times seem to show some agreement, transversely the predicted growth times do not fit the ones evaluated from the measured emittance increase. For the prediction of the IBS growth times, emittances from the ATLAS luminosity and luminous region data, as well as the used RF voltage and logged bunch length were used following the methodology developed in [5]. Full coupling between horizontal and vertical plane was assumed. Fig.14 and 15 show the IBS predictions and actual growth times for proton fill 1400. For ions the IBS predictions fit the observed values better, see Fig.16, 17 and 18 as an example.

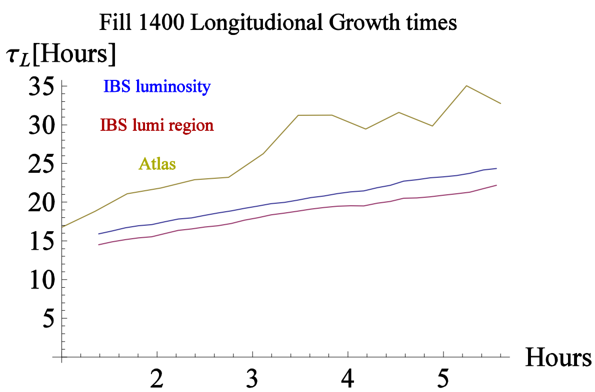

Figure 14 : Proton fill 1400: Longitudinal growth times from the ATLAS luminous region and predictions for IBS using the luminous region data or luminosity from ATLAS.

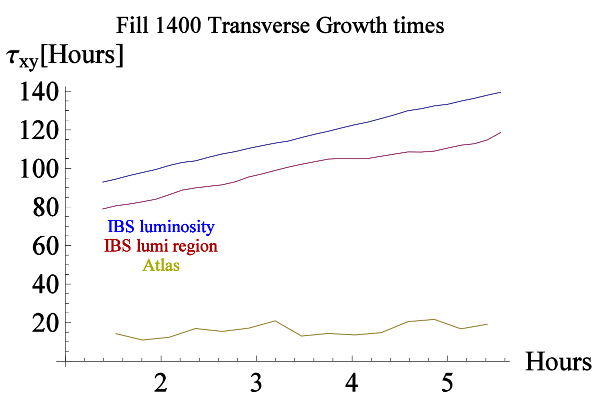

Figure 15: Proton fill 1400: Transverse growth times from the ATLAS luminous region and predictions for IBS using the luminous region data or luminosity from ATLAS.

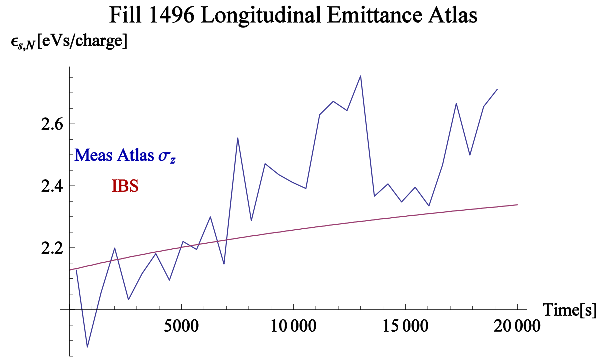

Figure 16: Ion fill 1496: Longitudinal emittance from the ATLAS luminous region and predictions for IBS using the luminous region data or luminosity from ATLAS.

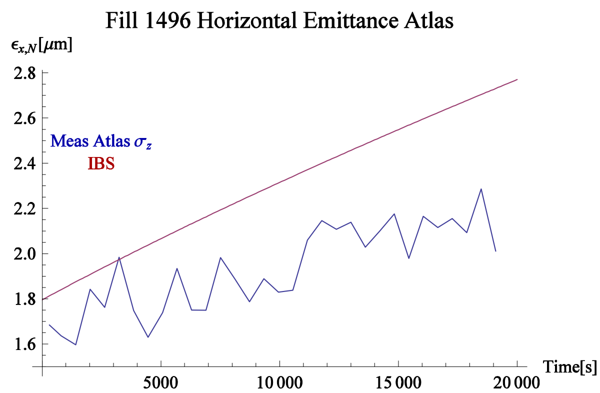

Figure 17: Ion fill 1496: Horizontal emittance from the ATLAS luminous region and predictions for IBS using the luminous region data from ATLAS.

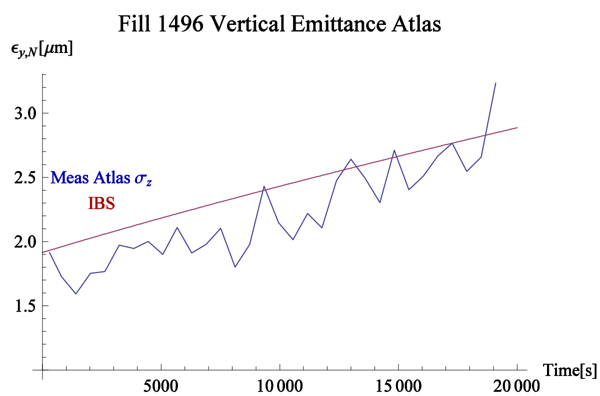

Figure 18: Ion fill 1496: Vertical emittance from the ATLAS luminous region and predictions for IBS using the luminous region data from ATLAS.

CONCLUSION AND OUTLOOK

The LHC 2010 run was a big success. The ambitious goal of 10^{32} cm^{-2}s^{-1} peak luminosity was achieved, proving the extremely good performance of the LHC machine and also the injectors. The LHC injectors managed to consistently provide bunch intensities above nominal and emittances of down to 2 μm (the nominal emittance is 3.5 μm). Due to this extra margin for these critical parameters not much effort was spent to study emittance preservation and to set up reliable emittance measurements in 2010. This will become one of the priorities in 2011.

The LHC injections are well matched and the transverse damper is working well. Dedicated studies and new instrumentation in the form of the LHC turn-by-turn matching screens will be needed in 2011 to quantify the actual emittance blow-up at injection. Beam 2 seems to have systematically bigger emittances than beam 1, especially in the vertical plane. The hump is definitely a promising candidate to explain the differences. Nevertheless possible calibration errors for the different wire scanner systems will have to be excluded.

Significant emittance growth from the injection plateau until the moment of collisions was estimated from the 150 ns run data. Due to the lack of good quality continuous machine emittance measurements, data from the experiments for luminosity and luminous region was used at flattop to be compared to the injection wire scanner values. This gives an estimate of about 30 % emittance growth.

During collisions the emittances grow with typical growth times of 15-20 h at the beginning of physics. Values below 10 h were obtained towards the end of the 150 ns run period. For protons IBS does not seem to be the main driver for emittance growth. For Ions IBS predictions fit the observed emittance growth better.

The so far obtained values are all of preliminary nature due to the lack of good quality continuous data from the SPS to LHC beam dump for protons. In 2011 reliable emittance measurements throughout the fill, bunch-by-bunch and shot-by-shot for the SPS must become priority. Small emittances - smaller than nominal - and large bunch intensities are a promising solution for high luminosities with sufficient operational margin. This requires reliable emittance measurements.

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LHC beam-beam effects- review and outlook

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Abstract

First experiences with colliding beams have been collected during the 2010 LHC run and some observations of beam-beam effects are reported. The observations are interpreted and critically compared with the expectations and strategies proposed at the previous workshop. Based on the available information, possible limitations are evaluated and strategies for the optimization are derived.

INTRODUCTION - WHAT IS A BEAM-BEAM LIMIT ?

To understand the possible problems related to the beam-beam interaction, it is worthwhile to consider the expected observations [1]. We have to distinguish between machines dominated by radiation and radiation damping such as LEP, and hadron machines mostly limited by non-linear effects and life time problems. In lepton colliders the transverse emittances are in general an equilibrium between excitation (e.g. through beam-beam effects) and the damping. Such an equilibrium emittance does not exist in a hadron machine.

- Possible problems in a lepton collider (e.g. LEP):
  - Increase of vertical equilibrium emittance with increasing intensity ($\mathcal{L} \propto N, \xi \approx const.$), the damping properties are all important, and the limit is very difficult to predict
  - The possible production of tails and bad life time is sometimes considered a "second beam-beam limit", however such problems can be (and are mostly) the result of other effects.
- Possible problems in a hadron collider (LHC):
  - May have slow emittance increase (over hours)
  - Will have beam losses (tails and dynamic aperture), bad life time, impossible to predict
  - Other possible effects are coherent beam-beam oscillations

The expected behaviour in LHC is very different from LEP and the lessons learned from LEP are of limited applicability.

REVIEW OF 2010 PROPOSALS

The main objective for proton running in 2010 was to get significant luminosity to the LHC experiments, details have been presented in [2]. The strategy proposed at the previous workshop [3] was closely followed.

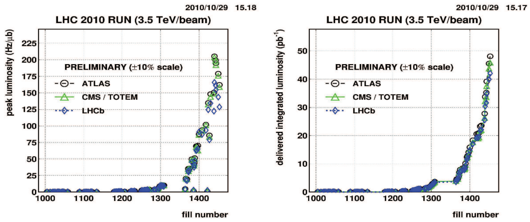

Figure 1: Peak and integrated luminosity in 2010.

The Fig.1 shows the evolution of the peak and integrated luminosity as a function of the fill number. The introduction of bunch trains and therefore the increased number of bunches is clearly visible.

COLLISIONS AT 450 GEV WITH NOMINAL BUNCH INTENSITY

Early in the run it was attempted to collide bunches with the nominal intensity around 10^{11} protons per bunch at the injection energy of 450 GeV. The purpose of this experiments was twofold: to explore the possibility to collide high intensity bunches and to test whether such bunches can be collided with a static offset, as foreseen for the ALICE experiment to control the luminosity. To simplify the test, only 2 bunches per beam have been injected to provide collisions in all four interaction points [4].

Head-on tune shift

The normalized emittances measured during the test were slightly smaller than nominal. When the collisions were adjusted, the life time was very reasonable and tune shifts close to nominal were achieved on this first attempt. These findings indicate little problems with the head-on beam-beam interaction and a small contribution from lattice non-linearities which was expected to be important at injection energy. As a result of this test, the bunch intensity was pushed close to nominal rather early for the following luminosity runs.

Offset collisions in IP2

The luminosity in IP2 has to be controlled to avoid a large pile up in the detector. One proposal was to collide the two beams with a static offset in the transverse plane. To test the feasibility of this procedure, the two beams were scanned against each other in the horizontal plane and the life time and possible emittance growth was recorded [4].

No significant effect was observed during this test in agreement with earlier tests at the SPS collider [5]. As a result of this study, the static offset became a standard operational procedure.
However, the number of long range interactions was small during the entire running period in 2009 and it remains to be demonstrated that additional long range encounters do not significantly change the dynamics.

OFFSET COLLISIONS

Discussing collisions with an offset, one has to distinguish different regimes with very different implications for the beam dynamics:

- Small offset ($\leq$ 0.5 σ), unavoidable due to PACMAN effects [1, 7].
- Medium offset ($\approx$ 1.0 σ), desired for luminosity levelling [2, 8].
- Large offset ($\approx$ 3.0 - 6.0 σ), desired for luminosity reduction.
- Very large offset ($\geq$ 10.0 σ), beam separation at parasitic encounters.

The different offsets can lead to quite different consequences such as e.g. emittance growth, reduction of dynamic aperture, excitation of coherent motion, orbit effects and other effects [1]. The study of the various effects requires different approaches and models and tools exist to evaluate and understand the implications [1, 15].

FILLING SCHEMES

One of the features of the LHC is its flexibility to use very different filling schemes, tailored to fulfill the requirements from the machine and the LHC experiments. This allows to slowly increase the number of bunches in the beam and provide the desired sharing of luminosity between the experiments. For the filling schemes used in 2010, we can distinguish two different periods:

- Initially: egalitarian filling schemes:
  - All IPs equal number of collisions.
  - At the beginning: maximum n collisions for $2n$ bunches per beam.
  - Improved with 3 bunch scheme (and other schemes derived from it).
- Later: maximize collisions in IP1 and IP5, non egalitarian
  - Achieved with bunch trains, mainly 150 ns spacing

When the number of bunches and therefore the luminosity was low, the filling schemes were designed to deliver equal number of collisions to all four experiments. Initally, the schemes were inefficient as they provided only n collisions per interaction point for $2n$ bunches per beam. A modified scheme based on 3 bunches per beam allowed a better yield and had some special features:

- The arrangement allowed two collisions per IP for 3 bunches per beam, i.e. the best ratio collision/bunches: $\frac{2}{3}$
- Special features (unwanted):
  - Parasitic encounters in IP1 and IP5 forced to introduce crossing angle earlier than foreseen
  - PACMAN effects: between 1 and 3 collisions per bunch !

Side effects of this scheme were parasitic encounters close to interaction points IP1 and IP5 which forced the introduction of crossing angles. The other side effect was a strong collision asymmetry: the bunches in the beam had between 1 and 3 head-on collisions, leading to a different integrated beam-beam effect. This is shown clearly in Fig.2 where

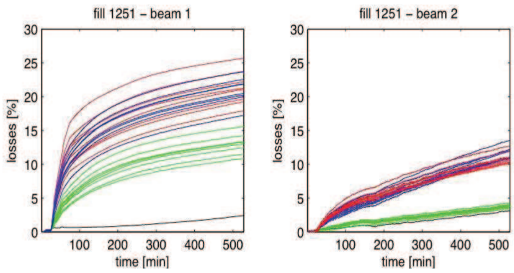

Figure 2: Beam losses for different bunches during fill with different collision schedules [6].

the losses during a fill are shown for the bunches separately and the colour code indicates the number of head-on collisions. It shows clearly that bunches with a larger number of collisions experience more losses that those with fewer interactions [6]. This is a strong indication of the expected PACMAN effects [7].
The scheme was easily extended by adding identical 3-bunch schemes, displaced longitudinally around the ring. Filling schemes with up to 50 bunches per beam have been developped using this strategy.
Since the LHC operated already with a crossing angle, the single bunches were replaced earlier than foreseen by bunch trains of 8 bunches per train, spaced by 150 ns within a train. The intermediate steps with 43 and 156 bunches per beam and without crossing angles have been skipped. Introducing these trains had no detrimental effect on the achievable head-on beam-beam tune shift. Adding more trains in small steps allowed to increase the number of bunches up to a maximum of 424. This procedure has an advantage for the beam dynamics. Once the maximum

number of bunches per train is established, the full complement of head-on and long range encounters is provided. Adding more trains of the same type does not affect the behaviour of the bunches already present before. Additional bunches behave like bunches already present in the machine. One therefore should expect that the performance is independent of the total number of bunches. This is demon-

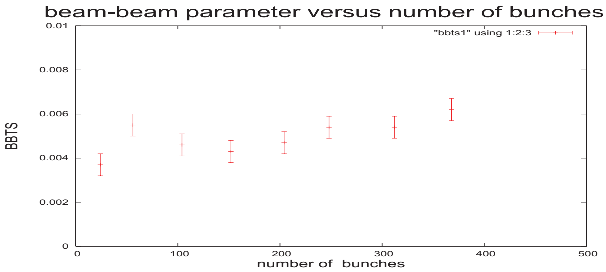

Figure 3: Beam-beam parameter as function of total number of bunches.

strated in Fig.3 where the head-on beam-beam tune shift is shown as a function of the total number of bunches in the machine. No dependence, and in particular no decrease can be observed. This is a unique feature of the bunch train and crossing angle geometry of the LHC. Colliders like SPS or Tevatron where the beam separation is provided by a "pretzel" scheme around the machine would no show this beneficial behaviour.

OPERATION WITH TRAINS AND 150 NS BUNCH SPACING

After the operation with trains and 150 ns spacing was established, the operation became routine with typical parameters like:

- Normalized emittances $\approx$ 2 to 3 μm.
- ξ per crossing $\approx$ 0.006 (i.e. up to 0.02 total for 3 collisions).
- Crossing angle (IP1/5) $\pm$ 100 μrad, β^* = 3.5 m, i.e. very small long range contribution [1].

Given the rather large β^* and the crossing angles of $\pm$ 100 μrad, the separation of the parasitic encounters in the drift space was approximately $d_{sep} \geq 13\ \sigma$, i.e. significantly larger than nominal ($\approx$ 9.5 σ). Together with the smaller number of long range interactions due to the large spacing, the contribution from parasitic crossings to the overall beam-beam effect was very small in this configuration.

Angular scan

To probe the importance of long range interactions given the large separation and their small number, a test was performed at injection energy where the crossing angle between the beams was reduced from the nominal $\pm$ 170 μrad

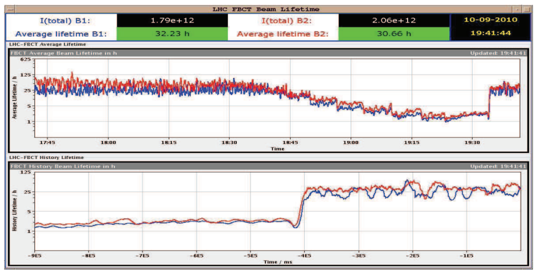

Figure 4: Beam intensity during angular scan. Upper curve shows beam intensities, lower curve zoomed to the last few minutes.

and the effect on the life time was recorded. The beam intensity during this scan is shown in Fig.4 and the steps of the crossing angle are clearly visible. During the entire scan the parallel separation at the central collision point was maintained at its nominal value, i.e. the separation was never smaller than $\approx$ 3.5 σ. The main observations can be summarized as:

- Little effect on life time between $\pm$ 170 μrad and $\pm$ 120 μrad
- First (very small) effect at $\pm$ 100 μrad
- First (significant) effect from $\pm$ 100 μrad to $\pm$ 90 μrad
- Final drop to less than 1 hr (parallel separation still on)
- Returning to $\pm$ 100 μrad restored the beam lifetime

The effect of long range interactions can clearly be observed when the separation becomes small enough, even with only a few encounters. A more detailed analysis

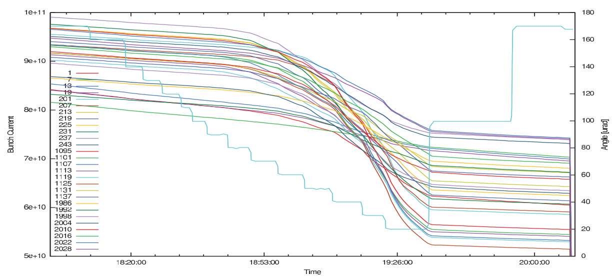

Figure 5: Losses per bunch during angular scan [13].

is shown in Figs.5 and 6 where the intensity is plotted for individual bunches as a function of the steps of the crossing angle also indicated in the figure. In particular in Fig.6 it is demonstrated that bunches with fewer long range interactions tend to have fewer losses and a better life time, indicating again the importance of PACMAN effects. Similar effects have been observed at the Tevatron [10] where the bunch position dependent emittance growth is related to the different long range interactions.

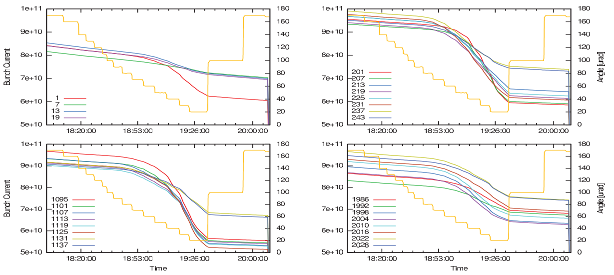

Figure 6: Losses per bunch during angular scan. Plotted per train [13].

EXPECTED BEAM-BEAM TUNE SHIFT

Some confusion is related to the maximum expected head-on beam-beam tune shift for the LHC. The nominal head-on tune shift was derived from SPS experience, taking into account possible contributions from the lattice non-linearities and significant long range contributions. The nominal value of ξ = 0.0037 was defined to provide a coherent set of parameters to reach the target luminosity of $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It should be considered as conservative and not as an expected upper limit, in particular in the absence of strong long range interactions. In the first collider runs, the SPS was operated with 3 p against 3 $\bar{p}$ bunches. In this configuration total tune shifts of 0.028 were obtained but the $\bar{p}$ life times at the beginning of a coast were poor. In the configuration with separated beams ("pretzel scheme"), i.e. in the presence of 3 head-on and 9 long range encounters, operating with a total tune shift of 0.02 was standard [9]. A typical tune shift per collision of 0.006 to 0.007 imposed no life time problems.

Similar numbers are reported from the Tevtron [10]. It should be expected that similar values can be reached at the LHC.

Optimization strategy

At the present stage of the commissioning, the LHC is not yet beam-beam limited and moreover it is unclear whether the limit will come from head-on or long range interactions. The strategy for optimization will crucially depend on which limit is encountered first.

The head-on tune shift depends only on the bunch intensity and the normalized emittance, i.e. is independent of β^* and the energy [1].

$$\Delta Q_{ho} \propto \frac{N}{\epsilon_n}$$

If the head-on interaction is the beam-beam limit, it is therefore advantageous to increase the bunch intensity together with the transverse emittance since this would keep the tune shift unaffected, but increases the luminosity proportional to the intensity. The luminosity is further increased by a reduction of β^*, without affecting the beam-beam parameter ξ.

The situation is very different for the contribution of long range interactions where the tune shift depends on the beam separation d_{sep}^2 and is proportional to [1]:

$$\Delta Q_{lr} \propto \frac{N}{d_{sep}^2} = \frac{N \cdot \epsilon_n}{\alpha^2 \cdot \beta^* \cdot \gamma}$$

i.e. depends on β^*. Any change of β^* or the energy γ requires to adjust the crossing angle α to keep the long range tune shift constant:

$$\alpha \propto \sqrt{\frac{N \cdot \epsilon_n}{\Delta Q_{max} \cdot \beta^* \cdot \gamma}}$$

This feature is again very different from a pretzel separation like SPS or Tevatron where a change of β^* does not affect the separation at long range encounters.

This has vital significance for the optimization strategy, i.e. whether a large number of bunches with a moderate β^* is preferred (in case of long range limits) or the focusing is pushed to smaller β^* when the machine is limited by head-on interactions.

Limits for optimization

It was proposed at this workshop [11] to squeeze to a minimum β^* of 1.5 m. This value is limited by the available aperture and the required crossing angle [11]. Given the dependence of long range contributions on β^*, the operation at this value has to be understood, in particular with the foreseen larger number of bunches with a small bunch spacing (75 ns or 50 ns). In case of problems, a slightly larger value of β^* may be desirable and can easily be implemented.

Much less flexibility is available to decrease or increase the size of the crossing angle since it must compromise two opposite requirements:

- Large enough for sufficient separation
- Small enough for aperture requirements

The ultimate limit must always come from beam dynamics and stability consideration and may eventually limit the minimum value of β^*.

Given the absence of any experience with a small β^* and many long range interactions, it is proposed to assume a conservative crossing angle at the start, providing a separation of at least 12 σ since such a separation proved workable for 150 ns bunch trains in 2010.

The increase of number of bunches per train as a consequence of a shorter bunch spacing has important consequences for long range beam-beam effects since it increases their number significantly. The numerology of the interaction count for different bunch spacings and configurations is summarized in Tab.1. A significant increase of all types of interactions is expected when the LHC is operated with the nominal filling scheme. As a demonstration of this strong effect, in Fig.7 the head-on and long range footprints (i.e. tune spread) are shown for different bunches

	25 ns 72b	150 ns 8b	50 ns 12b	50 ns 24b	75 ns 36b
bunches	2808	424	108	108	936
head on	4	3	3	4	4
long range	120	18	45	64	40

Table 1: Number of head-on and long range interactions for different spacings and configurations. First column are nominal parameters, second column operational scenario in 2010, following columns possible schemes for 2011.

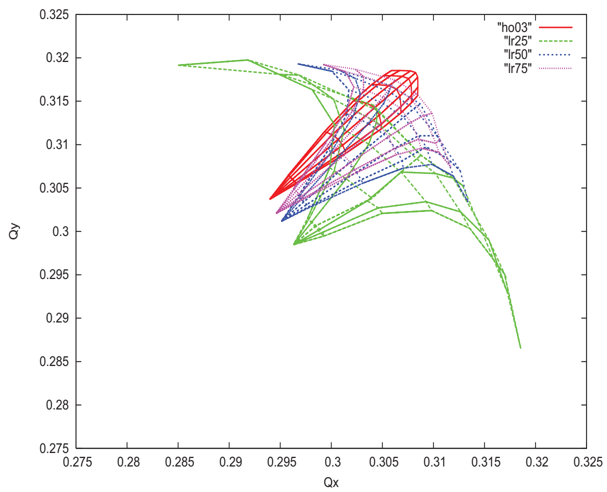

Figure 7: Tune footprint for different bunch spacings. Shown is a footprint for head-on collisions only as well as full footprints for head-on and long range interactions with different bunch spacings. All figures for 3.5 TeV and $\beta^* = 3.5$ m.

spacings with otherwise identical conditions. While for a large enough spacing the spread is dominated by the head-on contribution, for many bunches the long range spread is most significant, in particular for the nominal spacing of 25 ns between bunches. Although the tune spreads, i.e. the footprints in Fig.7, are not the main source of detrimental effects, they serve as a quantitative argument that a very significant change of behaviour may be expected for a change of spacing from 50 ns to 25 ns.

Test with 50 ns bunch spacing

A short test was done with trains of 12 bunches and a spacing of 50 ns. However 12 bunches per train do not provide the full number of long range encounters expected for this bunch spacing and the test was not fully relevant. A short test was made with beams offset by a few σ since a luminosity levelling is required by LHCb in 2011 to minimize the pile up [2, 8]. No life time effect was observed but the test should be repeated with the full long range contribution to draw reliable conclusions.

BEAM LOSSES

In the environment of superconducting magnets, beam losses are always a major concern. The understanding and minimization of these losses are therefore of vital importance.

Beam losses at beginning of a fill

The Fig.8 shows the losses at the beginning (first 6 minutes) of a typical high luminosity fill [6]. Losses of the

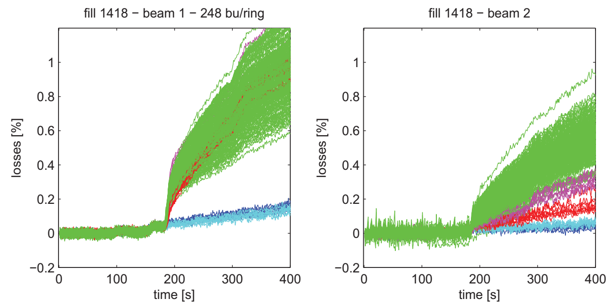

Figure 8: Beam losses at beginning of fill 1418 [6].

order of 1% can be expected and should not lead to beam aborts. A detailed understanding of the losses requires a bunch-by-bunch diagnostics [12] but the already well established dependence on the number of collisions is again visible. A very different picture is shown in Fig.9 where

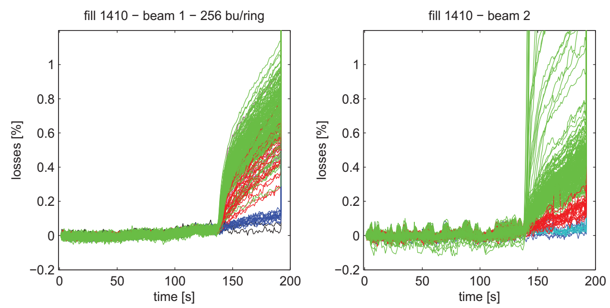

Figure 9: Beam losses at beginning of fill 1410 [6].

some bunches have lost several percent of the intensity after the beams were brought into collision. Such a behaviour is not typical and led to the loss of the fill. Possible sources are mismatched beams during some of the injections since only certain bunches of one train exhibited the bad lifetime. Additional diagnostics would allow to understand and possibly avoid such losses.

For comparison, the beginning of a fill at a well understood and "old" machine is shown in Fig.10 when beams were brought into collisions at RHIC [14]. Initial losses will be difficult to completely avoid since small mismatches or tails in the transverse plane will be swept away by the beam-beam effect. Such a behaviour is well known and observed in many other machines such as SPS or HERA.

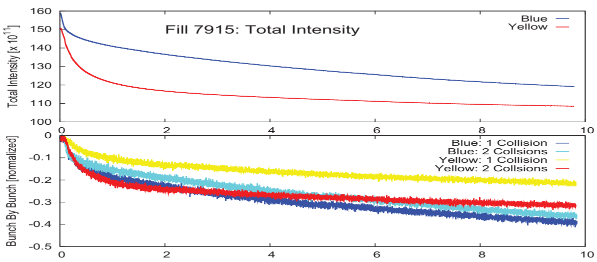

Figure 10: Beam losses at beginning of fill in RHIC [14].

Sudden beam losses during a fill

In the early days of luminosity production occasional sudden beam losses from one of the beams have been observed and have been a worry. In a window of a few minutes some bunches lost up to 10% of their intensities like shown in Fig.11, which displays a typical picture of these losses. In almost all cases the losses were closely related to

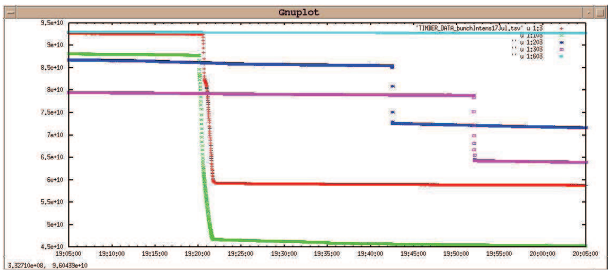

Figure 11: Sudden beam losses during fill.

the luminosity optimization procedure where the beams are moved against each other. The losses of Fig.11 are shown again in Fig.12 together with the steps of a luminosity optimization in IP2 [13]. The correlation is very strong and was observed at other occasions. Initially, when the LHC

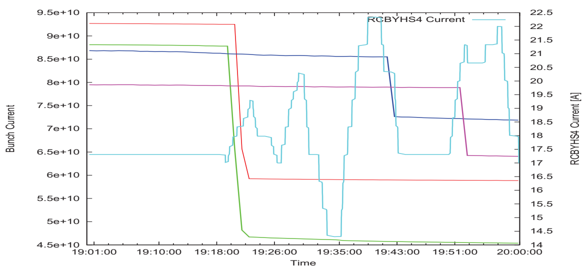

Figure 12: Sudden beam losses during fill and separation scan in IP2 [13].

was run with single bunches, the onset of coherent oscillations has been observed and as a cure a significant tune split between the two beams was introduced and kept.

In a test the tune split between the two beams was inverted and the losses moved to the other beam [6]. It is believed that the increased tune space required is responsible for the bad life time of one of the beams. After removing the tune split the problem did not re-occur.

OBSERVATION OF COHERENT BEAM-BEAM EFFECTS

Coherent oscillations have been reported which could be associated to coherent beam-beam modes. Such modes are expected when few bunches are in the machine or for bunches with very few (i.e. 1) collisions [1] because their excitation requires a high degree of symmetry. If present, they can be cured with a tune split between the two beams or a transverse damper [1]. The observation was however not clear since in many cases the coherent signal was present before the beams were colliding. A further investigation is foreseen to understand this signal. It is also expected that the presence of additional bunches, i.e. additional interactions, breaks the symmetry efficiently to avoid a collective motion [1, 15].

OUTLOOK AND PROPOSALS

Given the first significant experience with beam-beam effects in the LHC, one can attempt an outlook to running scenarios for the LHC in 2011.

Prospects for the head-on beam-beam tune shift

Small contributions of the lattice non-linearities as well as a careful setting of the machine allowed to quickly reach (and exceed) the nominal head-on beam-beam tune shift. The transverse emittances were significantly smaller than nominal and together with intensities slightly higher than nominal allowed head-on tune shifts around $\xi = 0.006$ per interaction point. It has to be seen whether this can be maintained in the presence of many more long range interactions. Yet there is no reason to assume that a head-on limit is reached and it is proposed to push the tune shift further by increasing the intensity with small emittances. The latter have the advantage to ease the provision of large enough separation at the long range encounters.

Possible strategy for maximum luminosity

Given that the limits are not yet reached, the full head-on limit should be explored with small emittances, i.e. values around 2.5 μm and below. Since a high luminosity can only be reached with the maximum number of bunches, the operation with more bunches and 50 ns or 75 ns spacing must be pursued. Using the argument as before, the maximum number of bunches per train should be explored at an early stage and the attainable β^* be found.
The levelling of the luminosity in IP8 [2] requires offsets in the order of 1 - 2 σ and needs to be studied, in particular in the presence of many long range interactions.

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Strategy for Luminosity Optimization

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Abstract

Integrated luminosity is a key parameter for the performance of a particle collider and depends both on beam parameters and operational efficiency. The experimental detectors are turned on and start acquiring useful data only when the machine is declared as stable, it is therefore important to minimize the duration of the activities from the collapsing of the separation bumps until STABLE BEAM is declared. After a review of the current procedure and tools used to bring beams into collision and optimize luminosity, observations and lessons learnt during the 2010 proton run will be presented. The reproducibility and implication of the current procedure regarding machine protection and operation efficiency will be discussed based on this first experience.

INTRODUCTION

The event rate $\dot{N}$ of a process of cross section σ and the instantaneous luminosity $\mathcal{L}_0$ are related for head-on collisions of Gaussian shaped beams by:

$$\mathcal{L}_0 = \frac{N_1 N_2\, f\, N_b}{2\pi\sqrt{(\sigma_{1x}^2+\sigma_{2x}^2)(\sigma_{1y}^2+\sigma_{2y}^2)}} = \frac{\dot{N}}{\sigma}, \qquad (1)$$

where N_1 and N_2 are the bunch intensities, f the revolution frequency, N_b the number of bunches per beam and $\sigma_{ix,iy}$ the effective transverse beam sizes. The two counter rotating beams do not always collide head-on and the beams can be separated in the horizontal and vertical directions by arbitrary amounts δx and δy. The luminosity is then expressed as:

$$\mathcal{L} = \mathcal{L}_0\, \exp\left[-\frac{\delta x^2}{2\,(\sigma_{1x}^2+\sigma_{2x}^2)} - \frac{\delta y^2}{2\,(\sigma_{1y}^2+\sigma_{2y}^2)}\right]. \qquad (2)$$

A fit of the measured interaction rates as function of the separation will allow to determine the optimal beam positions to maximize the collision rate. This method was used at the LHC to optimize the luminosity at the four interaction points [1]. As seen in Equation 2 separation scans can also be used to measure the effective beam sizes at the interaction points and therefore normalize the luminosity [2].

AUTOMATED OPTIMIZATION ALGORITHM

A control software was developed for the purpose of luminosity calibration and optimization using separation scans to allow for fast and automated optimization of the four LHC interaction points. Luminosity optimization is usually performed at the beginning of fills when the luminosity lifetime is the worst. The key parameter to develop a routine for luminosity optimization is therefore the efficiency. A simple routine was developed for this purpose which algorithm can be described as follows:

- **1**: take a reference at current location. Integrate the luminosity over n seconds.
- **2**: compute average and rms at this point.
- **3**: move beam1, beam2 or both by d.
- **4**: integrate over n and compute average and rms.
- **5**: compare the two points.
- **6**: step by d if the new point is larger than the reference or by -2d if it is smaller.
- **7**: repeat steps 3 to 5 until the new acquisition is smaller than the previous one displacing the beams in the direction set in step 6.
- **8**: compute a parabola (analytically) from the last three points and find the optimum settings.
- **9**: move to the optimum and take a last acquisition to confirm the increase with respect to the reference.

The user inputs for this routine are n which corresponds to the integration time per step and d which corresponds to the step size. d should be large enough to ensure a significant change in rates between two consecutive acquisitions. The operator can also specify the IP beam and plane that requires an optimization and which signal (detector) should be used. This method, developed at RHIC [3], allows for fast optimization with simple input parameters of a single interaction point or several in parallel or in series.

COMMISSIONING

Figure 1 shows the optimization of all IPs in series during a squeezed optics proton physics fill with a luminosity of about $5\,10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The luminosity was significantly increased in all IPs except for IP1 where no correction was needed. Each scan consisted of 3 steps of 30 s with a range of $\pm 2\sigma$ for a total duration of a few minutes. The overall duration of the full procedure was about 45 minutes.

At low luminosity, the duration of a scan is constrained by the requirements on the statistical accuracy for each scan step. After each fill the optimum settings are saved and

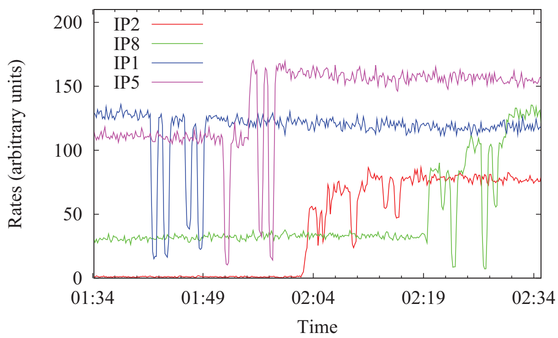

Figure 1: Optimization scans performed in series for squeezed optics in all IPs. The BRAN data shown here are not calibrated which explains the differences between the IPs.

used as the new reference for the next fill. Later on, the algorithm for automated parallel optimization was commissioned and reduced the duration of the optimization to a few minutes. This is shown in Figure 2 in the case of an ion physics fill where only three IPs were optimized as LHCb is not taking data during ions physics.

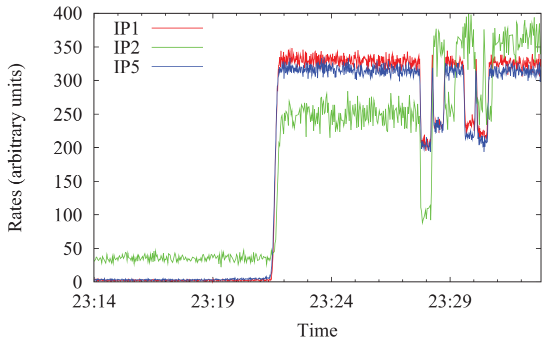

Figure 2: Parallel optimization during an ion physics fill. It took 10 minutes from collision to physics conditions out of which 3 minutes were used to optimize the collision point.

REPRODUCIBILITY AND STABILITY

The luminosity is generally optimized at the beginning of physics fills using dedicated closed orbit bumps. Looking at the variations of the amplitude of these bumps from fill to fill one can estimate the reproducibility of the optimal collision point. This is illustrated in Figure 3 where the fill to fill variations are shown for the last two month of the LHC 2010 proton run. It is seen that the amplitude of the corrections are in most of the case smaller than 60 μm which corresponds to about one beam σ at the IP for an energy of 3.5 TeV and a β^* of 3.5 m. Excluding IP2, the peak and rms corrections are 180 μm and 41 μm in the horizontal plane and 90 μm and 21 μm in the vertical plane. This is clearly sufficient to find the collision point as soon as the injection bumps are ramped down in the case of the 2010 beam parameters. The nominal LHC (7 TeV, β^*=0.55 m) IP beam size is of the order of 17 μm. It could therefore become necessary to improve the reproducibility as the IP beam size becomes smaller.

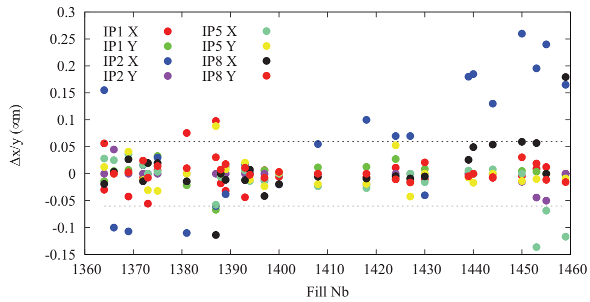

Figure 3: Amplitude of the corrections applied from fill to fill to bring the beams colliding head-on. The fill to fill reproducibility is of the order of 60 μm. Large fluctuations in the horizontal plane at IP2 are observed due to offset collisions.

The large fluctuations observed in the horizontal plane at IP2 are due to operation with offset collisions to reduce the luminosity to the level requested by ALICE. The corrections for IP2 only are shown in Figure 4, one can see on this plot that the vertical plane was in most of the cases not optimized. While some fluctuations are expected when setting the luminosity to a constant value at the beginning of fills when the emittance and intensity vary any offset in the opposite plane (in this case vertical) will also be compensated in the process and will represent an additional source of non-reproducibility. It is therefore desirable to systematically optimize the vertical plane before leveling the luminosity with a separation in the horizontal plane in order to keep the orbit as stable as possible.

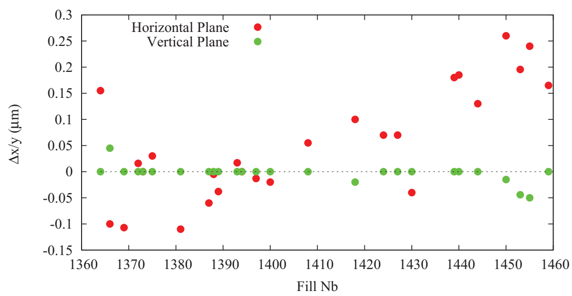

Figure 4: Corrections for IP2 only. Most of the time no corrections were applied in the vertical plane which could have helped reducing the fill to fill variations.

In order to assess the performance in terms of orbit stability during a fill a few scans were performed at the end of fills which results are shown in Table 1. No significant separation drift was observed over the duration of these physics fills which proves the excellent performance of the LHC in terms of stability. It is however important to assess the stability of the collision point in a more systematic way to determine how often these optimization scans would be needed. This could be done almost parasitically during physics fills by regularly performing optimization scans in order to derive some systematic behavior.

Table 1: Position of the peak luminosity as measured with end of fills scans.

	IP1		IP5	
Fill Nb	Δx (μm)	Δy (μm)	Δx (μm)	Δy (μm)
1366	3	3	2	10
1372	1	-4	7	-2
1373	6	16	-5	-3
1393	-5	-2	-2	-5
1450	-1	4	-	-

COLLAPSING THE SEPARATION BUMPS

The beams are brought into collision through a 'PHYSICS' beam process that ramps down the injection separation bumps and loads the optimized bump settings from the last physics fill. The overall duration of this operation was 108 seconds for protons in 2010. After that, global corrections are performed and the luminosity is optimized at the four interaction points with scans before STABLE BEAM is declared. As illustrated in Figure 2, from the moment when the injection bumps are ramped down it takes about 10 minutes to declare STABLE BEAM. During this time no physics data are acquired by the experiments as they can fully turn on their detectors only after STABLE BEAM is declared. It is therefore relevant to investigate possibilities to improve efficiency in order declare STABLE BEAM as soon as possible.

Injection separation bumps are generated with orbit correctors. In order to collapse the separation bumps the fraction of the field of these correctors used to separate the beams has to be ramped down to zero. In this process a parabolic-linear-parabolic ramp will be assumed. The parabolic phases depend on an acceleration term and the linear phase on dI/dt. The separation at the IP varies linearly with the current applied to the correctors. It is possible to find the minimum collapsing time by varying the strength of the MCBX.

Figure 5 shows the evolution of the collapsing time versus the MCBX angular kick at IP1 for the 3.5 TeV LHC optics (full 2 mm separation). Given the actual hardware settings, the limitation comes from the MCBX and the collapsing time only depends on its acceleration and ramping rate. About 20 seconds can be gained with the current hardware performance, increasing the ramp rate of the MCBX to 5 A/s (as initially foreseen) or splitting the strength between the different MCBXs would significantly reduce the overall duration. The collapsing time scales with energy as the required current in the orbit correctors will increase, in this case the gain becomes more significant as demonstrated in [4]. In 2010, the bumps were collapsed from the

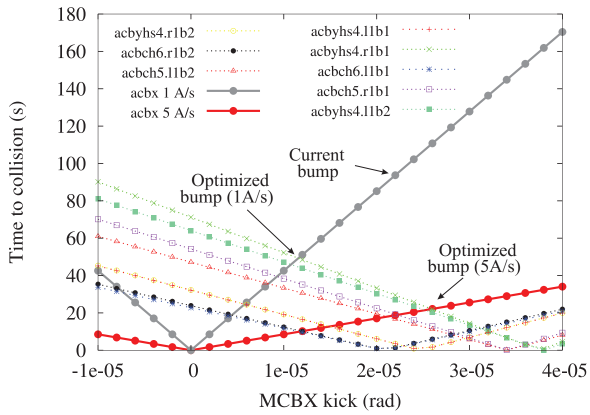

Figure 5: Time required to bring beams into collision as a function of the MCBX strength for IP1. About 20 seconds can be gained with the current hardware performance, changing the ramp rate of the MCBX to 5 A/s would reduce this time to about 20 seconds.

full 2 mm separation required at injection. As the beams are ramped to high energy the beam size at the IP is reduced and therefore the IP separation could also be reduced in this process in order to gain some time in the process of bringing them into collision.

LUMINOSITY OPTIMIZATION AND MACHINE PROTECTION

The beams are displaced at the IP via a closed orbit bump that consists of four magnets and allows to control the beams independently.

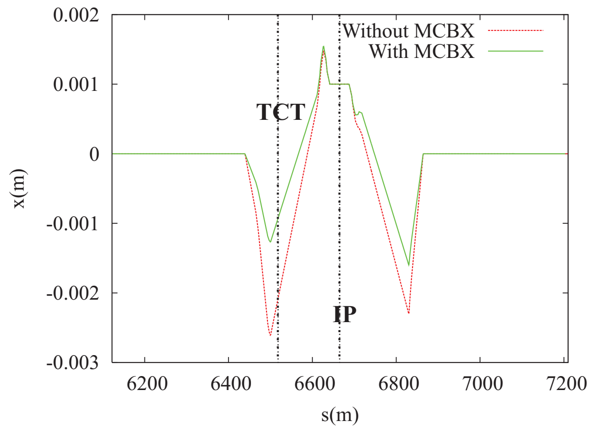

Figure 6: Example of closed orbit bumps using different orbit correctors at IP5. Displacing the beam at the IP also changes the orbit at the tertiary collimator location.

One can see in Figure 6 that a four magnet separation bump extends over a large fraction of the straight section around the IP. More specifically, displacing the beams at the IP will result in a change of orbit at the tertiary collimators (TCT). Given the non-negligible offset at the TCT introduced by the bumps, one has to ensure that while performing a separation scan the beams remain far enough from the aperture set by the collimators and that the displacement does not compromise the machine protection. In 2010, the displacement at the TCT was minimized by splitting the amplitude of the corrections required to find the optimum collision point between the two beams. Initial estimates [5] showed that in case the orbit is stable within tolerance and does not drift to far off the reference orbit, there should be sufficient margins to perform optimization scans with limited separation range while preserving the collimator hierarchy and the triplet protection. It is however important to confirm these estimates with experimental data.

A detailed study of the collimation system performance and estimates of the real available margins based on measurements for the 2010 proton run can be found in [6] and [7]. The margin was estimated to be of the order of 2.5 σ for the 3.5 m optics. On the two top plots of Figure 7 the orbit fluctuations at the TCTs expected from the scans (estimated from the bump amplitude) are shown. The two bottom plots show the measured orbit fluctuations from fill to fill. The estimated fluctuations from the scans are in general smaller than 0.2 σ and go up to 0.5 σ in the case of IP2 where the beams were colliding with an offset. This is well within the margin of 2.5 σ estimated in [7]. The measured orbit fluctuations are larger than what is expected from the scans only, and large offsets (up to 1.5 σ) are observed from the beginning. One can conclude from these observations that during the 2010 proton the optimization scans amplitude remained well within the safety margins and only contributed partially to the overall orbit fluctuations in the TCT region. A review of the procedure to control and correct the orbit in the IR regions could improve these performance and the stability of the collision point.

A possible scenario for the 2011 LHC proton run is to operate with a higher energy and a β^* of 1.5 m in which case the margin was estimated to 1.5 σ [7]. It is possible to estimate the contributions to the orbit fluctuations at the TCTs from scans by rescaling the 2010 measurements. This is shown in Figure 8 where an energy of 4 TeV was considered. In case the energy remains at 3.5 TeV this picture will improve as the beam size at the TCTs will be larger. It is seen that the maximum displacement is of the order of 0.2 σ for an rms of 0.05 σ which is well within the available margin, it should therefore be possible to safely operate the machine using the same procedure as in 2010 for luminosity optimization assuming the overall performance of the machine are the same. As β^* is decreased the aperture in the triplets becomes tighter. One should therefore make sure the triplets remain in the shadow of the TCTs when driving IP separation bumps to large amplitudes.

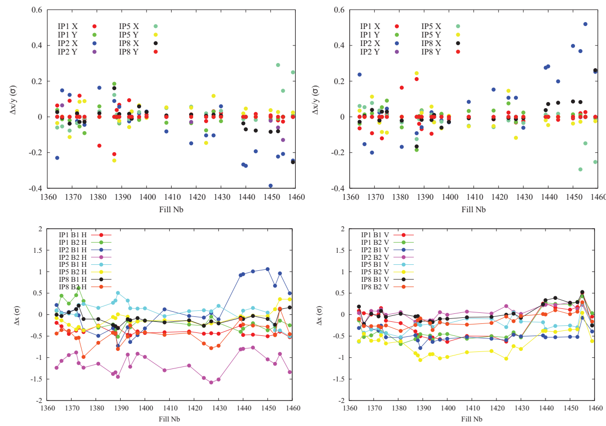

Figure 7: The two top plots illustrate the displacement at the TCT resulting from the optimization scans for beam 1 (left) and beam 2 (right). One can observe a symmetry between the two beams as the corrections amplitude is split in between them. The fluctuations are of the order of 0.2 σ. The two bottom plots show the difference with respect to the reference orbit at the TCT as measured from the BPMs in the horizontal (left) and vertical (right) planes. One can see that the fill to fill fluctuations are larger than what is expected from the scans.

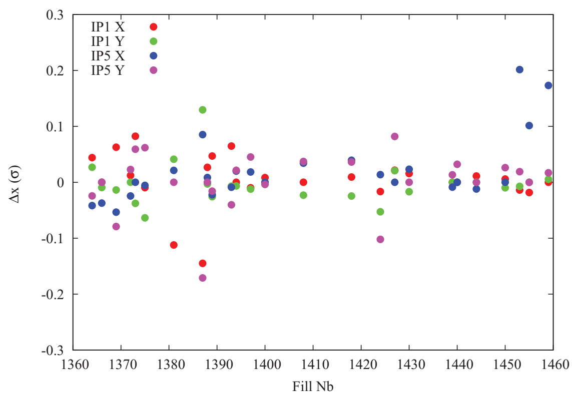

Figure 8: Rescaling of the observed displacement at the TCT from the scans at 3.5 TeV and β^*=3.5 m to 4 TeV and β^*=1.5 m. The expected fluctuations are of the order of 0.1 σ.

CONCLUSION

The procedures and tools for luminosity optimization were successfully commissioned and operated during the 2010 LHC run. The performance are excellent for a first year of operation. The fill to fill reproducibility could be further improved with a better control of the orbit in the IR region which could become necessary when the IP beam size is significantly reduced. No significant drift was observed during a fill. The interaction with the machine protection system proved to be small in 2010 and no significant issues are foreseen in the case of smaller β^* and higher energy as long as the performance in terms of reproducibility and stability remain the same. The bump amplitudes should however be carefully monitored in order to ensure that the orbit at the TCTs and at the triplets remains within the margins set by the collimation system. The procedure to bring beams into collision is well optimized. The efficiency could be slightly improved with an optimization of the separation bumps and a reduction of the separation during the ramp. The orbit fluctuations at the TCTs during optimization scans observed in 2010 as well as the estimates for 2011 are well within the available margins, performing these scans during STABLE BEAM could therefore be considered as a possible improvement of the procedure.

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The LHC optics in practice

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Abstract

During LHC 2010 run, approximately 40 experimental sessions for optics measurements were carried out. Both local and global corrections were implemented, demonstrating the feasibility of achieving 10% peak beta-beating. The long-term optics stability is presented with extrapolations of errors down to β^* of 0.55 m. Operational issues arising during corrections, such as the treatment of hysteresis, will also be discussed.

1. INTRODUCTION

The CERN LHC is the first hadron collider with tight design tolerances on optics errors to guarantee the machine protection during operation with beam. This called for a quest of the most convenient optics measurement techniques [1, 2, 3, 4] and instruments [5, 6, 7]. Several measurement and correction algorithms were tested in SPS [8, 9, 10], RHIC [11] and SOLEIL [12]. The first optics measurement of the LHC [13] revealed an unexpectedly large β-beating. The leading source of this error was identified as a cable swap between the two beam apertures of a trim quadrupole. This finding was only possible with the aid of a new approach for optics correction, the Segment-By-Segment Technique (SBST). This technique has evolved to include the full set of linear optics parameters in the general case of a coupled lattice, see Section 2.

Figure 1 shows the peak β-beating (top) and the rms orbit (bottom) of the LHC Beam 2 at injection energy versus the number of days in commissioning with circulating beam. In about 60 days of operation with circulating beam the dominant optics errors were identified and corrected at injection, considerably reducing the β-beating to values close to design targets. The evolution of the rms orbit features a clear correlation with the β-beating since the orbit correction uses the orbit response matrix from the ideal model. Figure 1 also shows the relevant events that affected the optics quality. "LSA tuning" refers to adjustments in the magnet model coefficients. "New cycle" refers to a modification of the energy evolution versus time during the ramp. A good stability of the optics is observed in periods over 30 days when the machine was unchanged. A more detailed stability analysis is presented in Section 8.

During the energy ramp the optics errors are considerably reduced due to the lower persistent current effects in the superconducting magnets and the lower remnant magnetization in the normal conducting magnets. Figure 2 shows the reduction of the β-beating in the beginning of the energy ramp as measured after the new MQW calibrations were applied in May 2010. For energies above 1 TeV

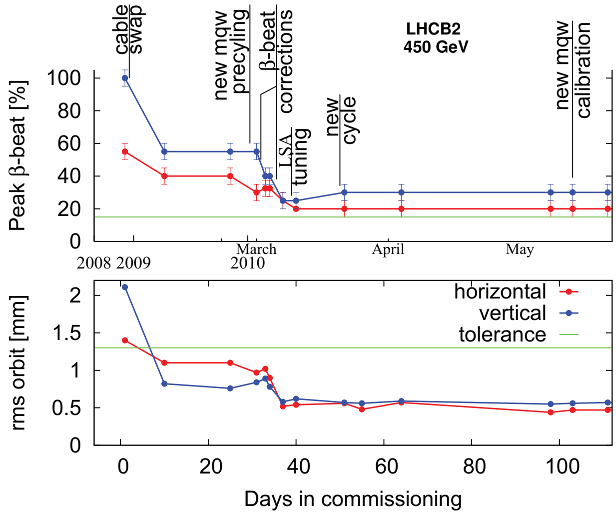

Figure 1: Measured peak β-beating (top) and rms orbit (bottom) at injection for Beam 2 versus the number of days of LHC operation after circulating beam was established in 2008. Relevant events affecting the LHC optics are also displayed. LSA stands for LHC Software Architecture [14].

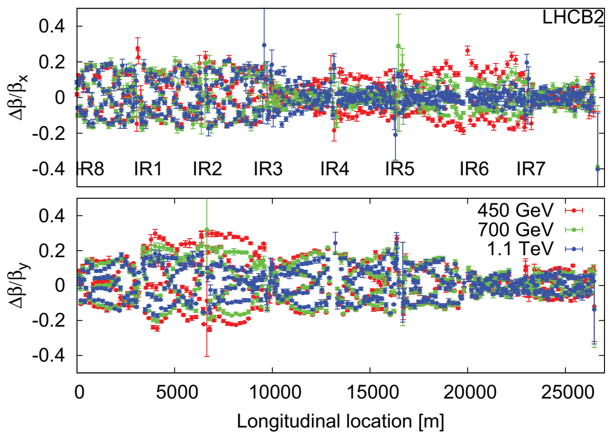

Figure 2: Measured β-beating for three energies in the beginning of the energy ramp.

the β-beating remains unchanged. The injection optics corrections are gradually remove with energy, being zeroed at 700 GeV.

At 3.5 TeV the β^* at the Interaction Points (IPs) were initially squeezed to 2 m to increase the luminosity. The commissioning of the four IPs β^* squeeze is summarized in Fig. 3 showing the peak β-beat and the four β^* versus

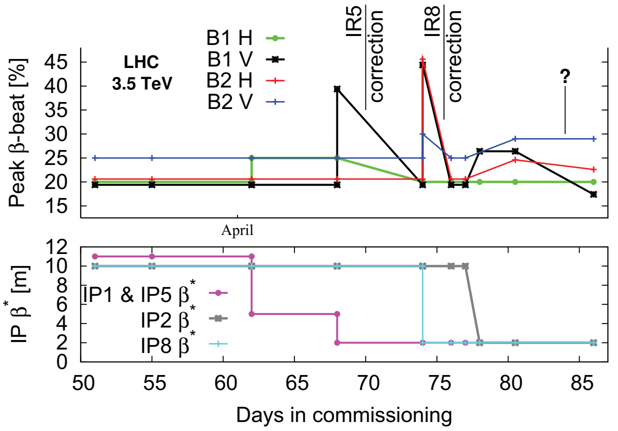

Figure 3: Measured peak β-beating (top) and β^* (bottom) versus the number of days of LHC operation during the commissioning of the β^* squeeze down to β^*=2 m. The question mark indicates the observation of an important variation of the vertical Beam 1 β-beating without any change in the machine.

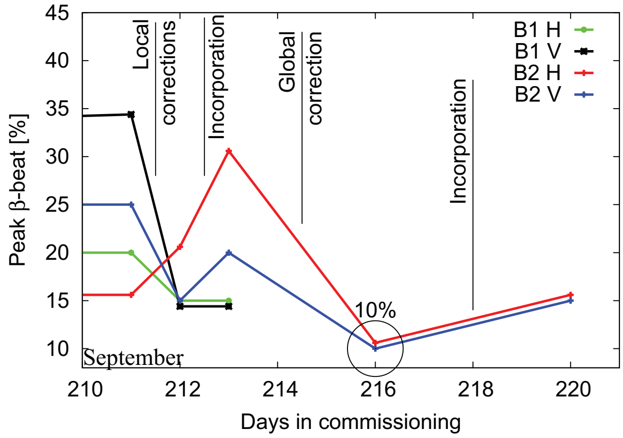

Figure 4: Measured peak β-beating versus the number of days of LHC operation during the optics corrections at β^*=3.5 m.

time. About 15 days were used to achieve 2 m at all IPs. Large optics errors became evident in the Interaction Regions (IRs) as β^* was being reduced. Local optics corrections were computed on-line and fully implemented in the squeeze procedures. After the squeeze a rather poor reproducibility of the vertical β-beating in Beam 1 was observed. This is described in more detail in Section 6.

After a short operation with β^*=2 m it was decided to increase β^* to 3.5 m at all IPs to allow for IP crossing angles with safe aperture margins in the triplets. Local and global optics corrections were applied reaching a 10% peak β-beating in Beam 2. Figure 4 shows the evolution of the optics errors versus time. Unfortunately important differences were observed between the on-line corrections (perform with trims) and the corrections as incorporated in the magnet functions. These discrepancies have been fully understood and their origin is described below.

The next sections describe: the theory concerning the extensions to the SBST (Section 2); the implications of using AC dipoles (Section 3); the K-modulation technique (Section 4); the experimental measurements and corrections at injection (Section 5); at β^*=2 m (Section 6); at β^*=3.5 m (Section 7); the optics stability (Section 8); a summary of β^* measurements (Section 9); extrapolations to lower β^* (Section 10); the coupling compensation (Section 11); triplet higher order correctors (Section 12); and the summary and recommendations (Section 13).

2. EXTENDED SBST

In [13] and the SBST was introduced to identify the dominant optics error in the LHC in 2008. This error was responsible for approximately 50% of the β-beating in the vertical plane of Beam 2, see Fig. 1. Since then the SBST was extended to localize and correct linear optics errors, both normal and skew [15]. The basic concept of the SBST relies on splitting the machine into various sections and therefore treat them as independent beam lines. The measured optics parameters at the beginning of each section are used as initial optics conditions. This was first applied to β and α functions, which are inferred from the phase measurements between three BPMs [16]. The phase advance within the segment proved to be a more precise and local observable. The horizontal and vertical dispersions can also be incorporated in the SBST by computing the angular dispersion ($D'_{x,y}$) at the start of the section. The dispersion measurement at the first two BPMs is used to infer $D'_{x,y}$ by assuming the ideal model between them. A more subtle and innovative addition to SBST is the transverse coupling. All the coupling parameters need to be measured at the start of the segment and translated into the MADX [17] formalism for propagation through each section. The real and imaginary parts of the difference (f_{1001}) and sum (f_{1010}) resonance terms are extracted from the measured spectrum of the normalized complex signal [18, 19], $h_x = \hat{x} - i\hat{p}_x$, which is parametrized to the first order as

$$\begin{aligned} h_x(N) &= \sqrt{2I_x}e^{i\phi_x(N)} - \\ &\quad i2f_{1001}\sqrt{2I_y}e^{i\phi_y(N)} - i2f_{1010}\sqrt{2I_y}e^{-i\phi_y(N)} \\ h_y(N) &= \sqrt{2I_y}e^{i\phi_y(N)} - \qquad (1) \\ &\quad i2f^*_{1001}\sqrt{2I_x}e^{i\phi_x(N)} - i2f_{1010}\sqrt{2I_x}e^{-i\phi_x(N)} \end{aligned}$$

where $I_{x,y}$ are the action invariants and $\phi_{x,y}(N) = 2\pi NQ_{x,y} + \phi_{x0,y0}$ describe the turn-by-turn phase evolution. The LHC double plane BPMs allow the measurement of $\phi_{x0,y0}$ from the horizontal and vertical tune spectral lines. With the measured phases the real and the imaginary parts of f_{1001} and f_{1010} can be calculated from both the horizontal and vertical spectra as shown by Eqs. (1). In order to achieve a measurement independent of BPM calibration and beam decoherence, the values obtained from

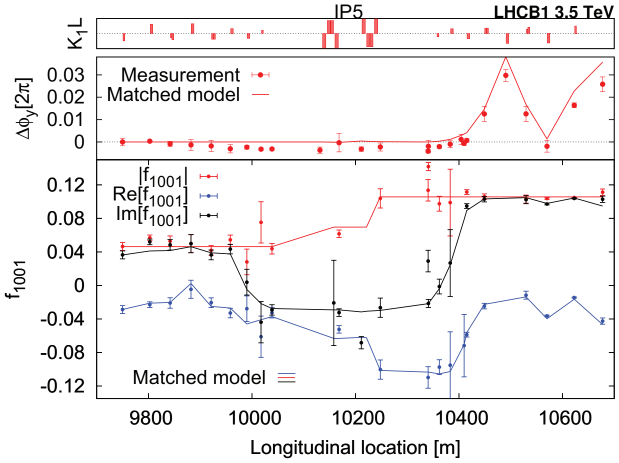

Figure 5: Example of the extended SBST applied to the correction of the IR5 normal and skew optics errors for Beam 1 at 3.5 TeV. The IR quadrupoles (top), the vertical phase advance error (middle plot) and the difference resonance term f_{1001} (bottom) are shown. The lines represent the matched model with normal and skew errors located in the triplets.

the horizontal and vertical planes are geometrically averaged as described in [20]. The measured f terms unambiguously determine the coupling matrix $\bar{\mathbf{C}}$ using the following relations [21],

$$
\begin{aligned}
f_{1001} &= \frac{1}{4\gamma}(\bar{C}_{12} - \bar{C}_{21} + i\bar{C}_{11} + i\bar{C}_{22}), \\
f_{1010} &= \frac{1}{4\gamma}(-\bar{C}_{12} - \bar{C}_{21} + i\bar{C}_{11} - i\bar{C}_{22})\,, \qquad (2)
\end{aligned}
$$

where $\det(\bar{\mathbf{C}}) + \gamma^2 = 1$. These equations are fundamental to translate the measured coupling terms f_{1001} and f_{1010} into the initial optics conditions in the MADX formalism. An illustration of the extended SBST applied to the correction of IR5 normal and skew gradient errors in the triplet is shown in Fig. 5. The lines represent the propagated model matched to the measurement. The normal gradient errors generate the vertical phase-beating. The skew gradient errors cause the jumps of $|f_{1001}|$, which would stay constant in the absence of coupling sources. The matching of f_{1001} uses the inner triplet skew quadrupole correctors as coupling sources for convenience. There is one skew corrector located between the second and the third quadrupole of each triplet. Consequently, only two jumps of $|f_{1001}|$ are observed in Fig. 5.

3. AC DIPOLE

AC dipoles were initially applied in hadron accelerators to overcome intrinsic spin resonances [22]. AC dipoles force long-lasting betatron oscillation without emittance growth when ramped up and down adiabatically. The long-lasting oscillations are ideal for transverse beam dynamics measurements. The slow increase of the oscillation amplitude guarantees the effective response of the machine

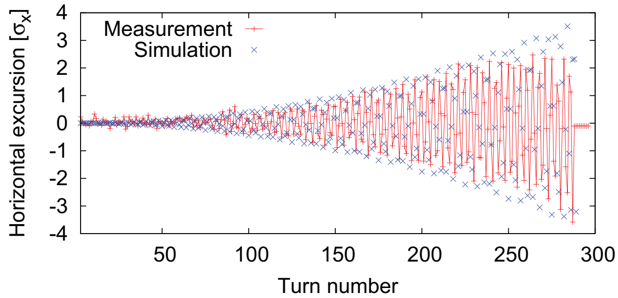

Figure 6: Measured and simulated horizontal beam excursions with the AC dipole ramping up on the tune resonance.

protection devices in case of a failure [6]. These properties make the AC dipole an ideal transverse exciter for the LHC. Dedicated measurements were performed in the LHC to verify the safe operation of the AC dipole and to confirm the trajectory predictions in [6]. Figure 6 shows the measured and simulated beam excursion while ramping the AC dipole to 20% of its maximum strength in 2000 turns with a frequency equal to the tune. At the turn 290 the beam was cleanly dumped by the machine protection system after having detected losses at the primary collimators (with a half gap of 6σ). This, together with the good agreement between measurement and simulation, validated the AC dipole as a safe instrument.

However forced oscillations differ from free oscillations proportionally to the distance between the driving tune and the machine tune [23, 24, 25, 26]. In presence of an AC dipole the measured β functions differ from the machine β functions. This difference is simply modeled as a quadrupole error in the location of the AC dipole [27]. This equivalence allows to apply exactly the same analysis to all experimental data but using a modified reference model which includes the quadrupole error according to the AC dipole settings. The measured difference resonance term $\hat{f}_{1001}$ also differs from the machine f_{1001} as follows [26, 28],

$$
\hat{f}_{1001} = \frac{\sin\left(\pi(Q_x - Q_y)\right)}{\sin\left(\pi(Q_{ac} - Q_y)\right)} f_{1001}\left(1 + O(\delta)\right) \qquad (3)
$$

assuming a horizontal AC dipole with driving tune Q_{ac} and $\delta = Q_x - Q_{ac}$. The fraction on the right hand side is a global factor easily taken into account. More precise expressions, also for the sum coupling resonance, can be found in [28]. In the LHC it is customary to excite at $|\delta| = 0.005$ without significant emittance blow-up, yielding a systematic error of about 3% in f_{1001}.

4. K-MODULATION

A change in the integrated strength of a quadrupole ΔKL yields a change in the tunes $\Delta Q_{x,y}$ that can be unambiguously used to determine the average $\beta_{x,y}$ functions at the quadrupole [29],

$$\beta_{x,y} \approx \pm 4\pi \frac{\Delta Q_{x,y}}{\Delta KL} , \tag{4}$$

where the $\pm$ sign refers to the horizontal and vertical planes, respectively. This equation neglects the effects of transverse coupling and it is applicable for $2\pi|\Delta Q_{x,y}| \ll 1$ and $Q_{x,y}$ far away from the integer and the half-integer. During 2010 first tests of K-modulation were carried out using the triplet quadrupoles. However the resolution of these measurements was limited by transverse coupling. Future K-modulation measurements will be preceded by a good coupling correction ($\Delta Q_{min} \leq 0.001$).

5. OPTICS CORRECTIONS AT INJECTION

Optics measurements during 2009 at injection energy allowed to identify the largest error sources [30]. The sections with the largest error sources are the warm regions IR3 and IR7, which are dedicated for collimation, followed by the triplets in IR2 and IR8 and by the quadrupolar error in the main dipoles (the b_2 component). It is worth mentioning that due to injection constraints the triplets in IR2 and IR8 feature a larger gradient than those in IR1 and IR5 [31]. The error sources in IR3 and IR7 vanish at higher energies [30]. Some quadrupoles in IR3 and IR7 are powered below 1 Ampere at injection. These findings allowed magnet experts to identify a wrong magnetic pre-cycle in the main quadrupoles of IR3, IR7 and the triplets [32]. The quadrupoles in IR3 and IR7 operate at room temperature and they belong to the type MQW. The pre-cycles for the MQW magnets were changed in 2010 to improve reproducibility at injection energy where magnetic hysteresis plays an important role, see Fig. 1, improving the horizontal β-beating in Beam 2. Nevertheless optics corrections were still required. Figure 7 shows the β-beating before and after correction for Beam 1. All the corrections were computed via the SBST to ensure locality. Figure 8 illustrates the local optics correction in IR3. IR3 and IR7 insertions are particularly constrained for optics correction since the main warm quadrupoles (MQWA) are powered in series on both sides and for both beams, while the trim quadrupoles (MQWB) are powered in series for both beams (but not for both sides) [33]. The size of the required relative corrections is at the 1% level for the MQWA quadrupoles and between 10% and 200% for the MQWB quadrupoles. The MQWB quadrupoles are trim magnets nominally set to a very low field. This explains the larger relative errors in the transfer function of these quadrupoles. These large corrections could only be understood by the fact that the magnetic pre-cycle of the MQW magnets was still not identical to that used during the magnetic measurements. New magnetic measurements of two spare MQW quadrupoles were performed using exactly the same magnetic cycle as in the LHC operation. The results of these measurements agree to a large extent with the optics corrections applied earlier. Table 1 shows nominal gradients and relative gradient errors for the settings before and after the optics correction using the new magnetic measurements as reference. The gradient errors after the optics corrections are substantially reduced for all magnets. The locality of the optics corrections based on the SBST proves to reach the magnet level thanks in part to the lack of degeneracy between variables (magnet strengths) and observables (phase advance at the BPMs).

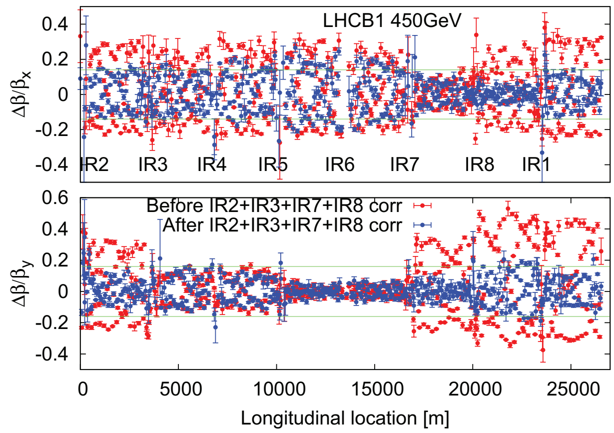

Figure 7: β-beating for Beam 1 before and after corrections at injection energy.

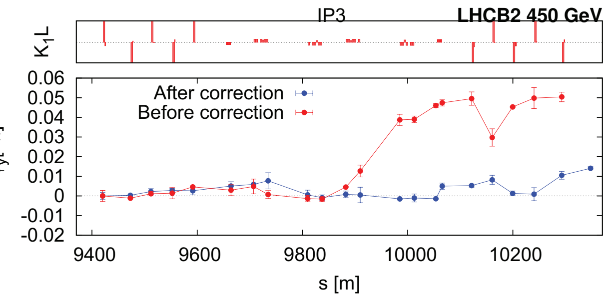

Figure 8: Illustration of the local optics correction in IR3 for Beam 2 at injection.

It was decided to update the MQW calibrations in the LHC controls system according to the new magnetic measurements. As expected, the current β-beating is comparable to that previously obtained with the optics corrections, see Fig. 9. Further corrections can improve the optics but the β-beating level is considered to be acceptable for the existing aperture (due to a lower than expected rms orbit, see Fig. 1).

6. OPTICS CORRECTIONS AT β^*=2 M

At 3.5 TeV the IPs were first squeezed sequentially (IP1 and IP5, IP8 and IP2) allowing for local optical corrections after each IP reached 2 m, as shown in Fig. 3. All IPs were finally squeezed simultaneously. All measurements at 3.5 TeV are performed with the AC dipoles. Measure-

Magnet	Nominal gradient [T/m]	Estimated error before correction [%]	Estimated error after correction [%]
MQWA5.LR3	1.957	1.1	-0.5
MQWA4.LR3	1.863	1.3	-1.5
MQWA5.LR7	2.005	1.0	-0.1
MQWA4.LR7	1.972	1.1	-0.6
MQWB5.L3	1.459	-11.1	-1.1
MQWB4.L3	1.034	-18.7	-2.5
MQWB4.R3	1.034	-16.6	1.5
MQWB5.R3	1.459	-11.2	-0.6
MQWB5.L7	0.049	-83.4	-8.5
MQWB4.L7	0.498	-32.6	1.9
MQWB4.R7	0.498	-44.1	-15.2
MQWB5.R7	0.049	-81.5	3.8

Table 1: Gradient errors of IR3 and IR7 quadrupoles at injection energy before and after optics corrections as inferred from the new magnetic measurements performed on the spare MQWA and MQWB magnets. All errors are substantially reduced by factors between 2 and 25 with the exception of MQWA4.LR3.

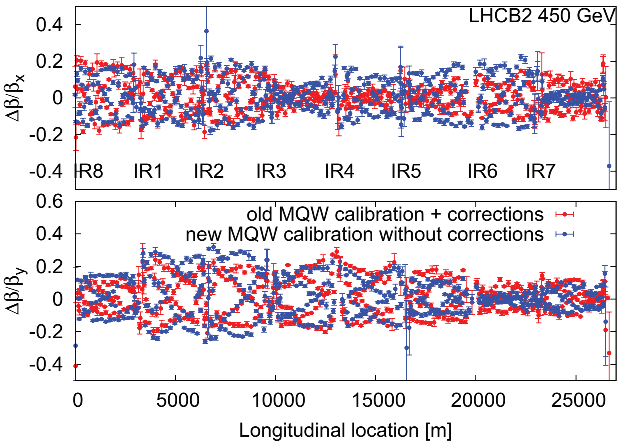

Figure 9: Beam 2 β-beating at injection before and after updating the MQW magnetic calibrations, showing a comparable performance.

ments prior to the local IR corrections at β^*=2 m reveal unexpectedly large optics distortions as shown in Fig. 10. Up to 60% β-beating is observed in the vertical plane of Beam 1. Table 2 shows the magnets used for this correction. For IR5 it was possible to find a triplet correction that would correct both beams. Figure 11 illustrates the simultaneous two-beam correction showing the local IR5 phase-beating before and after correction for the vertical plane of Beam 1 and the horizontal plane of Beam 2.

The dominant optics error source appears in IR8. In this IR it was not possible to find a local correction for both beams using only the common triplet magnets. A practical approach was to use only independent magnets, resulting in the large relative corrections reported in Table 2. The triplets in IR8 have known relative calibration errors in the order of 1.3×10^{-3}. After the corrections were applied it

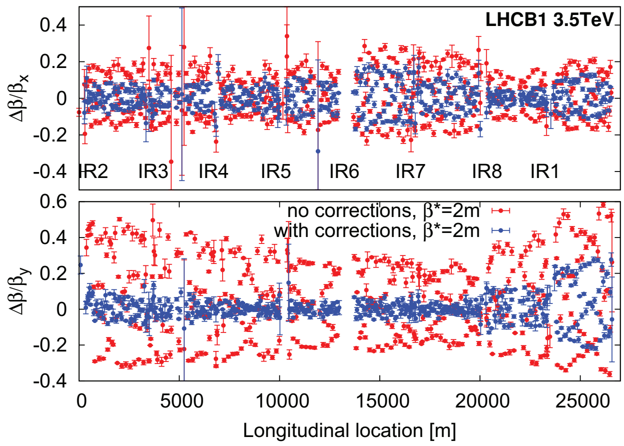

Figure 10: Beam 1 horizontal (top) and vertical (bottom) β-beating before and after correction with all IPs at β^*=2 m at 3.5 TeV.

Table 2: Magnets used to correct the β-beating at 3.5 TeV with the IPs at β^* of 2 m. Design and maximum strengths are shown together with the relative corrections.

Magnet	Design K_1 [m^{-2}]	Maximum K_1 [m^{-2}]	Correction [%]
MQXB2.R5	-0.0087	0.018	-0.15
MQXB2.L5	0.0087	0.018	0.12
MQ5.R8B1	-0.0029	0.013	5
MQ6.L8B2	0.0056	0.013	1.8

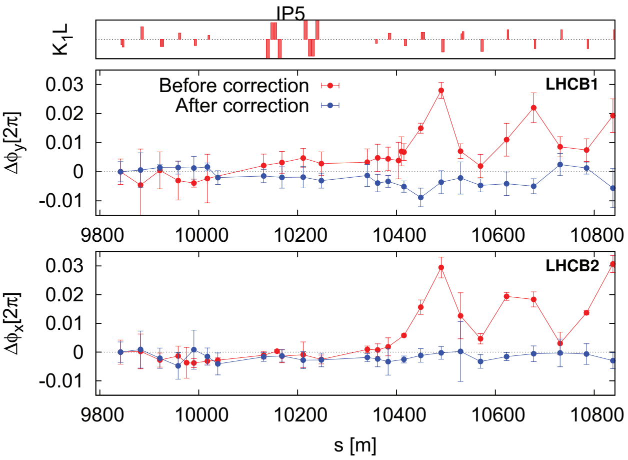

Figure 11: Illustration of the two-beam β-beating correction using the IR5 triplets.

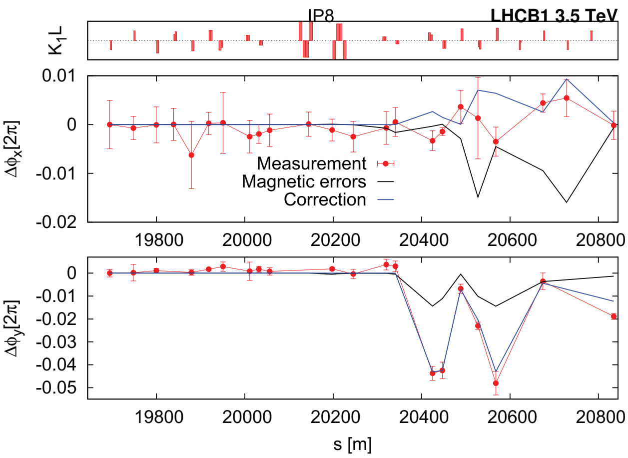

Figure 12: Local Beam 1 IR8 correction increasing by 5% the fifth quadrupole to the right of IP8.

was checked that these errors explain about 30% of the vertical phase-beating for Beam 1, see Fig. 12. Updating the calibration of the IR8 triplets would reduce the required correction from 5% to 3.3%. Figure 10 shows the reduction on the β-beating due to all the local corrections combined.

In an attempt to better understand the error sources the SBST was applied to the horizontal and vertical dispersion in IR8, see Fig. 13. However no significant dispersion error is observed. This is probably due to the low dispersion values across the IR8 triplet. No crossing angles were used at the time of the measurements.

A lack of reproducibility of the β-beating in the 10% level was observed for the first time with the squeezed β^*. Figure 14 shows the difference of the β-beat between two measurements separated by five days. The first measurement was performed immediately after the squeeze while the second was done at the end of a 30 hours physics fill. Figure 14 shows abrupt jumps at IR8 and IR2. A possible explanation is the decay of the quadrupolar errors in IR

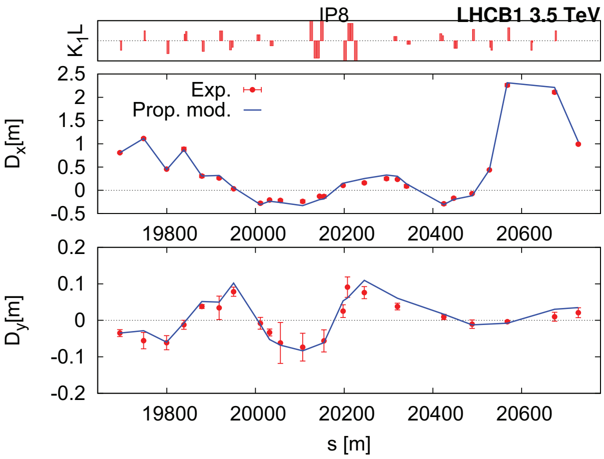

Figure 13: Measured and propagated horizontal and vertical dispersions across the IR8. No significant error is observed from the dispersion functions.

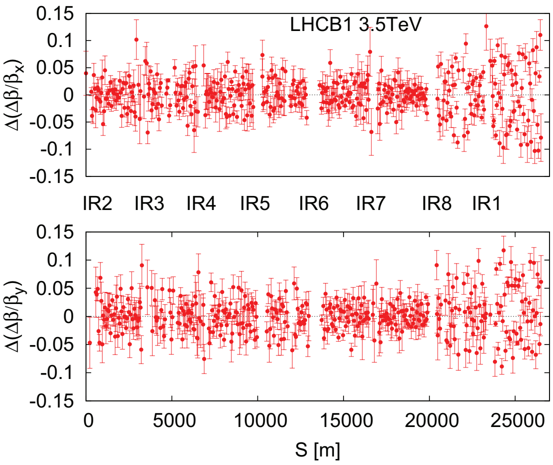

Figure 14: Difference of the Beam 1 β-beating between 2 measurements at β^*=2 m separated by 5 days. The second measurement was performed at the end of a 30 hours fill.

superconducting magnets along the fill. Such a decay was observed in magnetic measurements with the 7 TeV settings [34] but there is no data available for the settings at 3.5 TeV. More statistics are needed to better understand the level of reproducibility and the possible "dynamic" error sources.

7. OPTICS CORRECTIONS AT β^*=3.5 M

In September 2010 the speed of the energy ramp was increased from 2 A/s to 10 A/s. This motivated a re-commissioning of various systems including the β-beating correction at β^*=3.5 m. Local corrections in IR1, IR2, IR5, IR6 and IR7 considerably reduced the peak β-beating in three of the four transverse planes of the two beams, as shown in Fig. 4 and illustrated for Beam 1 in Fig. 15. The quadrupoles used in the local correction are shown in Table 3.

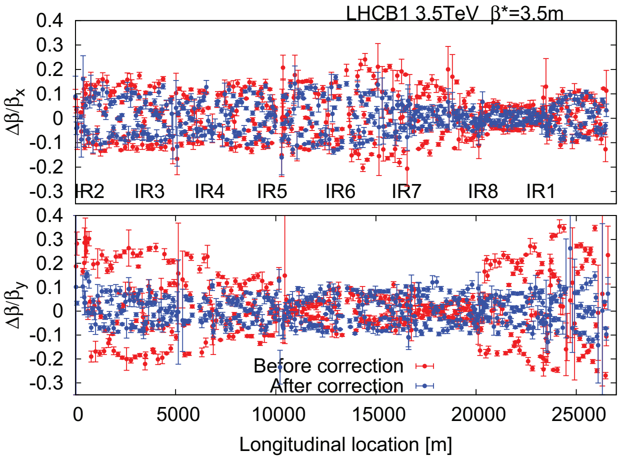

Figure 15: β-beating before and after the local correction for Beam 1 with β^*=3.5 m.

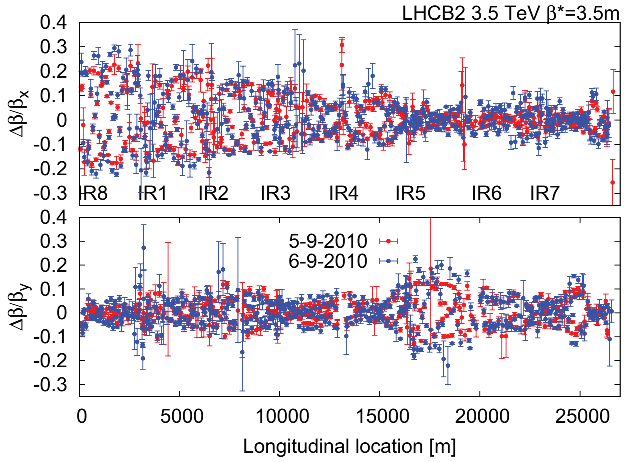

Figure 16: Comparison of the Beam 2 β-beating between trimming and incorporating the local correction with β^*=3.5 m.

Table 3: Magnets used for the local correction at 3.5 TeV with β^*=3.5 m. Design strengths are shown together with the relative corrections.

Magnet	K name	Design $[m^{-2}]$	Correction [%]
MQXB2.R1	ktqx2.r1	0.00871	0.09
MQM.5R2.B2	kq5.r2b2	0.00350	0.48
MQY.5L2.B2	kq5.l2b2	-0.00255	2.00
MQM.9R2.B1	kq9.r2b1	-0.00530	1.30
MQXB2.R5	ktqx2.r5	0.00871	-0.11
MQXB2.L5	ktqx2.l5	-0.00871	0.11
MQY.5L6.B2	kq5.l6b2	-0.00661	0.50
MQY.5L6.B1	kq5.l6b1	0.00644	0.60
MQM.6L8.B1	kq6.l8b1	-0.00535	0.50
MQY.4R8.B1	kq4.r8b1	0.00353	0.48
MQXB2.L8	ktqx2.l8	0.00882	0.26
MQXB2.R8	ktqx2.r8	-0.00882	-0.06

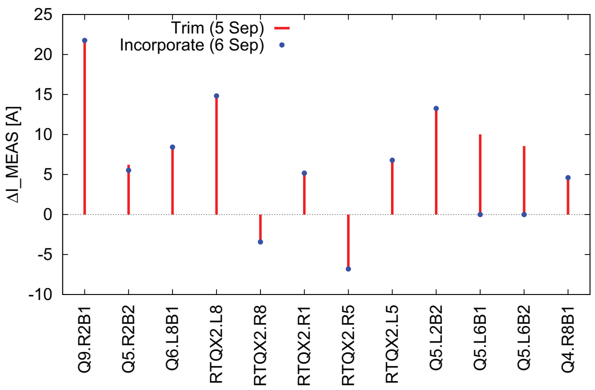

Figure 17: Quadrupole currents deviation with respect to nominal after trimming the local correction and after incorporation.

After incorporating the local corrections in the LSA settings the measured β-beating differed from the previous measurement after trimming on-line the corrections as illustrated in Fig. 16. The quadrupole currents for these two measurements have been retrieved from TIMBER [35] and they are compared in Fig. 17. Clear differences appear which are better understood below when discussing the global corrections.

The Beam 2 horizontal β-beating after incorporating the local corrections increased to 30%. The most effective way to significantly reduce this β-beating was to apply a global correction using about 100 quadrupoles distributed around the LHC Beam 2 as shown in Fig. 18. This was the first time global optics corrections were performed in the LHC. The β-beating was reduced to about 10% in both transverse planes of Beam 2 as shown by the red points of Fig. 19. This is the first time 10% peak β-beating has been achieved in the LHC and probably in any hadron collider. The record low β-beating only lasted for a short period. After the incorporation of the global correction it increased to about 15%, blue points of Fig. 19. Again, we compare the quadrupole currents between trim and incorporation for the global correction in Fig. 20. Only the quadrupoles showing discrepancies are displayed.

Two distinct discrepancy modes are observed:

- At incorporation the correction is ignored ($\Delta I_{MEAS} = 0$) for quadrupoles in IR3, IR4, IR6 and IR7. This has been recently identified as a feature in the controls system for not driving these IRs during the β^* squeeze.
- 1 A difference between trim and incorporation are caused by the controls system interpreting a change of hysteresis branch caused by the correction itself.

The optics discrepancies between trim and incorporation were dominated by not driving quadrupoles in IR3, IR4,

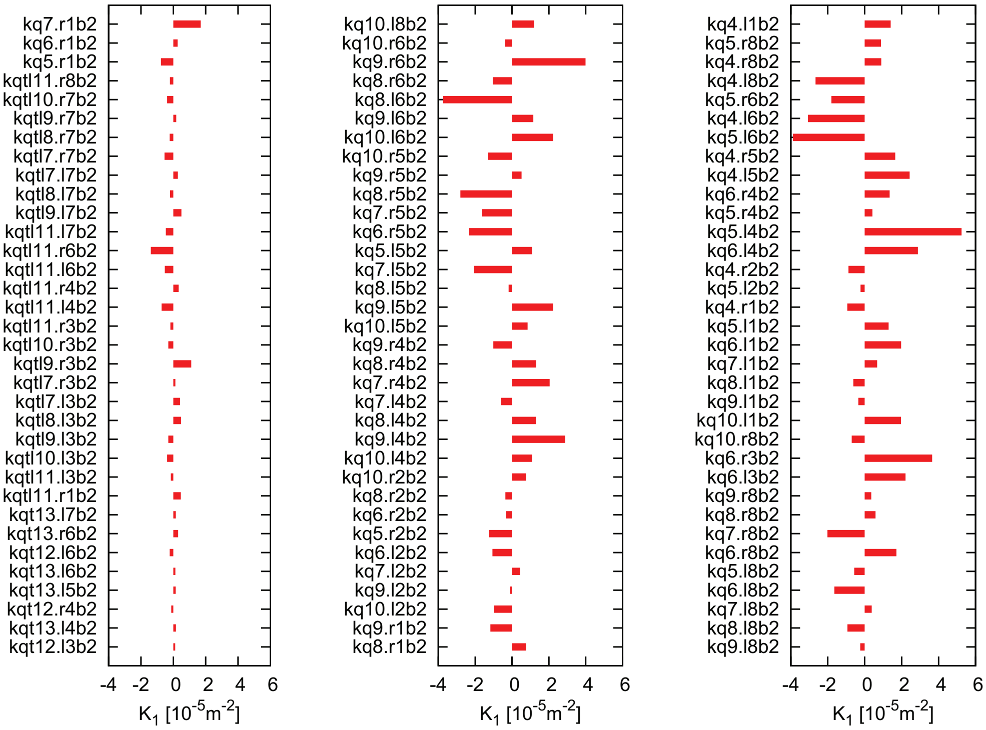

Figure 18: Quadrupole gradients of the global knob at β^*=3.5 m.

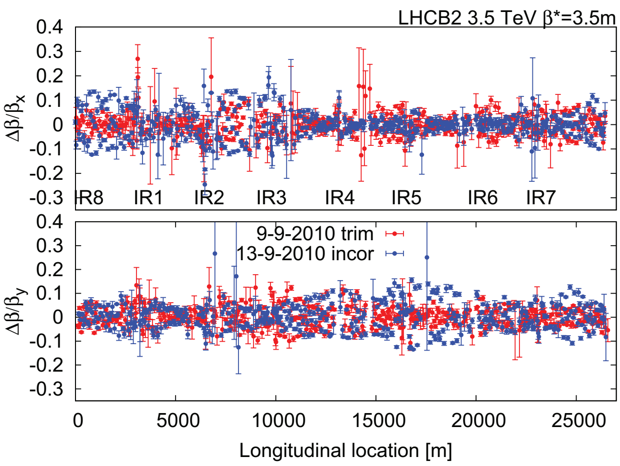

Figure 19: Comparison of the Beam 2 β-beating betweeen trimming and incorporating the global correction with β^*=3.5 m.

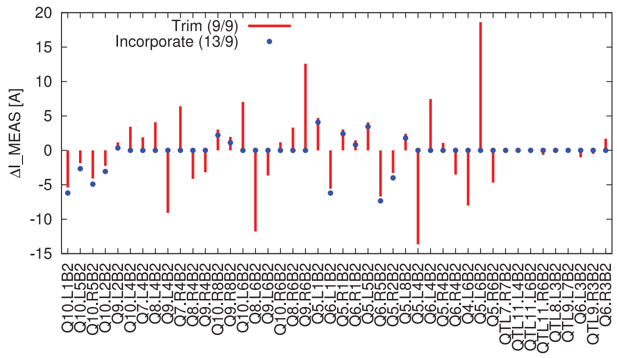

Figure 20: Quadrupole currents deviation with respect to nominal settings after trimming (red) and incorporating (blue) the global knob. The quadrupoles not shown on the plot feature exactly the same currents at trimming and incorporation.

IR6 and IR7. This will be easily fixed in the future. The effect of hysteresis is less relevant. However, at lower β^* the hysteresis might become more significant [37]. Figure 21 shows the peak β-beating as generated by the hysteresis errors versus β^*. At the lowest β^* hysteresis errors might be severe, however the MQX magnets in IR1 and IR5 are not changed during the current squeeze and should not suffer from hysteresis. The blue curve of Fig. 21 does not include hysteresis errors from these magnets. At β^*=1.1 m about 10% peak β-beating from hysteresis is expected. It has been decided to disable the hysteresis considerations in LSA and apply the appropriate correction only at the end of the squeeze.

8. OPTICS STABILITY

During 2010 there were periods of three months without changes in the accelerator settings both at injection and at 3.5 TeV with β^*=3.5 m. This gives the unique opportunity of assessing the long term stability of the LHC optics. These periods include three measurements both at injection

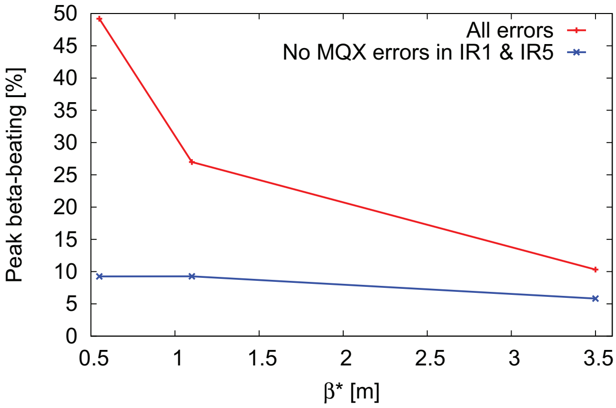

Figure 21: Peak β-beating among the four transverse planes of the two LHC beams due to the measured magnetic hysteresis errors versus β^*. IR2 and IR8 are not squeezed below 2 m.

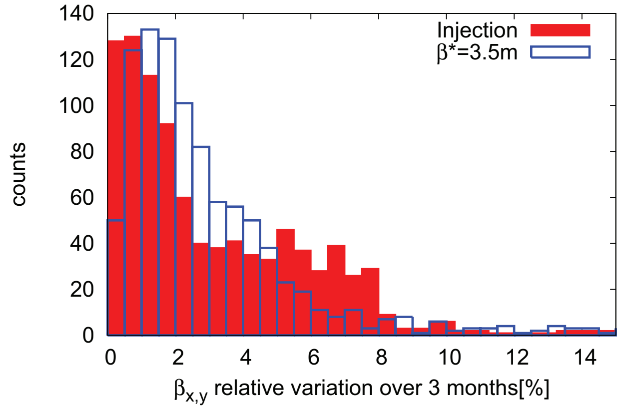

Figure 23: β function stability over 3 months.

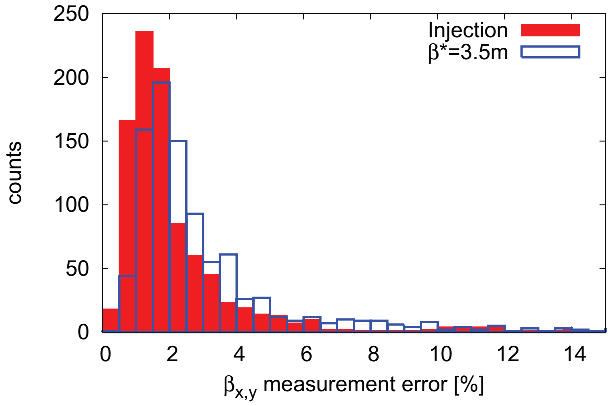

Figure 22: Histogram of measurement errors.

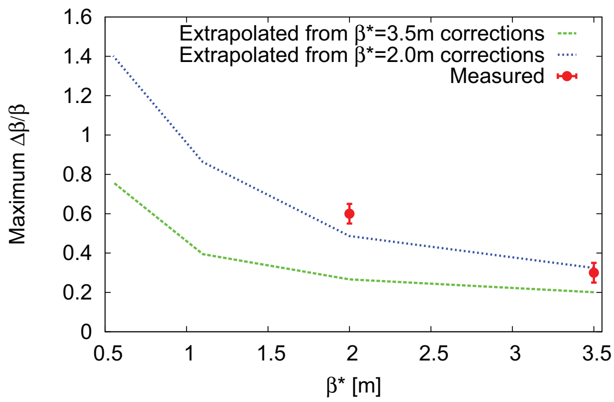

Figure 24: Extrapolation of the maximum uncorrected β-beating versus β^* from the corrections at 2 m and 3.5 m. IR2 and IR8 are not squeezed below 2 m.

and at 3.5 TeV. The random errors of these measurements are shown in Fig. 22. The resolution is slightly better at injection than at 3.5 TeV due to the larger excitation and the more regular optics. Both rms resolutions are in the 2% level.

The stability over three months is shown in Fig. 23. Very good rms stability about 4% is observed, being just slightly above the resolution of the measurement. However, a clear drift is observed at injection up to a level of 8%. This suggests that regular optics checks at injection and possibly corrections are required in the long term operation of the LHC.

9. SUMMARY OF 2010 β^* MEASUREMENTS

Tables 4-7 summarize the four relevant β^* measurements for physics in chronological order. Further details will be given in [39]. Two measurements at β^*=2 m are shown since important discrepancies in the 10% level between the beginning and the end of the fill (30 hours) were found. The two measurements at β^*=3.5 m correspond to before and after correction.

10. EXTRAPOLATIONS TO LOWER β^*

The local corrections as applied at β^* of 2 m and 3.5 m can be directly used to make predictions of optics errors at lower β^*. This approach is only partially correct since magnet errors also change with β^*. Figure 24 shows the maximum β-beating among the four transverse planes of the two LHC beams versus β^* as extrapolated from the two experienced local corrections. These extrapolations suggest that up to 80% β-beating might be expected at β^*=1.1 m. The hysteresis error at the same β^* would be 10% as shown in Fig. 21, i.e. small compared with the 80% due to optics errors.

11. COUPLING CORRECTION

The transverse coupling is generally compensated online [36] by using two orthogonal global knobs constructed

Table 4: β^* measurements at design β^*=2 m right after the squeeze. Valid between 25-4-2010 and 6-6-2010.

IP	Beam	β_x^*	error	β_y^*	error
IP1	1	2.02	0.01	1.78	0.05
IP2	1	2.02	0.06	1.80	0.01
IP5	1	2.10	0.02	2.02	0.04
IP8	1	2.11	0.10	1.92	0.01
IP1	2	2.00	0.04	2.05	0.03
IP2	2	2.03	0.04	2.13	0.10
IP5	2	1.95	0.12	2.11	0.05
IP8	2	2.21	0.03	1.85	0.01

Table 5: β^* measurements at design β^*=2 m after a 30 hours fill. Valid between 25-4-2010 and 6-6-2010.

IP	Beam	β_x^*	error	β_y^*	error
IP1	1	2.08	0.01	1.92	0.02
IP2	1	2.01	0.08	1.84	0.01
IP5	1	2.07	0.02	2.05	0.02
IP8	1	2.06	0.10	1.96	0.03
IP1	2	2.12	0.11	2.08	0.03
IP2	2	1.97	0.01	2.16	0.09
IP5	2	1.89	0.01	2.14	0.02
IP8	2	2.30	0.03	1.79	0.04

Table 6: β^* measurements at design β^*=3.5 m before correction. Valid between 6-6-2010 and 4-9-2010.

IP	Beam	β_x^*	error	β_y^*	error
IP1	1	3.54	0.01	3.96	0.05
IP2	1	3.44	0.02	2.74	0.05
IP5	1	3.86	0.05	3.35	0.08
IP8	1	3.54	0.07	3.72	0.07
IP1	2	3.81	0.05	3.42	0.06
IP2	2	3.20	0.05	4.17	0.21
IP5	2	3.53	0.14	3.90	0.1
IP8	2	3.86	0.08	3.09	0.03

Table 7: β^* measurements at design β^*=3.5 m after correction. Valid between 13-9-2010 and 6-12-2010.

IP	Beam	β_x^*	error	β_y^*	error
IP1	1	3.59	0.06	3.90	0.57
IP2	1	3.37	0.21	3.24	0.04
IP5	1	3.82	0.06	3.73	0.17
IP8	1	3.65	0.15	3.73	0.07
IP1	2	3.42	0.05	3.58	0.17
IP2	2	3.89	0.06	3.66	0.13
IP5	2	3.50	0.12	3.64	0.08
IP8	2	3.57	0.06	3.33	0.09

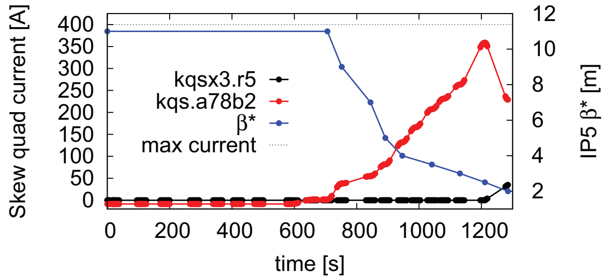

Figure 25: Skew quadrupole current along the squeeze. kqsx3.r5 is one of the IR5 triplet skew quadrupole correctors. kqs.a78b2 is one of the skew quadrupole families used in the global coupling correction.

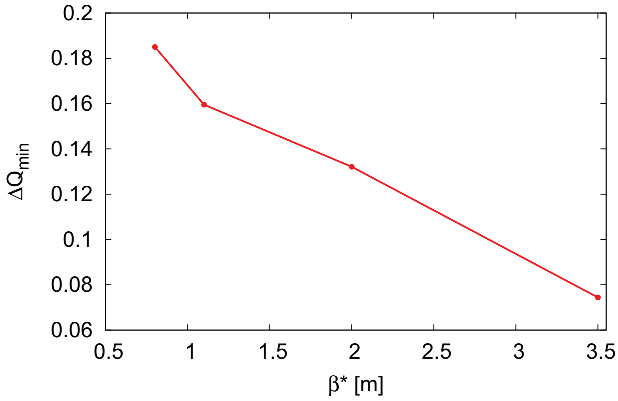

Figure 26: Closest tune approach generated only by the identified sources in the triplets versus β^*.

with arc skew quadrupoles to correct the real and imaginary parts of f_{1001}. During the squeeze these global knobs need to be stronger as the β^* decreases in the IPs (β functions increase in the triplets) as shown in Fig. 25. With all IPs at β^*=2 m the global knobs were not sufficiently strong to correct the coupling and the IR local coupling correction was mandatory.

The extended SBST was applied to all IRs, as shown in Fig. 5 for IR5. The strengths of the inner triplet skew quadrupoles were computed to reproduce the measured f_{1001}. A considerable reduction of the required strengths of the global knobs was achieved after the local coupling correction. Applying local coupling corrections also at larger β^* is advisable in the future to reduce the strength of the arc coupling correctors. Figure 26 shows the closest tune approach versus β^* as extrapolated from the identified sources in the triplets.

12. TRIPLET HIGHER ORDER CORRECTORS

This section tries to estimate at what β^* the higher order correctors should be used by computing the Dynamic Aper-

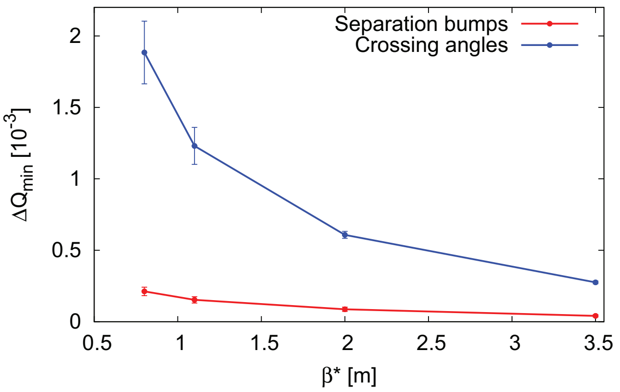

Figure 27: Closest tune approach generated by the IR separation bumps (red) and the IR crossing angles (blue) from feed-down of the triplet multipolar errors versus β^*.

ture (DA) and estimating feed-down effects[1]. These calculations use models including statistical representations of the measured magnetic errors.

The IR crossing angles and separation bumps cause skew quadrupolar errors by feed-down from the uncorrected non-linear triplet errors. The closest tune approach (ΔQ_{min}) generated by these mechanisms is shown in Fig. 27 versus β^*. The ΔQ_{min} coming from the crossing angles (blue line) is to be compared with that generated by the existing skew quadrupole errors of Fig. 26, since the squeeze sequence is carried out with crossing angles. At β^*=1.1 m the identified errors produce 100 times more coupling than the crossing angles.

The separation bumps are removed after the squeeze sequence. From the magnetic measurements we would expect a ΔQ_{min} of 2×10^{-4} at β^*=1.1 m. This is 50 times smaller than the usual fractional Q_x-Q_y separation of 0.01. If it will be decided to squeeze IR2 down to 1.1 m the ΔQ_{min} could increase at most by 30% both for the separation bumps and crossing angles cases. This could be the case during the ion physics run.

Figure 28 shows the DA with and without triplet correctors for different β^* between 0.8 m and 3.5 m. In these studies IP2 and IP8 are not squeezed below 2 m. The correctors seem to improve the DA for x-y angles below 45° only for $\beta^* \leq$1.1 m. The DA for angles above 45° are unaffected by the correctors for all β^*. For simplicity in these DA calculations the separations and crossing angles are set to zero.

13. SUMMARY & OUTLOOK

Unexpectedly large optics errors have been observed in the LHC at injection energy and at 3.5 TeV after the β^* squeeze. The dominant errors were locally corrected by applying the extended SBST. The results of this new technique at injection have been corroborated by dedicated magnetic measurements of the spare MQW magnets. The new magnetic calibration curves have been implemented in the LHC controls system without requiring further corrections at injection.

It has been demonstrated that a 10% peak β-beating is achievable in the LHC by applying global corrections after having canceled the main error sources locally. This should allow to reduce the current β-beat margins in the aperture and therefore push the machine performance by further reducing the β^*, provided the closed orbit stability is also well within tolerances.

The treatment of quadrupole hysteresis in LSA caused some minor discrepancies between trimming and incorporating corrections. It has been decided to neglect hysteresis effects and apply the appropriate corrections only at the end of the squeeze [37]. The major cause of trimming-to-incorporate discrepancies was identified as not driving quadrupoles in IR3, IR4, IR6 and IR7. This is easily fixed.

In general a very good long-term stability of the LHC optics has been observed. At injection a maximum drift of 8% β-beating in three months has been measured. This suggests that regular checks and possibly corrections should be envisaged at injection. At 3.5 TeV and β^*=3.5 m the measurements show a long-term stability comparable to the resolution of the measurement. At β^*=2 m two measurements separated by five days show an important difference of about 10% β-beating in Beam 1. A possible explanation could be the decay of the quadrupolar error of the superconducting magnets as the second measurement was taken after a 30 hours fill. This feature was observed for MQM and MQML magnet types during magnetic measurements. It is strongly recommended to monitor the optics along the usual duration of a physics fill after the squeeze.

An effective model of the LHC is being built using PTC and the measured magnetic and alignment errors [38]. First β-beating calculations from this model show a remarkable agreement with the measured β-beating after the correction of local errors.

A detailed summary of the β^* and waist measurements will be presented in [39]. Storage of the optics measurements in the database will be explored during 2011.

The use of the inner triplet skew quadrupoles to correct the local coupling with moderately low strength is mandatory at β^*=2 m (3.5 TeV). It is advisable to use the triplet skew quadrupoles at higher β^* to reduce the strength of the arc coupling correctors. The required triplet quadrupole tilts to reproduce the observed local coupling range between 0.5 mrad and 2.0 mrad for different error distributions. Recent alignment measurements show a tilt of 0.6 mrad in one of the IR5 quadrupoles [40]. This error explains about 40% of the local coupling error observed in IR5.

From DA and ΔQ_{min} considerations triplet higher order correctors start to be effective at about β^*=1.1 m. Nevertheless, it is recommended to make the sextupole correctors

[1] S. Fartoukh suggested investigating feed-down effects during the Evian workshop, December 2010

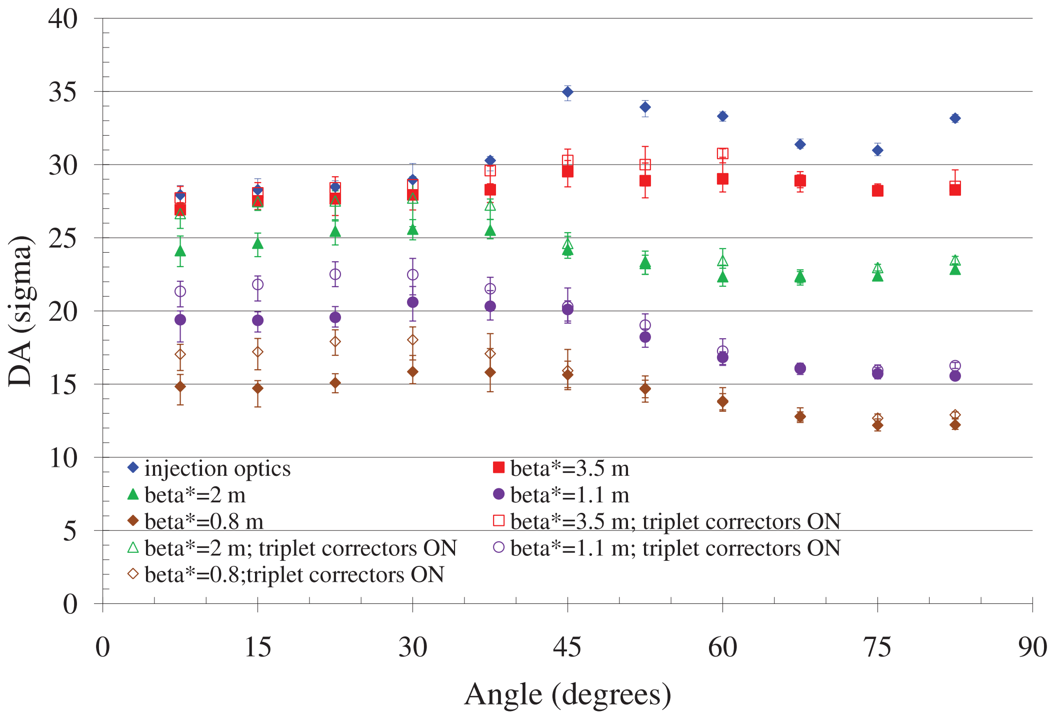

Figure 28: Dynamic aperture with and without non-linear triplet corrections versus angle in the x-y plane for different β^* between 0.8 m and 3.5 m. The points and the error bars represent the average and the spread of the DA, respectively.

available in case measurements during the beam commissioning would indicate a beneficial impact on the machine performance.

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HUMP: HOW DID IT IMPACT THE LUMINOSITY PERFORMANCE AND STATUS

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Abstract

The status of the measurements performed to characterize and identify the origin of the so-called hump will be presented as well as its impact on beam performance and the countermeasures found to mitigate its effects. The directions for future investigations will be outlined.

INTRODUCTION

Since the 2009 start-up with beam, tune spectra have evidenced the presence of a source of external excitation (so called "hump" because of its broad-band structure in the tune spectrum) mostly affecting Beam 2 and to a lesser extent Beam 1 [1]. The observed excitation was visible mainly in the vertical plane after correction of the machine coupling.

The main characteristics of the hump are summarized below [1][2][3][4]:

- the signal is mainly visible in the vertical plane for Beam 2;
- no dependence of the hump frequency on momentum offset or tune variation;
- the frequency of the hump is changing with time sometimes sweeping a large frequency span;
- there is a clear frequency correlation between the hump frequencies observed in the vertical plane for Beam 1 and Beam 2;
- the amplitude of the oscillation decreases with the inverse of the beam momentum;
- no evident dependence on the optics at the experimental straight sections has been observed (i.e. no evident dependence of the amplitude of the hump during the squeeze of the optics in IR1, IR2, IR 5 and IR8) has been observed;
- the amplitude of the signal on beam 2 does not depend on the presence of beam 1;
- blow-up of the vertical emittance is observed when the vertical tune is moved on top of the hump frequency (see Fig. 1).

The above observations are consistent with an oscillating horizontal dipolar field with amplitude independent from the energy of the beam and variable frequency.

During the 2010 run systematic tests have been performed to determine/exclude the possible origin of the above phenomena. The sources below can be excluded as a result of the tests conducted [1][2][3][4]:

- experimental magnets and compensators in all the four experiments;
- transfer line magnets (including injection septa);
- 60-120-600 A vertical orbit correctors;
- spool pieces (skew sextupole, octupole and decapole);
- transverse feedback;
- RF cavities;
- injection kickers;
- GSM or Fire Brigade Radio Network in the tunnel;
- triplet beam screen cooling (consistent with observations during the squeeze).

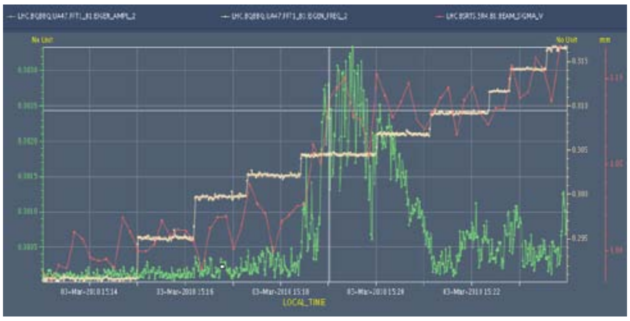

Fig. 1 : Beam size evolution (red) vs. time when the vertical tune frequency (ochre) is varied. The amplitude of the vertical oscillation (green) reached its maximum when the tune overlaps the hump tune (0.304). Courtesy R. Steinhagen.

EFFECTS ON LUMINOSITY

At injection the hump is responsible for the blow-up of the vertical emittance observed during the injection plateaus (see Fig. 2). The blow-up rate depends on the distance of the hump frequency from the tune sidebands $(n \pm Q) \times f_{rev}$ where Q is the tune, f_{rev} is the revolution frequency and n is an integer.

Although the relative emittance blow-up due to the hump at top energy (3.5 TeV) is smaller than at injection (450 GeV) in collision beam-beam acts as a strong non-linear lens and oscillations induced by external excitation will de-cohere faster than at injection leading to the generation of tails and to losses.

The hump excitation can also drive beam-beam coherent modes leading to losses. Faster decrease in intensity and lower lifetime have been observed with ions and protons when no transverse feedback was operated in collision.

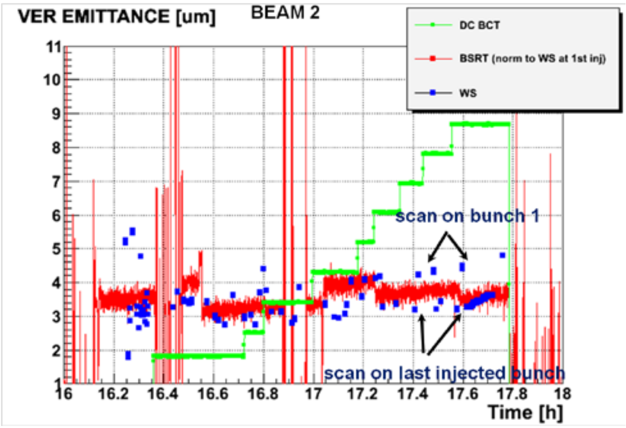

Fig. 2: Vertical emittance of beam 2 versus time during injection. The measurement of the vertical emittance of the first bunch injected shows a linear increase at a rate of 1.5 µm/hour. Courtesy M. Meddahi, F. Roncarolo.

Fig. 3 shows the time evolution of the hump frequency while in collision. The vertical tune line (at 0.32) is artificially suppressed and indicated by a vertical line for convenience.

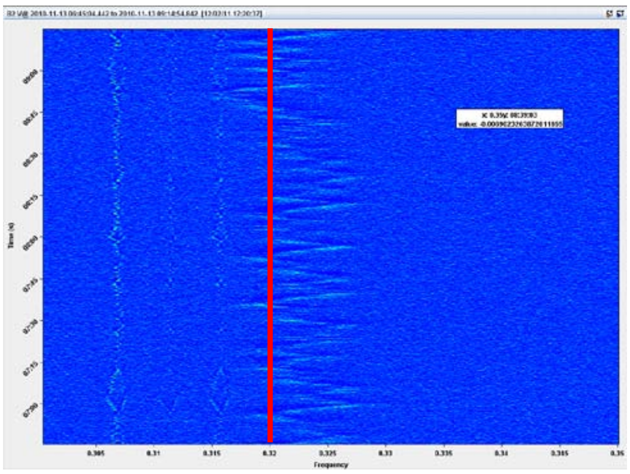

Fig. 3. Hump frequency versus time for beam 2 (vertical plane) while in collision. The vertical tune is indicated by the red line.

The hump frequency oscillates very close to the tune frequency and approximately two hours after the start of the acquisition (08:45 in the plot) its average frequency overlaps the tune frequency. When the overlap is largest beam losses appear as shown in Fig. 4.

No evident change of the beam size is visible at that time although a continuous slow increase of the vertical beam size is visible. Likely tails are generated which are lost at the collimators (see Fig. 5) with no significant change of the core size.

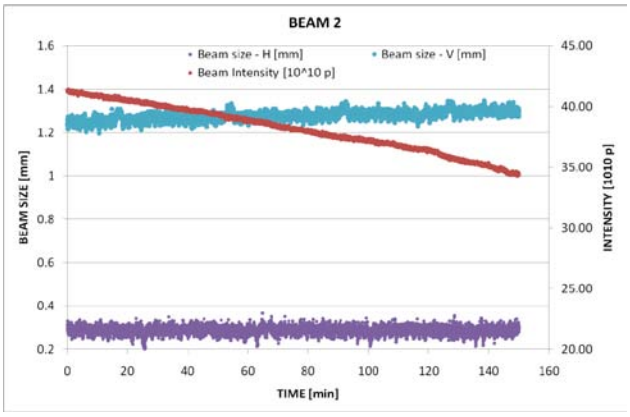

Fig. 4. Beam intensity, horizontal and vertical beam size for beam 2 for the same time span (in minutes) considered for the frequency spectrum in Fig. 3.

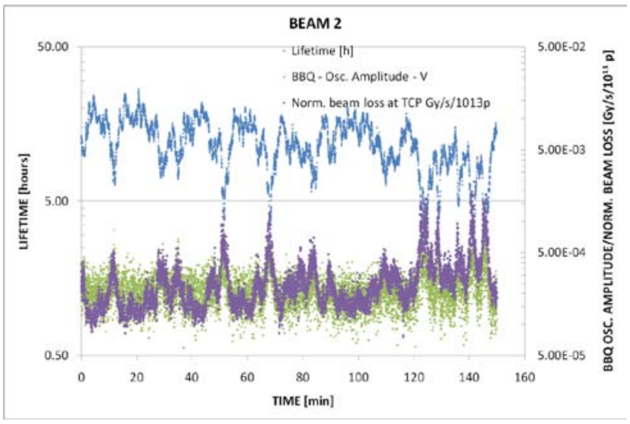

Fig. 5. Lifetime, maximum vertical oscillation amplitude and beam losses at the primary collimator for beam 2 for the same time span (in minutes) considered for the frequency spectrum in Fig. 3.

MITIGATION MEASURES AND NEXT STEPS

In parallel to the search for the origin of the hump, mitigation measures have been studied and implemented in order to damp this external excitation by means of the transverse feedback, first of all at low energy where the relative emittance blow-up is largest and in collision to avoid the excitation of beam-beam modes.

In presence of a source of emittance blow-up from a dipolar external excitation leading to an emittance blow-up rate $(d\varepsilon/dt)_{w/o\ fdbk}$, the emittance blow-up rate when a transverse feedback is used to damp the external excitation, $(d\varepsilon/dt)_{w\ fdbk}$, can be expressed as a function of the gain g of the transverse feedback and of the r.m.s. noise $X_{noise\ \ rms}$ at the input of the power part of the feedback [5]:

$$\left(\frac{d\epsilon}{dt}\right)_{w\,fdbk} \propto \frac{\Delta Q_{rms}^2}{g^2}\left[\left(\frac{d\epsilon}{dt}\right)_{w.o.fdbk} + \frac{f_{rev}g^2}{2\beta_{BPMfdbk}}X_{noise\ rms}^2\right]$$

$$for\ \Delta Q_{rms} < g < 1$$

where $\beta_{BPMfdbk}$ is the β function at the monitor used for the measurement of the beam position on a turn-by-turn.

For that reason it is necessary to operate the feedback at high gain and to reduce the noise of the detection module of the feedback. After summer 2010 a resolution of 1-2 µm could be achieved in the measurement of the turn-by-turn and bunch-by-bunch position used for the transverse feedback [6] allowing to see the hump signal at least when its frequency is close to the tune frequency. Figure 6 and 7 show the effectiveness of the transverse feedback in dumping the hump line when its gain is increased to -10 dB or higher (0 dB corresponds to the maximum gain achievable by the feedback). In Fig 6 the hump frequency is visible at ~ 0.29 and it is dumped when the gain is increased from -24 dB to -10 dB. The two bands appearing symmetrically around the tune line when the damper is operated at high gain are delimiting the range of frequencies at which the feedback is working in a stable regime [6]. No significant blow-up due to the transverse feedback has been observed also in this regime.

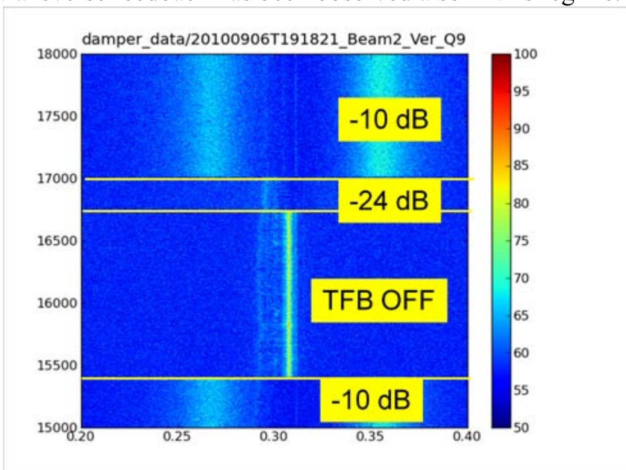

Fig. 6. Vertical tune spectrum for beam 2 for different gains of the transverse feedback. The vertical tune is set to 0.31.

A similar behaviour is seen for Beam 1. In this case the hump frequency is sweeping the tune spectrum and crossing the tune line twice. The reduced excitation for the higher damper gain is clearly visible.

Following the noise reduction campaign on the transverse damper pick-ups and given the positive results of the above described tests, the machine has been operated with the feedback at high gain at injection. The gain was then reduced before starting the ramp to have enough residual excitation for the tune feedback to track the tunes and correct them during the ramp. A sketch of the damper gain during the machine cycle is shown in Fig. 8. The damper was switched off before starting the squeeze and it was switched on again at the end of the squeeze before going in collision. No time was available during the run to commission the operation of the transverse feedback during the squeeze.

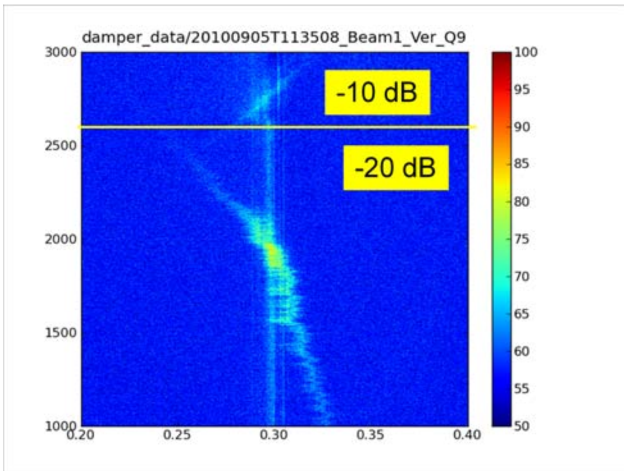

Fig. 7. Vertical tune spectrum for beam 1 for different gains of the transverse feedback. The vertical tune is set to 0.3.

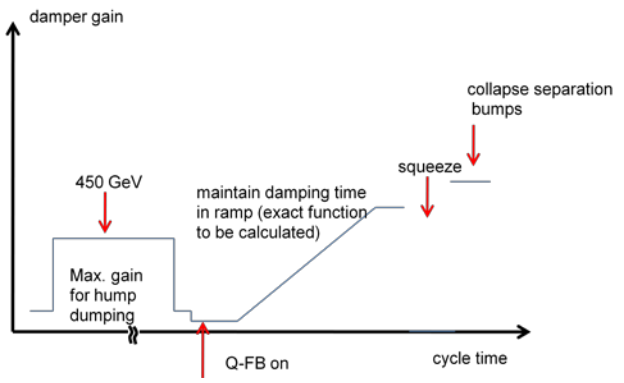

Fig. 8. Damper gain during machine cycle (schematic). Courtesy W. Höfle.

Operation of the transverse feedback has allowed colliding beams with emittances below nominal and with emittance blow-up limited to 20-30% during injection and ramp by the end of September.

Optimization of the gain has not been done in collision yet, furthermore noise levels are more critical at high energy in terms of relative emittance blow-up as the physical emittance is smaller at high energy. So far the transverse feedback has been operated at low gain in collision and some effects of the hump are still visible in that phase when the hump frequency is crossing the tune line, as shown in Fig. 9. In that case a reduction of the specific luminosity is observed at the same (Fig. 10) time indicating an increase of the beam size.

The noise properties of the transverse feedback system are being studied and improvements are going to be proposed for implementation at the latest during the next long shut-down [6].

Extensive analysis of the time evolution of the frequency of the hump over long periods is ongoing and has shown that the hump is always present but with a different frequency pattern and for that reason it can have a different impact on the beam quality according to the distance that the hump frequency has from the tune.

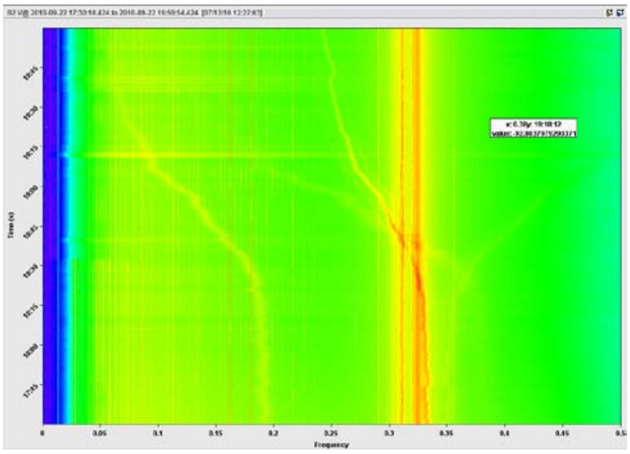

Fig. 9. Tune spectrum versus time. The hump line initially just above the vertical tune crosses the tune line (0.32) while in collision. The horizontal tune line is also visible (0.31). The time interval from 17:30 to 20:00 on 22/09/2010 is shown (Fill #1364)

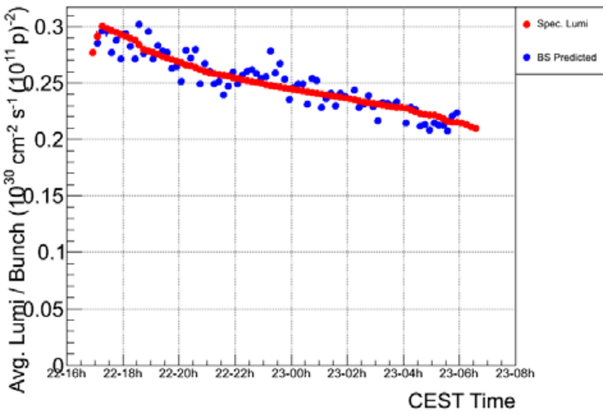

Fig. 10. ATLAS Specific luminosity for fill #1364.

Fig. 11 shows the frequency evolution of the hump over time intervals of few hours each, in different periods of the run. There is not a region of the tune spectrum which is completely immune from the hump and sudden variations in the time evolution of the hump frequency have been observed and are presently under investigations in order to determine possible correlations with external events or actions on the machine hardware.

A dedicated fixed display showing the evolution of the hump spectrum as a function of time has been implemented in the control room to facilitate the correlation between these sudden variations in the frequency evolution of the hump and any possible action on the machine or on its technical systems. A typical snapshot of the fixed display is shown in Fig. 12. In this case (coast #1372) the hump frequency is slowly varying very close to the vertical tune frequency over a period of two hours and lifetime could have been improved by shifting slightly the working point to minimize the overlap between the hump frequency and vertical beam 2 tune. Systematic use of the fixed display at injection or in collision to optimize the working point for beam 2 when the hump frequency is slowly varying is recommended for the 2011 run.

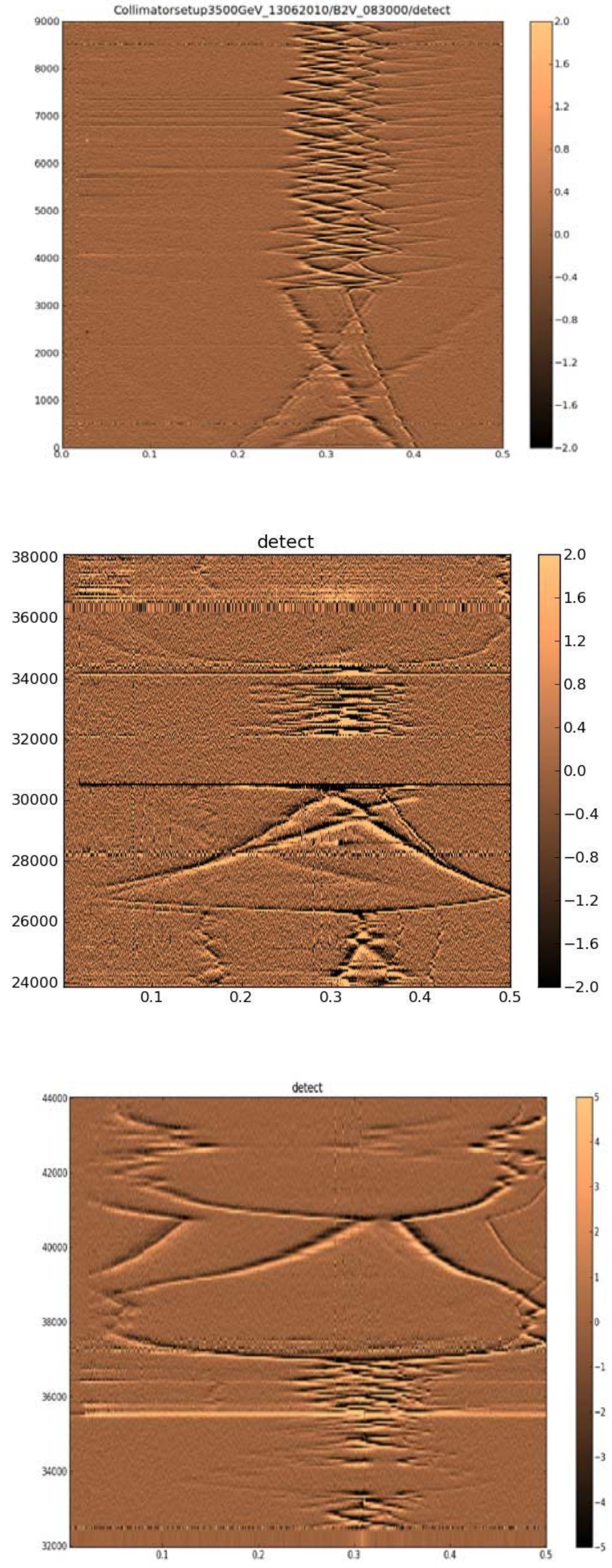

Fig. 11. Time (in seconds) evolution of the hump frequency during different periods of the run. The intervals of time when no signal was observed (e.g. in the

plot in the middle) correspond to periods with no beam circulating in the machine.

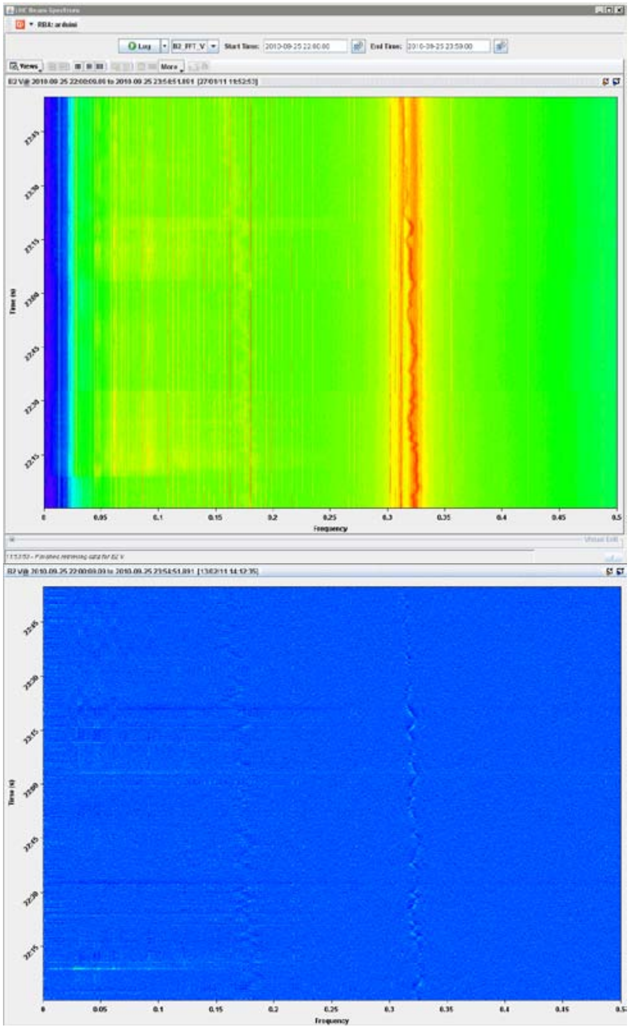

Fig. 12. Snapshot of the hump frequency display: raw data (top), after suppression of the frequencies which are constant in time (bottom) (Courtesy R. De Maria and M. Terra Pinheiro Fernandes Pereira).

RECENT PROGRESS

Beam measurements

All the measurements described so far were performed with the tune measurement system (BBQ) [7] which allows one acquisition per turn of the average beam position. The frequency of the hump cannot be determined univocally but it can be any of the sidebands of the revolution frequency $(\pm Q_{hump}+n)\times f_{rev}$ with $0 < Q_{hump} < 0.5$ where Q_{hump} is the frequency of the hump measured by the BBQ in units of the revolution frequency and n is an integer. BPMs and the Schottky monitor have not enough resolution to discriminate the amplitude of the oscillations induced by the hump which are in the micrometer range when the hump is close to the tune frequency.

In the last part of the 2010 run (second half of November) turn-by-turn/bunch-by-bunch position measurements have been possible with the transverse damper pick-ups and measurements have been performed during ion operation with ion filling schemes with a minimum bunch spacing of 500 ns. This has allowed extending the range of the measurement of the real frequency of the hump up to 1 MHz. The measurements are being analyzed in detail but the preliminary results evidence lines at the following frequencies f_0: 243 kHz, 335 kHz, 487 kHz (this is likely the second harmonic of the first frequency), 532 kHz (see Fig. 13).

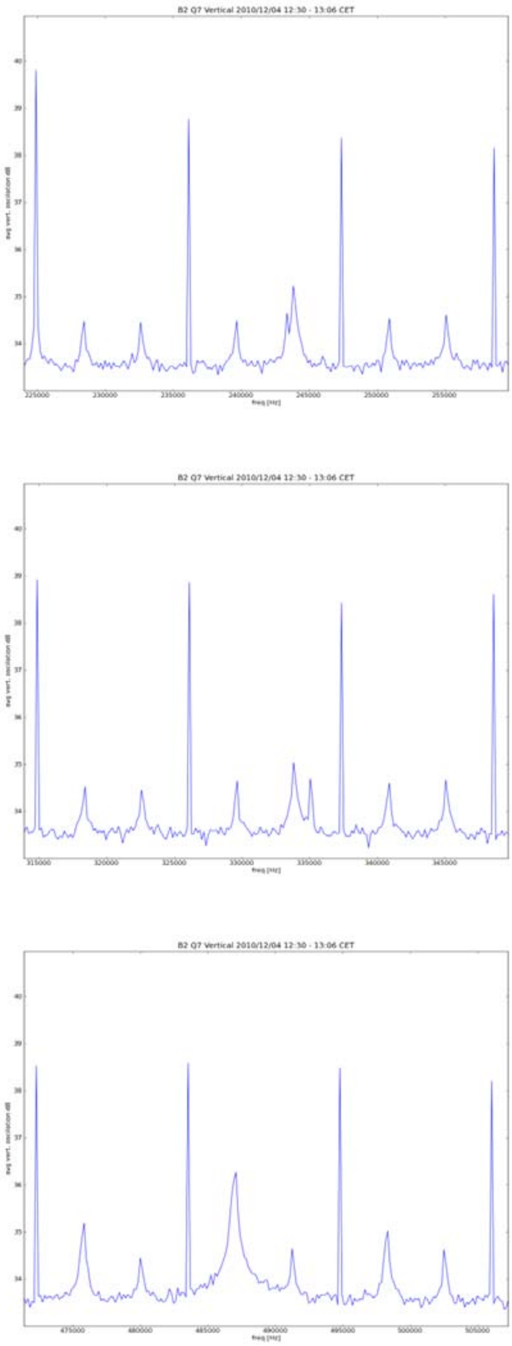

Fig. 13. Frequency spectra from bunch-by-bunch measurements performed with the ion beam (Courtesy R. De Maria).

Given that the minimum spacing among bunches is 500 ns the above frequencies could be aliases and the real frequency of the hump could be any value $f = \pm f_0 + n\times2$ MHz. If confirmed, the above observations would rule out UPS (Uninterruptible Power Supplies) as the possible origin of the hump.

So far no systematic and monotonic variations of the average tune of the hump have been evidenced during the ramp (see Fig. 14). This would be the case if the frequency of the hump is not correlated with the RF frequency and it is a sufficiently large harmonic of the revolution frequency as the sampling frequency of the turn-by-turn position is varying during the ramp. For the lead ion beam the RF frequency sweep during the ramp is largest as compared to that of the ion beam and amounts to 5513 Hz, corresponding to a sweep in revolution frequency of ~0.155 Hz. The frequency f of the hump is therefore smaller than 16.8 MHz assuming that we could resolve systematic variations of the hump tune larger than 0.02 during the ramp and that the frequency of the hump is not correlated to the RF frequency.

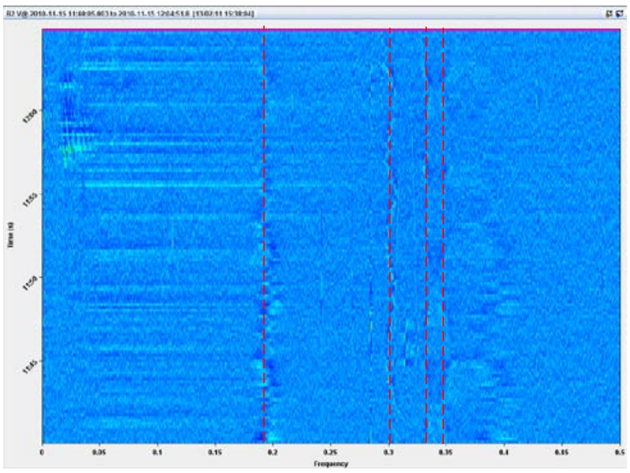

Fig. 14. Evolution of the hump tunes during a ramp with ions. The ramp starts at 11:44 and finishes at 12:02.

Magnetic measurements

Remote magnetic measurements by means of coils installed in the tunnel have been performed during the machine run and are continuing during the Christmas stop to attempt localizing the source of the hump (in a sector of the machine) and in general to determine all the possible sources of noise affecting the beam.

The comparison of magnetic and beam measurements performed in November 2010 show a very good agreement in the periodicity of the frequency evolution of the hump frequency and noise measured in the tunnel (See Fig. 15 - in this case in point 5), although the absolute amplitude of the variation does not correspond. At the time of the measurement the sampling frequency for the magnetic measurements was 200 kSamples/s and the quoted values of the frequencies could be aliases of higher frequencies.

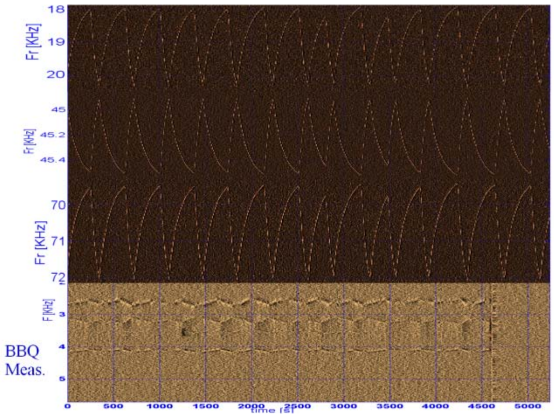

Fig. 15. Frequency evolution of the noise measured in the tunnel (point 5) with coils and with the BBQ system with beam. Courtesy O.O. Andreassen, P. Galbraith, D. Giloteaux, G. Golluccio, L. Walckiers.

Preliminary measurements conducted during the Christmas stop indicate that noise at frequencies of a few hundreds of kHz is visible (see Fig. 16).

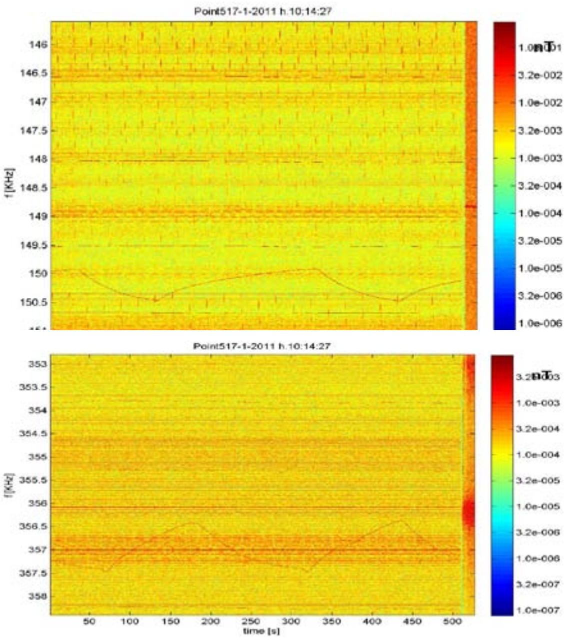

Fig. 16. Frequency evolution of the noise measured in the tunnel (point 5 in this case) with coils. Courtesy O.O. Andreassen, P. Galbraith, D. Giloteaux, G. Golluccio, L. Walckiers.

SUMMARY

The hump affects luminosity performance due to blow-up (particularly at 450 GeV). In collision it can excite beam-beam coherent modes or generate tails and therefore losses.

Priority has been given to implement mitigation measures: the transverse feedback has proven to be effective to mitigate these effects and as a result of that beams with emittances in the range of 2.5 micrometers could be regularly brought in collision.

The identification (and possibly eradication) of the origin remain the (challenging) goal of the ongoing analysis and measurements.

ACKNOWLEDGEMENTS

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LHC BEAM PARAMETERS: PUSHING THE ENVELOPE?

E. Métral

Abstract

The goal for 2011 is to deliver an integrated luminosity of one inverse femtobarn to the experiments. This will require to gain an order of magnitude in peak luminosity, i.e. run with values of more than 10^{33} cm^{-2}s^{-1}, whereas a maximum of ~ 2.07 10^{32} cm^{-2}s^{-1} was achieved so far. Many collective effects were observed this year, first when the intensity per bunch was increased and subsequently when the number of bunches was pushed up and the bunch spacing was reduced. A critical review will be made to examine which parameters can be realistically used to increase the luminosity, analysing the risks and the consequences. A scenario is proposed as well as a back-up solution.

INTRODUCTION

The highest LHC peak luminosity (~ 2.07 10^{32} cm^{-2}s^{-1}) was achieved on Monday 25/10/10 on the fill number 1440 with a total intensity per beam of ~ 4.35 10^{13} p and beam parameters given in Table 1. The missing factor 50 to reach the nominal peak luminosity can be explained by the missing number of bunches (~ 8) and the missing factor for the β* (~ 6), realizing that the loss by a factor 2 from the beam energy was compensated by transverse emittances which were about two times smaller than nominal.

Parameter	Achieved	Nominal	Missing factor
Bunch population [p/b]	1.15 10^{11}	1.15 10^{11}	1
Number of bunches / beam	368	2808	
Bunch spacing [ns]	150	25	
Colliding bunch pairs	348	2808	8.07
Beam energy [TeV]	3.5	7	*2*
β* [m]	3.5	0.55	6.36
Norm. trans. emittance [μm]	~ 2.1	3.75	*~ 0.56*
Full crossing angle [μrad]	200	285	
Rms bunch length [cm]	9	7.55	
Peak luminosity [cm^{-2}s^{-1}]	2.07 10^{32}	10^{34}	50

Table 1: Parameters used for the LHC maximum peak luminosity performance in 2010.

The integrated luminosity goal for 2011 is 1 fb^{-1}. Assuming the same peak luminosity as the maximum reached in 2010 (see Table 1), a total of ~ 100 operational days (see [1] where ~ 120 days are anticipated, i.e. about half of the total run length) and a Hubner (overall run) factor of 0.2 would lead to an integrated luminosity of ~ 1/3 of the 2011 goal. This means that one should aim at least at gaining a factor ~ 3 in peak luminosity, meaning that one should reach at least ~ 6 10^{32} cm^{-2}s^{-1}. To have some margin one should therefore aim for ~ 10^{33} cm^{-2}s^{-1}, which was also said in the past to be a goal for 2011. Hence, a factor 5 should be gained compared to last year.

Many collective effects were observed in 2010. The first in spring when the bunch intensity was increased to the nominal value. Accelerating a single-bunch, an horizontal single-bunch coherent instability from the machine impedance was observed and stabilized with Landau octupoles. The second collective effect appeared in summer when the number of bunches was increased and the crossing angle was scanned. First analyses revealed that the Head-On (HO) beam-beam effects alone seem to be fine, but the Long Range (LR) effects remain to be studied in detail [2]. Furthermore, when the transverse feedback was removed at top energy in the presence of many bunches (and small chromaticities, i.e. few units), the beam was lost which seems to indicate that a transverse coupled-bunch instability was stabilized by the transverse feedback, but this instability was not studied in detail yet. Finally, the third collective effect occurred in autumn when the batch spacing was reduced to 150 ns, 75 ns and finally 50 ns, which revealed some electron cloud effects (the smaller the batch spacing the more significant the electron cloud effects) [3]. In these conditions, which parameters can therefore be realistically used in 2011 to increase the peak luminosity by a factor 5 and reach the goals? A reduction of the β* from 3.5 m down to 2 m seems a reasonable assumption, and this value will be assumed for the rest of this paper (in fact 1.5 m is also contemplated at the moment) [4]. Furthermore, the energy is assumed to increase from 3.5 TeV to 4 TeV (even if the final decision will only be taken after the Chamonix2011 workshop), as the effect is rather small (14% increase in luminosity). These two effects would already increase the peak luminosity to ~ 4 10^{32} cm^{-2}s^{-1}. This means that "only" a factor ~ 2.5 remains to be gained, playing with the beam intensity and/or beam brightness, i.e. with 3 parameters: the bunch population, the number of bunches and the transverse beam emittance.

EXECUTIVE SUMMARY

Potential from the injectors (SPS)

All the possibilities are shown in Fig. 1, where the potential from the SPS injector is also mentioned. Several combinations should therefore be possible, neglecting for the moment the collective effects and the induced beam quality degradation. Note that with the current status of the injectors it is not possible to reach 10^{33} cm^{-2}s^{-1} using the 150 ns beam, which was used last year, because of the limited maximum intensity per bunch which can be delivered from the PS at the moment. With the maximum possible number of bunches (i.e. 468 bunches) and assuming a transverse emittance of ~ 2.5 μm (in collision), a bunch intensity of ~ 1.7 10^{11} p/b would be needed, whereas the current limit with the 150 ns beam is ~ 1.1 10^{11} p/b [5]. The intensity limit comes from a longitudinal coupled-bunch quadrupolar instability due to the high-frequency 40 and 80 MHz RF cavities. The reason why it went so well this year (according to the PS RF experts) is because the LHC asked for batches of only 8 bunches (and not 12) and because the LHC never asked for more than ~ 1.1-1.2 10^{11} p/b. In fact increasing the intensity to more than ~ 1.1 10^{11} p/b could work (even if the beam is unstable at the PS) but then some satellites might be created: it would then be up to the SPS and LHC to say if these satellites are fine or not. As concerns the 75 ns and 50 ns beams the potential from the injectors is summarized in Table 2.

75 ns	N_b [10^{11} p/b]	ε_n [μm]	L [10^{33} cm^{-2} s^{-1}]
1-batch	1.2	2	1.2
2-batch (to be studied)	1.2?	1?	2.3?
50 ns	**N_b [10^{11} p/b]**	**ε_n [μm]**	**L [10^{33} cm^{-2} s^{-1}]**
1-batch	1.15	2.5	1.4
1-batch	1.6	3.5	1.9
2-batch	1.15	1.5	2.2

Table 2: Potential from the injectors (SPS). In both cases, from 1 to 4 batches (of up to 36 bunches for the 50 ns beam and 24 bunches for the 75 ns beam) can be sent. For the 75 ns beam, the bunch intensity it limited to ~ 1.2 10^{11} p/b due to another longitudinal coupled-bunch instability on the PS flat top. The PS RF colleagues have some ideas for next year, but they still have to make the detailed studies [5].

Current constraints from the LHC

The impedance effects should be under control as first measurements revealed that they are very close to predictions (see next Section): (i) in the longitudinal plane, the loss of Landau damping can be avoided using a sufficiently large (closer to nominal) longitudinal emittance; (ii) Landau octupoles are needed to stabilize the transverse single-bunch instability (and higher order head-tail modes) and the transverse feedback is needed to damp the transverse coupled-bunch instability with small chromaticity (i.e. few units), otherwise some higher head-tail modes might develop which cannot be damped by the transverse feedback due to the bandwidth limitation.

As concerns beam-beam effects, which have been discussed in detail in Ref. [2], it seems that the HO tune shift (alone, i.e. without LR effects) can be larger than the nominal value by a factor more than ~ 2, meaning that we could increase the bunch brightness (i.e. intensity to emittance ratio) by a factor ~ 2, compared to the nominal situation (see Table 1). It is also worth reminding that we have more flexibility with the 50 ns beam than with the 75 ns beam as concerns the luminosity delivery to all the experiments. Finally, small transverse emittances are better for the LR effects (taking into account the aperture and the crossing angle).

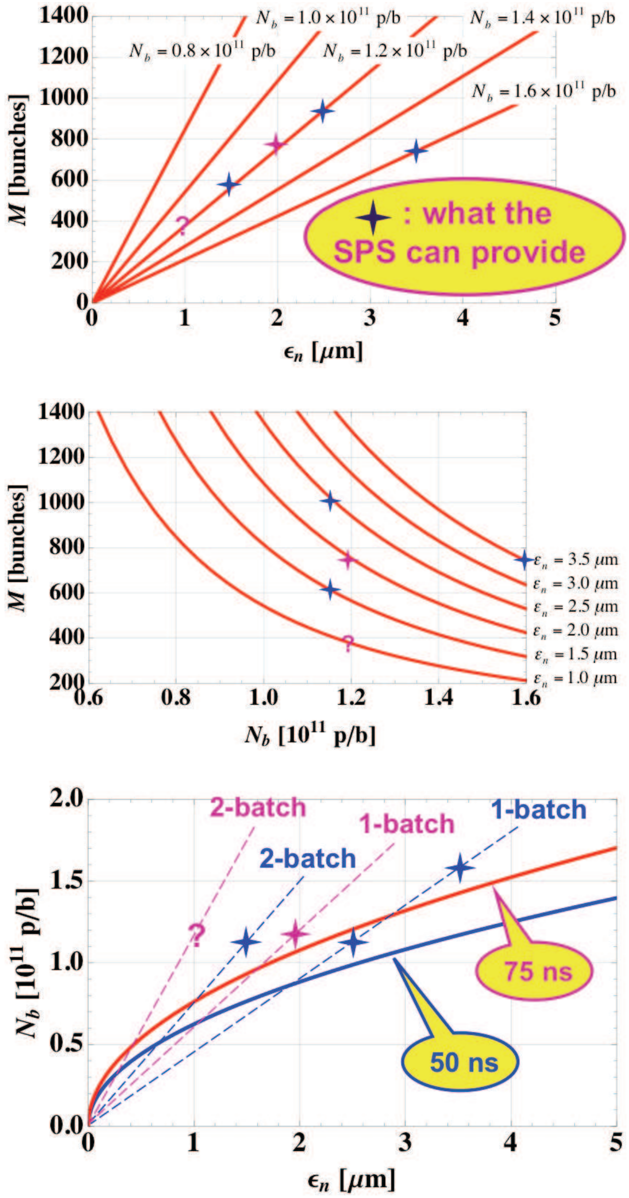

Figure 1: Relation between the bunch population, the number of bunches and the transverse beam emittance to reach a peak luminosity of 10^{33} cm^{-2}s^{-1}, assuming a beam energy of 4 TeV and a β* of 2 m. The blue star is used for the 50 ns beam while the red one is for the 75 ns beam. In the 3rd plot, the maximum number of bunches is assumed, i.e. 936 bunches for the 75 ns beam and 1404 bunches for the 50 ns beam.

As concerns electron cloud effects, which have been discussed in detail in Ref. [3], the 75 ns beam is safer for the production mode (824 bunches were already injected in 2010). It is however proposed to do a scrubbing run with the 50 ns beam (note that 108 bunches were already accelerated in 2010) as no scrubbing was observed in the arcs with the 75 ns beam with about nominal bunch intensity, and as some margin should be provided for acceleration etc. Furthermore, knowing that the electron cloud build-up is almost independent of the transverse emittances (far from the build-up threshold!) [6], and that the induced single-bunch instability is less critical for large transverse emittances, it is proposed to start with the largest (~ nominal) emittances at least at the beginning.

Proposed scenario to reach 10^{33} $cm^{-2}s^{-1}$

A scrubbing run of ~ 1 effective week should be performed as soon as possible in the run (may be after a recovery phase from last year performance). Some time should also be reserved to scrub at top energy if needed, as the situation at top energy is not exactly the same as at injection energy (even if it was observed in 2010 that a scrubbing run at injection energy was also effective at top energy). It is proposed to use the 50 ns beam with a bunch intensity of ~ 1.4 10^{11} p/b and a transverse emittance (rms. norm.) of ~ 4 μm (i.e. the maximum which is compatible with injection losses: may be this is too much in which case we should reduce it to the nominal value of 3.5 μm). A transverse controlled emittance blow-up should be used in the injector chain (for instance in the SPS, as was done in the past [7]). Then, the idea is to increase the number of bunches looking at the vacuum pressure gauges, remaining below the vacuum interlocks. Finally, the transverse emittance could be slowly decreased as the secondary emission yield decreases.

Concerning the production mode (MDs are not discussed here), either a staged approach can be used (as was done in the past) or a challenging plan can be proposed (with a plan B as fallback solution). In the staged approach, the idea would be to run with the 75 ns beam and then move to the 50 ns beam (which could be studied during MDs). In the challenging mode discussed here it is proposed to try and run after the scrubbing run with the 50 ns beam (see Table 3), with ~ nominal bunch intensity (1.15 10^{11} p/b) and a large transverse emittance at the beginning (~ 3.5 μm, provided by controlled transverse emittance blow-up from the injectors). Then we should try and increase the number of bunches up to ~ 1000 to reach a luminosity of ~ 6 10^{32} $cm^{-2}s^{-1}$. This scenario with the 50 ns beam is better than with the 75 ns beam for the luminosity flexibility between the different experiments. Decreasing the transverse emittance (reducing the controlled transverse emittance blow-up from the injectors) will increase the luminosity (LR effects will reduce/disappear and HO ones increase but there is some margin as previously mentioned). The goal luminosity of 10^{33} $cm^{-2}s^{-1}$ will be reached when the transverse emittance will be equal to ~ 2.3 μm (the SPS should be able to deliver ~ 2.5 μm in 1 batch and ~ 1.5 μm in 2 batches, which means that the double-batch beam with controlled transverse emittance blow-up would be needed). Finally, one should try and increase the number of bunches as much as we can (up to 1404) and then one could even try to increase the intensity per bunch.

In this case, the fallback solution (plan B) would be to use the 75 ns beam with a bunch intensity of ~ 1.2 10^{11} p/b and the largest transverse emittance at the beginning (~ 3.5 μm, provided by controlled transverse emittance blow-up from the injectors). Then the idea is to increase the number of bunches up to 936 (i.e. the maximum) to reach a luminosity of ~ 6 10^{32} $cm^{-2}s^{-1}$. Decreasing the transverse emittance (reducing the controlled transverse emittance blow-up from the injectors) will increase the luminosity (LR effects will reduce/disappear and HO ones increase but there is some margin as previously mentioned). The goal luminosity of 10^{33} $cm^{-2}s^{-1}$ will be reached when the transverse emittance will be equal to ~ 2.2 μm (the SPS should be able to deliver ~ 2 μm in 1 batch and ~ 1? μm in 2 batches; the latter case still need to be studied in detail during MDs).

Parameter	PLAN A	PLAN B
Bunch population [p/b]	1.15 10^{11}	1.15 10^{11}
Number of bunches / beam		936 (max)
Bunch spacing [ns]	50	75
Colliding bunch pairs	1000 (max = 1404)	936 (max)
Beam energy [TeV]	4	4
β* [m]	2	2
Norm. trans. emittance [μm]	2.3	2.2
Full crossing angle [μrad]	285	285
Rms bunch length [cm]	9	9

Table 3: Possible parameters to reach 10^{33} $cm^{-2}s^{-1}$ in 2011.

LHC IMPEDANCES

The imaginary part of the effective transverse impedance has been evaluated from tune shift measurements vs. intensity and revealed that it was within less than 40% compared to theoretical predictions. Furthermore, moving all the collimators of IR7 only, an even better agreement was obtained (as was already obtained in 2004 and 2006 in the SPS with a LHC collimator prototype [8]). The real part of the effective impedance was measured through the instability rise-time of an instability studied at 3.5 TeV (see next Section) and it seems to be within less than a factor of 2 compared to theory. All these measurements revealed therefore a good agreement with theoretical predictions. There was only one exception recorded so far, which concerns the TDI and the two TCLIs (all of them used only at injection): it seems that their induced tune shift is a factor ~ 2 - 2.5 larger than expected. This issue is followed up [9].

As concerns the longitudinal impedance, a first estimate of the imaginary part of the longitudinal effective impedance was deduced from the loss of Landau damping leading to undamped bunch oscillations at the beginning of the run with small longitudinal emittance: both theoretical predictions and measurements point to a similar value of ~ 0.09 Ω [10].

LHC BEAM COHERENT INSTABILITIES

Christmas tree in May!

A first ramp was tried with a single-bunch of ~ 10^{11} p/b (on both beams B1 and B2) on Saturday 15/05/2010. The bunch was unstable at ~ 1.8 TeV for B1 and ~ 2.1 TeV for B2. This led to the famous "Christmas tree" (see Fig. 2), which could be reproduced by simulations (when beam losses are introduced in the simulations). The Christmas tree is a consequence of a head-tail instability m = - 1 from the machine impedance predicted with a rise-time ~ 5 s without octupoles and intrinsic nonlinearities. This instability was measured in detail on Monday 17/05/2010 on the 3.5 TeV magnetic flat-top. The bunch was accelerated with some current in the (Landau) octupoles. At 3.5 TeV, the octupole current was

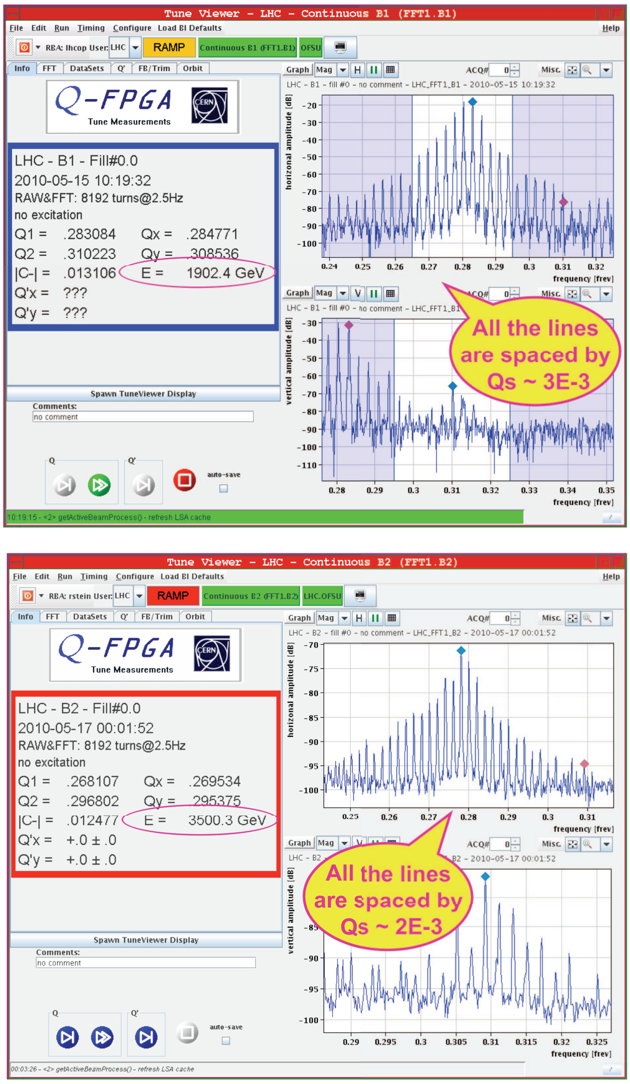

Figure 2: Observation of "Christmas trees" (with all the synchrotron sidebands excited) when the nominal intensity bunch was unstable at ~ 1.9 TeV (upper) and 3.5 TeV (lower).

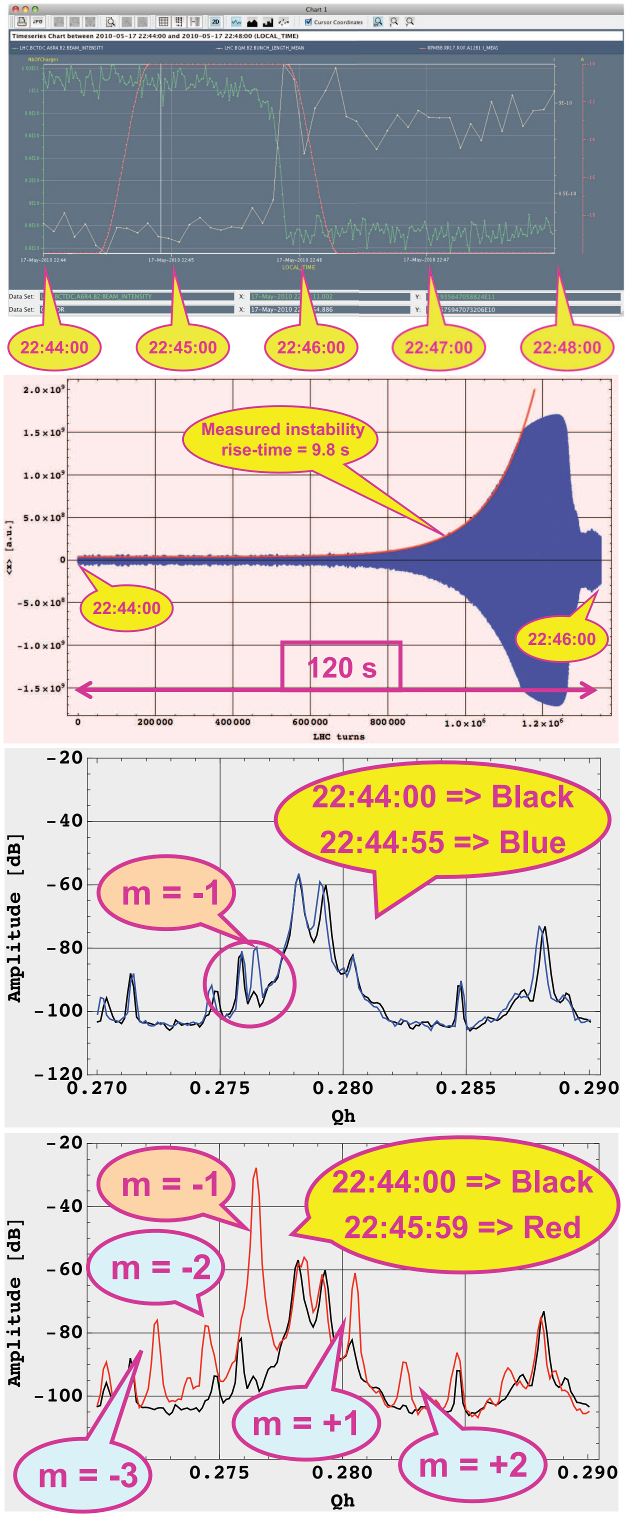

Figure 3: Beam losses observed at 3.5 TeV with a single-bunch when the octupole current reached – 10 A (a). The measured instability rise-time was ~ 10 s in the presence of an octupole current of – 10 A (b), and only one mode (m = - 1) clearly starts alone (c) before all the others (d).

"increased" (i.e. the effect decreased, as a negative current was used) from – 200 A to – 10 A by steps (see Fig. 3a). At – 20 A, the bunch was still stable whereas at – 10 A it was unstable with a rise-time of ~ 10 s and it could be clearly observed that only one mode (m = - 1) was first unstable and then, when the beam losses started to be observed, all the synchrotron sidebands were excited, leading to the Christmas tree (see Fig. 3d).

Transverse coherent instability induced by beam-beam?

A vertical instability was observed at 3.5 TeV in stable-beam conditions (see Fig. 4). A possible qualitative explanation could be a loss of Landau damping (whose origin is not clear yet), as the observed instability rise-time was ~ 10 s, i.e. very similar to the one observed in Fig. 3. Note that in the present case the instability appeared in the vertical plane, whereas it was in the horizontal plane in Fig. 3, but similar rise-times are predicted in both transverse planes.

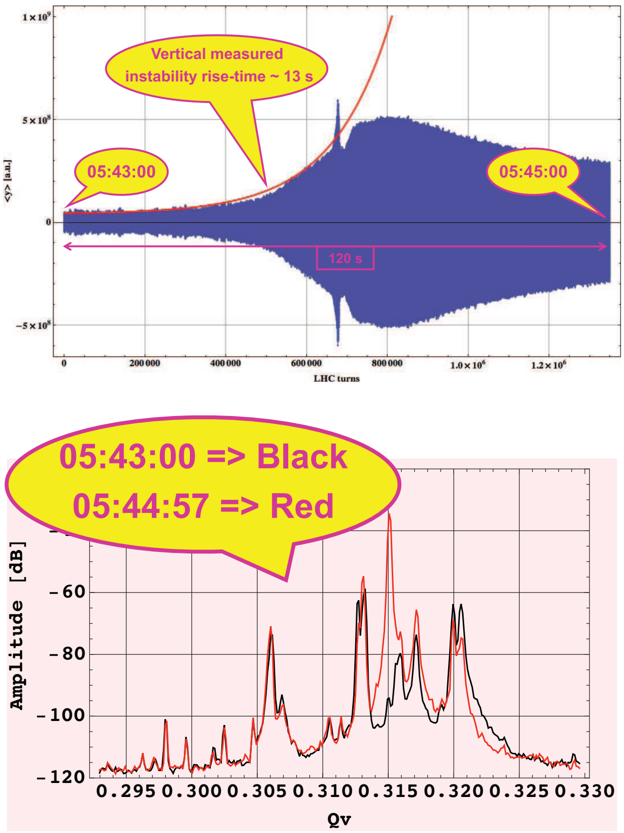

Figure 4: Observation of a single-bunch instability in stable-beam conditions, whose origin is not yet clear.

Transverse coupled-bunch instability with the 75 ns beam at 450 GeV?

During some machine studies, only the beam B1 was studied with 11 batches of 2 times 24 bunches spaced by 225 ns (with a batch spacing of 1.85 μs). The chromaticities were set to Q' ~ 10 in both transverse

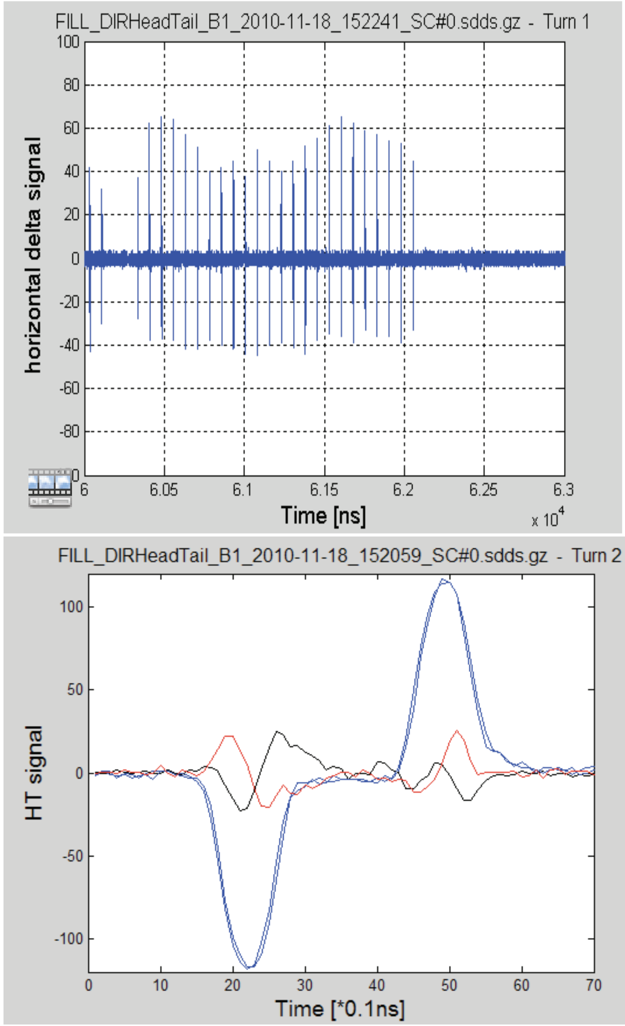

Figure 5: Observation of a transverse coupled-bunch instability (with the coupled-bunch pattern "clearly" visible on the upper plot) with a measured head-tail (within bunch) mode |m| = 1 from the Headtail monitor (lower plot). Note that the second signal of the second plot comes from the reflection. Courtesy of Benoit Salvant.

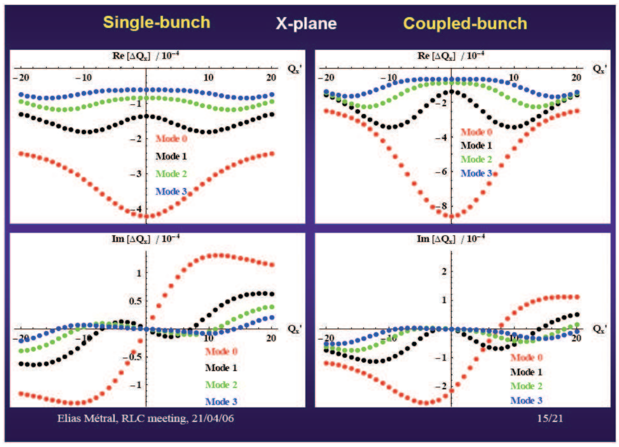

Figure 6: Theoretical predictions for the complex tune shifts of the nominal (25 ns) beam at injection.

planes. The beam was observed to be unstable with coupled-bunch coherent oscillations along the last batches (see Fig. 5a), without growing oscillations but with beam losses. This instability could be stabilized (and the beam losses removed) by increasing the chromaticities to Q' ~ 20. This observation is qualitatively compatible with a coupled-bunch instability $m = 0$ damped by the transverse feedback and the mode $|m| = 1$ which cannot be damped by the transverse feedback (see Fig. 5b). This would explain why there were no growing coherent oscillations (mode 0 is correctly damped by the transverse feedback) but still losses observed (mode 1 is growing). This is qualitatively what would have been expected from Fig. 6 (right), which was computed for the case of the nominal beam (25 ns beam) at injection: for Q' ~ 10, mode 1 could develop if not Landau damped (either by intrinsic lattice nonlinearities or by powering Landau octupoles). Increasing the chromaticity reduces the effect of mode 1 which might even become stable if the intrinsic nonlinearities are sufficient.

RECOMMENDATIONS

In the case of transverse coupled-bunch instabilities from the machine impedance and/or the electron cloud, the transverse feedback should be able to damp them [11]. Therefore, it is better to have the smallest chromaticity in order not to excite the higher order modes, which cannot be stabilized by transverse feedback (see Fig. 6 for a qualitative picture).

Moreover, one should not have a Transverse Mode-Coupling Instability (TMCI) from the machine impedance, and there is thus no reason to increase the chromaticity to stabilize the beam.

The only reason to increase the chromaticity could come from the electron cloud induced vertical single-bunch "TMCI-like" instability, which was most probably observed during the first MD with the 50 ns beam on 02/11/10. However, in this case a possible issue could come from transverse coupled-bunch instability from the machine impedance with head-tail mode |m| = 1 which could develop, and which cannot be damped by the transverse feedback. In this case, one should increase the chromaticity even more if mode 1 is not Landau damped (but in this case the beam lifetime will most probably be reduced) or increase the tune spread through Landau octupoles.

ACKNOWLEDGEMENTS

Many thanks to all the people who worked on impedances in the past (F. Ruggiero, L. Vos, F. Caspers, vacuum people etc.), and in particular B. Salvant and N. Mounet for the recent studies on impedances and single-beam coherent instabilities.

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Parameters and operation plans for 2011

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Abstract

The assumed LHC beam parameters for 2011 are first summarized. The overview of the 2011 schedule is presented and includes hardware commissioning, beam recommissioning, re-validation, scrubbing, technical stops, MD, ions and special physics run requests. A proposal is made for the strategy in intensity stepping up and potential issues are described together with possible actions. Finally, the potential peak and integrated luminosity are given.

INTRODUCTION

Client request

The LHC experiments wishes for 2011 may be summarized as follows:

- For ATLAS and CMS the (integrated) luminosity should be as high as possible. The integrated luminosity should exceed 1 fb^{-1}.
- For LHCb the luminosity should not exceed around $3 \times 10^{32} \mathrm{cm}^{-2} s^{-1}$, and the number of events per crossing μ should not exceed 2.5 (based on a visible cross-section of 72.5 mb).
- For ALICE the luminosity should not exceed around $4 \times 10^{30} \mathrm{cm}^{-2} s^{-1}$.
- TOTEM wants to operate during normal physics runs down to a distance of 15σ from the beam (as compared to 18σ in 2010). TOTEM would like a leading probe intensity bunch to be added to the standard filling scheme.

A number of special requests have also been expressed.

- Like in 2010, the experiments want to perform Van De Meer scans (i.e. extended luminosity scans). The exact conditions have not been defined yet. To simplify the scan procedure, the TCTs should be moved together with the beams.
- ALICE made a request for a special run at 1.38 TeV (the energy equivalent to the nucleon energy in Pb-Pb collisions). ALICE wants to collect around 50×10^6 events. This corresponds to a few fills with low intensity bunches.
- TOTEM (and ALFA) want to take data with the 90 m β^* optics (which must first be commissioned). The beams should be composed of a few bunches with a charge of $6 - 7 \times 10^{10}$ p. They would like to operate with Roman Pots at a distance of $7 - 8$ and $5 - 6\sigma$ from the beam. This requires closing the primary collimators to $3 - 4\sigma$. The emittances should be 3 and 1μm.

Finally both ALICE and LHCb would like to flip their spectrometer polarities from time to time (most likely during technical stops). The LHCb spectrometer affects only the horizontal orbit, the correction of the non-closure (non-reproducibility) using external compensators is working well. For ALICE the solenoid is flipped at the same time. In principle the ALICE spectrometer should only affect the vertical orbit, but due to the large coupling from the solenoid, there is an important perturbation of the horizontal orbit. In 2010 the structure of the crossing angle non-closure correction knobs mixed the horizontal and vertical planes, which made the reversal of the ALICE spectrometer and solenoid tricky. In 2011 a simpler correction of the non-closure will be available in YASP, and the knobs will properly decouple the planes (at least for ALICE).

ENERGY

It is assumed here that the LHC will be operated at 4 TeV, even if the decision will only be taken at the Chamonix workshop in January 2011. The difference with respect to 3.5 TeV is moderate in terms of operational issues:

- The reach in β^* is slightly increased at 4 TeV.
- The physical emittance scales with the inverse of the energy, luminosities at 4 TeV are 14% higher.
- The quench threshold is some 20% lower at 4 TeV, see Fig.1. This has a small effect on the criticality of UFOs.

BEAMS

The following beam types are considered as possible candidates for 2011 and are available in the injectors [1]:

- The 150 ns beam is operational, and up to 368 bunches were used at 3.5 TeV in 2010. With this scheme up to around 450 bunches may be injected into the LHC. The emittances at the exit of the SPS may be as low as 1.5 μm for intensities in excess of 1.2×10^{11} p per bunch.

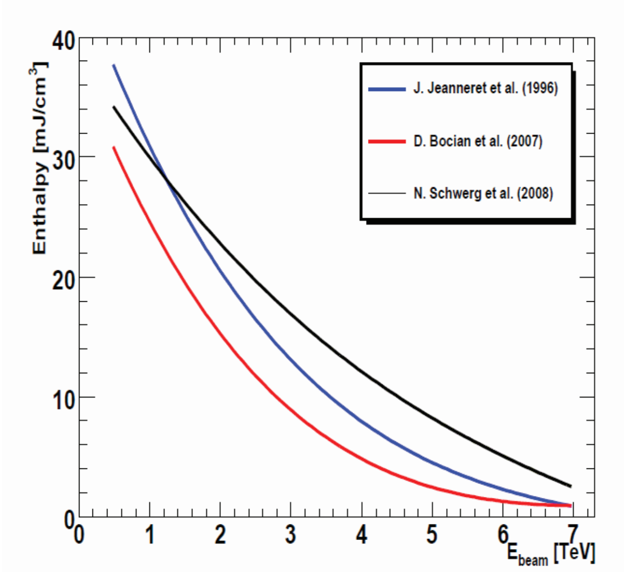

Figure 1: Estimated magnet enthalpy as a function of the energy for 3 different models (Courtesy M. Sapinski).

- The 75 ns beam is operational in the injectors, but some moderate scrubbing time is required to ensure adequate vacuum conditions with high intensity. Up to 950 bunches may be injected with this beam. At the exit of the SPS bunch intensities of 1.2×10^{11} protons with transverse emittance of 2μm have been achieved so far (single batch transfer PSB-PS).

- The 50 ns beam is likely to be only used for MD and beam scrubbing tests. Electron cloud effects have been observed in the arcs with this beam, and significant beam scrubbing time may be required before this beam may be in a state for use in regular operation [2].

With the good machine stability (and thanks also to the feedbacks), good lifetimes of the beams and excellent collimation performance, there is no limit on the total intensity for those beams.

The filling schemes will have to incorporate a leading probe bunch (intensity around 10^{10} protons) and a first injection with $12 - 24$ nominal bunches. Injections of up to 96 and 144 bunches should be achievable despite issues with the BLMs. Those constrains use up around 3μs of the LHC circumference.

Beam density

In terms of maximum beam density, the collimators are designed to stand the nominal beam at 7 TeV. For the TCDQ the exact limit is not yet known (work in progress), but the limit is expected to be lower than the nominal beam. It must be noted that for all the considered beams (50 ns or larger spacing) the beam load is a factor 2 and more less (in terms of number of bunches) than a nominal 25 ns beam.

The energy density ρ_E of the showers scale to first order as [3, 4]

$$\rho_E \propto \frac{N\,E}{\varepsilon_n/E} = \frac{N\,E^2}{\varepsilon_n} \tag{1}$$

where N is the number of particles and ε_n the normalized emittance. This simple rule is similar to the scaling law for the Setup Beam Flag (SBF) intensity limit N_{SBF} as derived in :

$$N_{SBF}\,E^{1.7} \propto \text{Constant} \tag{2}$$

where the effects of the shower length and emittance scaling with energy where taken into account (assuming a constant value for ε_n).

Given the possible beam intensity and emittance performance from the injectors, there is no limit on intensity and emittance in 2011.

β^* REACH

The reach in β^* is defined by the (knowledge) of the aperture, the tolerances for collimator alignment and the reproducibility of the orbit. The orbit reproducibility has increased along the 2010 run. The ion period was better than the 150 ns periods which was itself better than the single bunch run in July/August. The improvements are due to a better control and correction of the BPM electronics temperature effects ($\approx 50\mu\text{m}/\text{deg}$), as well to a better calibration procedure. The residual excursions that accumulate on the time scale of one month are around ± 0.2 mm peak-to-peak. Further improvements are anticipated in 2011 [5].

The reach in β^* has been presented elsewhere in this workshop [6]. With 'intermediate' collimators settings (as used in 2010) β^* of 2.5 m can be achieved without problems (thanks to the larger aperture in the triplets). With 'moderate' collimators settings (reduced margin TCT-triplet and TCT-TCDQ) β^* could be pushed down to 2 m or even 1.5 m. One must also take into account that below 2 m, the squeeze becomes more tricky, as the triplet errors start to play a non-negligible role. Aperture measurements should be performed in the early part of the 2011 run to define the final value of β^*. Squeeze settings should be prepared down to 1.1 m or so for CMS and ATLAS.

To gain aperture the separation of the beams should be reduced from ± 2 mm (injection and ramp) to ± 0.7 mm for the squeeze. This could be done in the first 2 minutes of the squeeze (or in the ramp). To keep things simple the crossing angles should be changed from injection ($\pm 170\mu$rad) to physics settings ($\pm 120 - 140\mu$rad) at the same time. The bumps changes will be implemented using the bump scaling feature of the orbit feedback. This will allow the squeeze to be performed in a single step.

ALICE

ALICE would profit from a β^* of 2 m for the vertex reconstruction. To reduce the separation during physics operation and gain aperture in IR2 (one critical point less) a β^* of 10 m could also be used. A squeeze to same β^* as the high luminosity IRs would reduce ion switch-over time, but this gain does not really justify to operate for the entire proton run with such a small β^*.

LHCb

LHCb has requested a β^* of 3.5 m as an optimum for integrated luminosity during intensity ramp-up and high luminosity operation at a recent LPC meeting. Overall a β^* of 4 to 5 m could represent a better optimum, which eventually also depends on the achievable (or expected) peak luminosity. To satisfy the LHCb requirements in terms of luminosity (see previous sections) a separation of up to $2\sigma^*$ may be required, unless β^* is squeezed dynamically during physics operation.

STARTUP 2011

The startup in 2011 will begin with a re-commissioning of the base machine:

- Inject the beams and obtain circulating beams. There is a good chance that a circulating beam may be obtained immediately with the settings of 2011 for the orbit, tune and chromaticity.
- Injection steering and rough optimization on TI2 and TI8.
- Establish asap a new base orbit for 2011. This orbit should be used on all phases, only the IRs bumps (separation and crossing) should change for different operating conditions. To establish this reference it is essential to have the best possible BPM calibration.
- The optics at injection must be checked and corrected if needed.
- The aperture should be measured at injection to confirm the reach in β^*.
- The collimators and absorbers must be setup completely around the new orbit at injection. The settings must be validated with beam tests (resonance crossing, debunched beam tests).
- Checkout ramp and squeeze with flat orbit and safe beam. Measure and correct the optics.
- Commission the ramp and squeeze with separation and crossing angles.
- Full collimator and absorber setup through the squeeze.
- Setup for collisions.

Numerous controls change are anticipated or have been requested, and some time must be anticipated for tests. Around 1-2 weeks are required for the machine protection system checkout.

RAMPING UP INTENSITY

The intensity ramp up strategy has not been discussed or decided at this moment in time. A reasonable guess based on the 2011 experience is:

- In a first phase the number of bunches is increased to 200 in steps of 50 bunches. This period will probably last around 10 days if all goes well. During this period the main sequence should be finalized. This ramp up could be done with 75 ns or 150 ns beams.
- A one week scrubbing run could possibly be inserted after this first phase.
- In a second phase the intensity would then be ramped up in steps op 100 (200) bunches up to around 900 bunches. A possible sequence could be: 200-300-400-500-600-700-900. Assuming a few fills at each step, this period would last around 3 weeks. The progress could be driven by e-cloud and vacuum, beam stability, UFOs, MPS issues, SEUs and OP considerations.

LUMINOSITY PERFORMANCE

The Hubner factor H relates the peak luminosity $\mathcal{L}_p$, the integrated luminosity $\mathcal{L}_{int}$ and scheduled time T_{op}

$$\mathcal{L}_{int} = \mathcal{L}_p \; H \; T_{op} \tag{3}$$

To set the scale: for $\mathcal{L}_p = 10^{32}\mathrm{cm}^{-2}s^{-1}$, $H = 0.2$ and T_{op} of 200 days, $\mathcal{L}_{int}$ is 172 pb^{-1}.

The Hubner factor may be estimated using the following simple model of the luminosity a typical fill. Assuming that each fill starts with a peak luminosity $\mathcal{L}_p$ and is dumped when the luminosity is halved, then the average luminosity is not far from $< \mathcal{L} >\simeq 3/4\mathcal{L}_p$. The integrated luminosity may therefore be expressed as:

$$\mathcal{L}_{int} = \mathcal{L}_p \; H \; T_{op} =< \mathcal{L} > \; \epsilon_{sb} \; T_{op} \simeq \frac{3}{4}\mathcal{L}_p \; \epsilon_{sb} \; T_{op} \tag{4}$$

where ϵ_{sb} is the ratio of time spent in stable beams with respect to the total run time T_{op}. From the above expression it is easy to deduce that

$$H \simeq \frac{3}{4}\epsilon_{sb} \tag{5}$$

for this simple model. To reach $H = 0.2$ the efficiency must be $\epsilon_{sb} \simeq 26\%$, a figure that has been achieved in 2010 in certain periods (for example during the ion period).

The tentative breakdown of the 2011 proton runs in terms of operational days taking into account MDs, technical stops, commissioning etc is given in Table 1: the total number of days at high luminosity T_{op} is 124 only days. For the following tables and figures $T_{op} = 125$ days will be assumed.

Table 2 presents luminosity estimates for 4 TeV based on 75 ns operation with 930 bunches for different values of

Item	Days
Run length	262
11 MDs (2 days)	-22
6 Technical stops (4+1 days)	-30
Special requests	-10
Commissioning	-28
Intensity ramp up	-40
Scrubbing	-8
Total	124

Table 1: Breakdown of the proton run in 2011 in terms of operational days.

β^* (m)	N_b (10^{10})	ε_n (μm)	E_{stored} (MJ)	$\mathcal{L}$ (cm$^{-2}s^{-1}$)	$\int\mathcal{L}$ (fb^{-1})
2.5	11	3.5	65.5	4.7×10^{32}	1.0
2.0	11	3.5	65.5	5.9×10^{32}	1.3
1.5	11	3.5	65.5	7.8×10^{32}	1.7
2.5	12	2.5	71.4	7.8×10^{32}	1.7
2.0	12	2.5	71.4	9.8×10^{32}	2.1
1.5	12	2.5	71.4	13.3×10^{32}	2.8

Table 2: Luminosity estimates for 75 ns operation, assuming 930 bunches. For 150 ns operation, the stored energy and luminosity figures should be halved. The integrated luminosity is based on 125 days of operation and H of 0.2

β^*, bunch population and emittance. For β^* of 2 m and below, it is possible to achieve peak luminosities in excess of 10^{33}cm$^{-2}s^{-1}$ provided the emittance is lower than nominal (but similar to what has been achieved for 150 ns in 2010) and the intensity slightly larger than nominal. The integrated luminosity is in the range of 1 to 3 fm^{-1} for 125 days of operation and H of 0.2.

Figures 2 and 3 indicate the bunch population and emittance required to reach $\mathcal{L}_p$ of 8×10^{32} and 10^{33} as a function of β^* assuming 950 bunches. The greyed area indicate the expected performance in terms of bunch population and emittance.

LUMINOSITY LEVELING

Luminosity leveling can be made with beam separation at the IR. This method was used very successfully and apparently without major impact on performance for IR2 in 2010. To reduce the peak luminosity $\mathcal{L}_p$ to the desired luminosity target $\mathcal{L}$, the required separation S is given in units of single beam size at the IP by:

$$S[\sigma] = 2\ln\left(\frac{\mathcal{L}_p}{\mathcal{L}}\right) \tag{6}$$

The separation is plotted as a function of the desired luminosity reduction in Fig. 4.

For ALICE the required beam separation is in the range of 3 to 4 σ^* depending on the final choice of β^*.

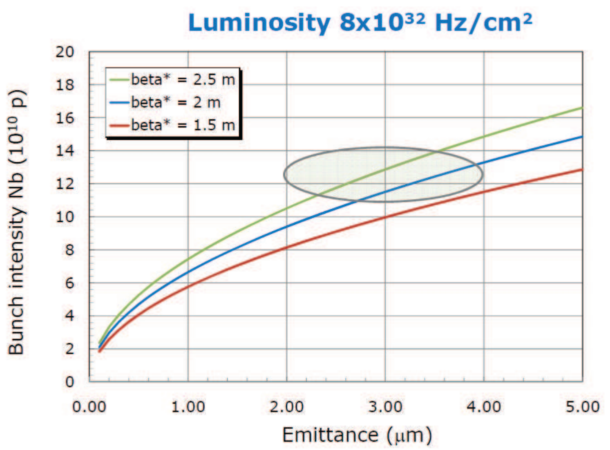

Figure 2: Required bunch intensity and emittance to reach a luminosity of 8×10^{32}cm$^{-2}s^{-1}$ as a function of β^* (assuming 950 bunches). The shaded region is the typical reach of the injectors (details depend on the beams).

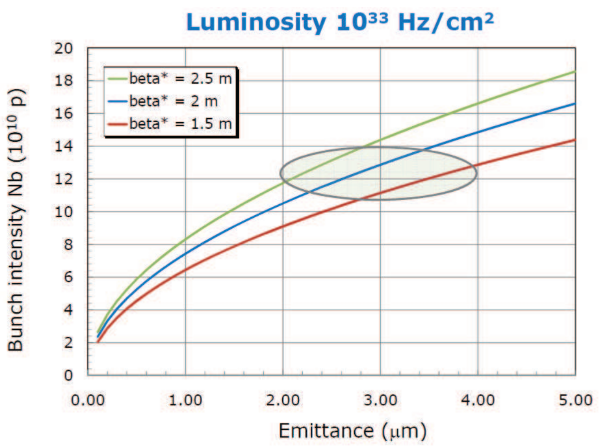

Figure 3: Required bunch intensity and emittance to reach a luminosity of 10^{33}cm$^{-2}s^{-1}$ as a function of β^* (assuming 950 bunches). The shaded region is the typical reach of the injectors (details depend on the beams).

For LHCb the beam separation and choice of β^* may be made like follows:

- Starting from the assumed peak luminosity in case of head-on collisions $\mathcal{L}_p$, the end-of-fill luminosity is assumed to be $\approx \mathcal{L}_p/2$.
- From the end-of-fill luminosity β^* is selected to match the LHCb peak luminosity. Some additional margin may be added (pick a somewhat lower β^*) to take into account that $\mathcal{L}_p$ could end up higher than expected!
- This ensures maximum luminosity up to the end of the fills, the luminosity being leveled with separation that can be reduced steadily as the luminosity decays in the fill.

Depending on the assumption on $\mathcal{L}_p$, the optimum β^* is in the range of 3 to 5 m. The required separation is in the range of 0.5 to 2 σ^*.

In case beam separation would eventually lead to beam-beam issues, the other choice for luminosity leveling is a continuous β^* reduction during a fill. In 2010 it was clearly demonstrated that the squeeze can be made very smooth thanks to feedbacks and reproducible optics, therefore this option could be envisaged. Technically one would have to define a number of squeeze points for LHCb, and 'jump' from one point to the next every now and then. In order not to loose to much time, those squeeze steps must be done in stable beams, else too much time would be wasted to move back and forth between stable beams and adjust. Such an operation would also require extra collimator setups and validations. Finally as a last word, it is worth mentioning that such a continuous β^* reduction is not an operation that is easy to commission with 900 bunches in the ring.

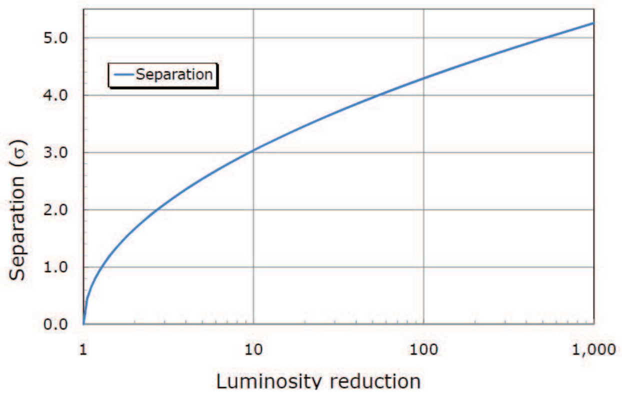

Figure 4: Separation of the beams at the IP (in terms of single beam size) as a function of the desired luminosity reduction.

IONS

The ion run foreseen at the end of 2011 will also profit from the β^* reduction used for the proton run. The current schedule foresees only 4 days of setup which could be tight in case the squeeze has to be commissioned for IR2. The reduction in β^* could boost the luminosity by a factor of roughly 2 with respect to 2010 (to $6 \times 10^{25}\mathrm{cm}^{-2}s^{-1}$). To increase the luminosity further the number of bunches must be increased beyond the maximum value of 139 used in 2011 with bunch spacing of 500 ns. This requires switching to the nominal ion scheme (100 ns bunch separation) and using crossing angles for collisions. It is important to note that in 2010 the bunch intensity was significantly higher than the design value, and that with the 100 ns nominal ion scheme the intensity per bunch will probably go down, reducing the gain from the increased number of bunches. Together with the β^* reduction, moving to the nominal ion scheme this could yield a total luminosity gain of up to a factor 10 (to $3 \times 10^{26}\mathrm{cm}^{-2}s^{-1}$) - but only if the bunch intensity remains high. It must also be noted that this increased luminosity will also make SEU effects more critical in the dispersion suppressors of IR1, IR2, IR3, IR5 and IR7.

CONCLUSIONS

The main conclusions concerning the performance in 2011 can be summarized as follows:

- The total number of days of high intensity operation is only around 50% of the total scheduled time for proton operation, around 125 days. In order not to waste more time operation must follow a good plan, diversion from the target of stable high intensity running will be very costly in terms of integrated luminosity.
- With 75 ns beams and β^* of 2 m or below it is possible to reach or even exceed peak luminosities of $10^{33}\mathcal{L}_{int}$. The integrated luminosity is in the range of 1 to 3 fm^{-1}.
- Operational efficiency is of prime importance and may favor certain beam parameters (for example lower emittances are better for injection) over others.
- Beam separation at the IR presents the simplest way of leveling luminosity for LHCb.

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EVIAN SUMMARY

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Abstract

A summary of the second Evian workshop in 2010 is attempted.

PREAMBLE

The second Evian workshop in 2010 came the day after last beam and was an intense two days spread over three. Following a brief introduction looking back at the successes of 2010, the sessions covered:

- **LHC beam operation**: review of 2010 and setting the scene for 2011, which looked at: experiments, efficiency, beam from injectors, experience with 75 & 50 ns. bunch spacing, intensity ramp up, and RF performance.
- **Driving the LHC**, which looked at: turnaround, software, the magnetic model, missing functionality.
- **Beam diagnostics and feedback systems**: bunch by bunch, feedbacks, transverse damper, BPMs, transverse beam size.
- **Machine protection systems**: MPS performance, LDBS, abort gap, minimum beta*, injection protection, the human factor.
- **Beam losses**: collimation, injection, extraction, UFOs, BLM thresholds.
- **Luminosity performance**: emittance preservation, the hump, beam-beam, luminosity optimization, optics, pushing the limits in 2011.

The wrap-up session included a look at 2011 running and possible integrated luminosity for the year.

2010 - OVERVIEW

The main milestones of the 2010 commissioning are outlined in table 1.

Table 1: main commissioning milestones 2010

Date	Milestone
March	Initial commissioning leading to first collisions
April	Squeeze commissioning
May	Physics 13 on 13 with 2e10 ppb
June	Commissioning of nominal bunch intensity
July	Physics 25 on 25 with 9e10 ppb
August	3 weeks running at 1 – 2 MJ
September	Bunch train commissioning
Oct - Nov	Phased increase in total beam intensity

The intensity ramp-up following the bunch train commissioning in August is shown in table 2.

Table 2: intensity ramp-up and associated performance

Date	Bunches	Colliding pairs	Luminosity
29th August	50	35	1×10^{31}
1 – 22nd Sept.	Bunch train commissioning		
22nd Sept.	24	16	4.5×10^{30}
23rd Sept.	56	47	2×10^{31}
25th Sept.	104	93	3.5×10^{31}
29th Sept.	152	140	5×10^{31}
4th Oct.	204	186	7×10^{31}
8th Oct.	248	233	8.8×10^{31}
14th Oct.	248	233	1×10^{32}
16th Oct.	312	295	1.35×10^{32}
25th Oct.	368	348	2.07×10^{32}
4th Nov.	Switch to heavy ions		
9th Nov.	17	16	3.5×10^{24}
15th Nov.	121	114	2.88×10^{25}

The two tables above tell a tale of remarkable progress and testament to an enormous amount of hard work before and during commissioning. Some of this is hopefully captured in these proceedings.

LHC BEAM OPERATION

Operational efficiency – Walter Venturini

The 2010 run was driven mainly by commissioning, and not operations for physics. In this regard, any analysis of operational efficiency should be regarded with some latitude. However for a first year the signs are very encouraging.

- Some huge equipment systems performed above expectations (considering mean time between failures etc.).
- Equipment groups are aware of the weak points and are working to improve them.
- Technical stops certainly caused problem initially but it got better through the year.
- There was truly impressive availability for a first full year.
- Fault statistics gathering must be improved!

Beam quality and availability from the injectors – Giulia Papotti

Beam quality from the injectors proved to be critical and a lot of time was spent at injection ensuring that things were up to scratch.

- Clear procedures are needed (covering scraping, blow-up etc.)
- Preparation must be made in good time; checklists should be implemented.
- We must be able to track beam quality through the injectors: emittances, intensities
- LHC requests must be communicated in good time to the injectors.
- There is a nice long list of RF improvements in the SPS. These must be followed up.
- Dedicated LHC filling is to be pursued.

Turnaround optimization – Stefano Redaelli

Analysis of last year's run showed that the injection process dominated the turn around time. Typically more than 2 hours was lost.

- A set of proposals was presented for reducing the length of time spent at injection. Significant improvement is required during this phase.
- "Manual" changes should be reduced to a minimum while driving the machine through the cycle. Clearly this opens room for mistakes and these tasks must be eliminated.
- 5 minutes can be saved with a faster ramp – to be tested in 2011.
- It is possible to gain 10 to 15 minutes by not stopping in the squeeze – a top priority.

We do not seem to be yet in the position to gain from more aggressive approaches, suggestions for which include: continuous functions for ramp, squeeze and collision; and a combined ramp and squeeze. These may become interesting when present issues are solved and a little more maturity has been brought to bear.

It should be noted that mistakes are expensive. It is a priority to eliminate these. One four hour turn around takes a lot of 5 minute savings to recuperate the lost time.

Software and controls – Delphine Jacquet

There is a long, well order list of improvements that includes: equipment control; injection sequencer; state machine; LSA; Alarms; Diamon etc. Of note:

- The nominal sequence needs to be nailed down in cooperation with the whole LHC section.
- Bunch-by-bunch diagnostics is required across the board.
- More exotic fixed displays might include: cryogenics heat load; vacuum activity; display of sub-threshold UFOs.
- Tune scans with on-line tune diagram and display of tune spread would be useful.
- Automatic plots, including bunch-by-bunch "Giulia plots", should be available after every fill.
- There is a long list of LSA improvements – thorough testing required.

There is a very short shutdown and some of the above will only be deployed during the year.

Magnetic model – Ezio Todesco

The deployment of FIDEL was a one of the year's major achievements. However, some improvements are still possible:

- Ramp-down/precycle for access (100 A in main bends) should be deployed having measured the effects on decay and snapback.
- The differences between precycle and ramp-down combo must be sorted out.
- There are procedures for individual circuit trips. The shift crews should recall these.
- Dynamic b3 compensation at injection. The magnitude of the observed decay is as expected by FiDeL but on much longer time constant. The decay should be measured and appropriate correction implemented.
- Remove hysteresis handling in the squeeze.
- Rollback decay driven trims (tune and chromaticity) before starting each injection.
- Chromaticity during ramp was tracked within ±7 units – we can improve in the initial part of the ramp.
- Tune decay is clearly observed at injection – source as yet unknown. Dynamic correction is to be considered.

The human factor – Alick Macpherson

- Documentation of procedures should be a lot better.
- Control room ergonomics must be improved.
- Machine protection envelope should be defined and implemented.
- Experience (or induction) can be a dangerous guide.

The LHC is a 5.4 GCHF investment. The personnel and material budget is around 299 MCF/year. There is an understandable desire to capitalize on the investment. One way of doing this is by having long operational years.

Operations and infrastructure teams with limited manpower have become stretched in some areas. Two points: potential risk of burnout of staff members; risk of less than fully safe operations and maintenance of the LHC.

RF, BEAM DIAGNOSTICS AND FEEDBACK SYSTEMS

Key systems have performed with a remarkable degree of maturity; inevitably some improvements are possible.

Bunch by bunch diagnostics will be required for: orbit; head-tail monitor; BCT; longitudinal profile; wall current monitor; longitudinal density monitor; synchrotron light telescope; the experiments' data; and if possible the tune.

Appropriate storage, access and display facilities should be provided.

RF: Operation 2010 and Plans for 2011 – Philippe Baudrenghien

It was a successful year all in all for the LHC RF team.

- Cogging works well
- 50 Hz is no problem in the ramp
- Blow-up in the ramp to avoid lost of Landau damping is operational and has performed…perfectly
- September - reconfigured the RF for higher intensity and faster ramp: no more idling cavities. All klystrons on.
- Counter phasing was implemented at 450 GeV.
- Capture losses: the sensitivity of the BLM dump system to injection losses must be decreased by 2 orders of magnitude (x100) or mitigating measures found.
- RF noise turned out to be a "no-problem" in 2010.
- We need a clear strategy for cavity trips in physics. But don't panic: 3 out of 8 cavities with 15% of nominal intensity was OK, but we will have to dump with nominal intensity.

- If you do fill the abort gap, wait. Strategy to be defined.

A number of technical problems were listed. Of note were the issues with noisy cavities: these problems are worrying. To be investigated during hardware re-start.

Incoming in 2011 are: SPS-LHC phase energy matching; longitudinal damper; and possible coupled bunch instabilities among other things.

Feedbacks – Ralph Steinhagen

Feedbacks performed well and facilitated fast commissioning. They were de-facto required during every ramp and squeeze with nominal beam and expect the same also for next year. More than half of all ramps would have been definitely lost without them although feed-forward would have clearly been pursued more rigorously had feedback not been available. Additional safety margin to operation can be provided if feed-forward is performed regularly – to be done in 2011.

- Tune peak-to-peak stability typically below 0.02 with margin to push it < 0.003
- There was little impact of residual tune error on transmission
- Most RT-trims correlated with Q'(t) – a possible feed-down effect?
- Q'(t) a bit neglected this year → some indication of trade-off: beam stability (low transmission losses) vs. beam size growth. Could we further explore this via dedicated/controlled measurements?
- Effective ADT noise floor and observed bunch-to-bunch cross-talk hinders reliable operation of LHC's Q/Q'-diagnostics and related feedbacks.
  Alternate BI diagnostic options have been explored. The ball is now on the RF group's side of the court.

There was good overall performance with little transmission losses and minimal hick-ups related to Q/Q' instrumentation, diagnostics and Q/Q' & orbit feedbacks. However in 2011 1% losses may become more critical.

Transverse dampers – Wolfgang Hofle

An impressive year for the transverse damper system:

- commissioned damper at 450 GeV, during ramp and with colliding beams;
- nominal damping rate reached and surpassed;
- commissioned operation with bunch train;
- commissioned damper for ions at 450 GeV and with colliding ion beams;
- abort gap cleaning and injection slot cleaning successfully used;
- diagnostics (logging, fixed display, multi-bunch acquisition) available.

There are lots of improvements incoming in 2011. The tune measurement options were listed and the team will work on compatibility with tune feedback. One suggestion was injecting witness bunches. The strategy is to be defined.

BPMs – Eva Calvo

- The global performance of the system was very good with around 97% channel availability.
- There were a number of improvements made throughout the year including temperature calibration/compensation.
- Synchronous mode will be available in 2011. This will solve the double trigger issue on the IR BPMs.
- Multi-turn orbit on selected bunches will be available.
- IR BPMs: cable adapters will be installed during the Christmas technical stop.
- Pre-flight checks with beam that will test acquisition and calibration should be routinely deployed.
- Intensity dependence crossover – the observed beam one behaviour was caused by a small impedance mismatch at the input of the intensity module. The intensity card will be replaced by a termination card in the IR BPMs this technical stop.

Transverse emittance measurements – Federico Roncarolo

- The wire scanners offer turn and bunch-to-bunch capabilities. They are the reference for transverse beam size measurements but care is required.
- The synchrotron light telescope (BSRT) is available in DC and pulsed mode. Resolution is given by the optics of the system. Given accuracy is via cross-calibration with the wire scanners, however correction factors are not stable. Things are complicated in ramp with changes of focusing etc. Bunch by bunch, turn by turn functionality is incoming via a fast camera.
- The BGI is in the commissioning phase. Calibration with bumps is foreseen. MD time is required

MACHINE PROTECTION

Machine protection system has functioned remarkably well with long list of improvements foreseen for 2011.

Intensity ramp up strategy in 2010 was well judged. The dangers must again be taken seriously in 2011. A clear strategy for 2011 is required.

Injection protection becomes essential, we are now injecting unsafe beam into the LHC. A more rigorous approach at injection is required following a beam dump/post mortem when there is more than 500 kJ in the machine.

Machine protection system response – Markus Zerlauth

- LHC Machine Protection Systems have worked extremely well during 2010 run thanks to a lot of commitment and rigor of operation crews and MPS experts.
- Most failures are captured before effects on beam are seen. We have still seen no quenches with circulating

beam (with ~ 30 MJ per beam and 10 mJ required to quench a magnet).
- Beam dumps above injection are rigorously analyzed, we can do better at injection (avoiding repetitive tries without identifying the cause).
- Still a lot of room for improving tools for more efficient and automated analysis.
- No evidence of major loopholes or uncovered risks, but bypassing of protection layers was/is still possible. Follow-up of MPS Review recommendations is required.
- Still we have to remain vigilant to maintain current level of dependability of MPS systems, especially when entering longer periods of 'stable running'.

LBDS – Chiara Bracco

In general, it was a very good performance from the LBDS. Faults seen:

- 1 energy tracking error at 3.5 TeV due to instabilities of 35 kV power supplies (30/03/2010: media day)
- Asynchronous beam dump, during energy scan without beam (due to spark on the outside of the gate turn-off GTO thyristor): 1 at 5 TeV; 2 at 7 TeV.
- 4 internal triggers due to vacuum interlocks on the MKB for beam 2. These were due to false vacuum pressure readings. The logic has been changed to use only the VAC signal.
- 1 Asynchronous beam dump with beam
- 2 beam dumps induced by TCDQ faults

LBDS failures occurrence were in agreement and not worse than requirements and expectations. No damage or quench during synchronous and asynchronous beam dumps. Leakage to downstream elements within specifications. The TCDQ needs tender, loving, care, and long-term plans are to be defined.

Open questions include Machine protection validation tests, procedures and tests frequency: Is the strategy adequate (too often, too rarely)? Could the tests be improved? Do they really insure machine safety?

Injection protection – Verena Kain

Injection protection is fully operational and working well; all problems so far caught. In fact it has already saved the LHC from damage several times (beams onto TDIs).

- Are we taking it seriously? Most of it: yes. Injection interlocking etc. looks good.
- Injection oscillations + orbit will be tightening up in 2011.
- It has been too easy to put full injected batch onto TDI: to be improved.
- How can we make it safer? Concept of intermediate intensity + injection oscillation interlock; threshold management of injection protection; timing system fix for GPS problems; tightening up operational settings tolerances on MKI;
- Checks in Injection Scheme Editor for filling patterns to take abort gap keeper into consideration.

BEAM LOSSES

There was excellent performance of collimation system with no quenches with beam above 450 GeV. There are issues at injection with fast losses. UFOs are a primary concern.

Multiturn losses and cleaning – Daniel Wollmann

The phase-I LHC collimation system delivers expected collimation efficiency. The impact of imperfections is a factor 2 smaller than predicted (better orbit control in DS).

• The setup procedure has been refined and optimized (15-20 minutes per collimator needed)

• Validity of collimation setup is around 5-6 months, then close to the edge. Might require two setups in 10 months run in 2011.

• <u>The instantaneous peak loss rate about factor 9 lower than specified: with this we should be good for nominal intensity at 3.5 and 4.0 TeV (in terms of cleaning efficiency).</u>

• But: instabilities can increase loss rate and therefore cause collimation induced intensity limitations (possible for higher intensities and energies).

• Cleaning with ions much less efficient than for protons (as expected): Leakage in orders of percents into DS magnets and TCTs, very localized losses observed.

Injection and extraction losses – Wolfgang Bartmann

- Limits for 2011: 96 or 108 bunches per injection for operation look OK
- Injection Tests with higher intensity or 25 ns spacing might be possible depending on TL shower/capture loss mitigation.
- Extraction losses on Q4/Q5 are dominated by shower from TCDQ.
- Loss mitigation at injection are necessary to go beyond operational intensity scope. Potential techniques to further reduce losses need to be commissioned (e.g. Injection cleaning); installed (e.g. TCDI and TDI shielding - partly available in 2011); or deployed (e.g. BLM sunglasses).

Losses away from collimators: statistics and extrapolation – Barbara Holzer

UFOs are a big concern.

- Observed around the ring (triplet, IRs and arcs) but interestingly there are hot and cold regions out there
- Rate scaling up with total intensity – extrapolations look worrying.
- Beam loss events don't appear to get harder with intensity
- Loss duration falls with intensity

The first line of defence will be to maximize UFO acceptance by threshold adjustment at the appropriate time scales.

BLM hardware failures are acceptable!

LUMINOSITY PERFORMANCE

Beam-beam – Werner Herr

- In 2011 we should establish the limits by pushing the bunch population and small emittances. The full long-range effect should be probed; the established limits should set the boundary conditions for the squeeze.
- The offset in LHCb should be OK
- Effort should be made to equalize the beam sizes.
- MD time is required.

Luminosity optimization – Simon White

Fully automated scans with optimization in parallel were delivered – excellent performance.

- Very good fill-to-fill reproducibility +/- 60 micron fluctuations.
- Stability during a fill – excellent
- Should optimize vertical plan in Alice as well
- Could declare stable beams while optimizing (?)
- Should be able to speed up collision beam process by ramping down separation during ramp.
- Movement at TCTs is a concern: either tighter, enforced limits or move the TCTs during a scan. Functionality for the latter is in place but to be tested.
- The luminosity scan software has to be passed on as Simon moves to pastures new.
- Automatic luminosity levelling was raised as a possibility.
- Dithering was also mentioned as a possibility.

Optics – Rogelio Tomas-Garcia

The beating at injection, and during squeeze is well corrected and correction to the 10% level was achieved at 3.5 m. The beta functions at the IPs were also correct to within 10%. Excellent long-term stability is noted. There were, however, a number of issues.

- 2 m. mystery - a 10% drift was noted
- Beating was slightly worse when the correction were implemented in LSA. This turn out to be due to not driving IRs 3, 4, 6 and 7 after the global correction had introduced trims in these areas.
- It is estimated that hysteresis effects could cause up to 10% beating at 1.5 m.
- A non-negligible drift of 8% observed at injection
- Beating is going to get worse as we squeeze further, but it should be correctable.
- Local coupling correction in the interaction regions will become mandatory below 2 m.
- Hysteresis handling in LSA should be dis-continued

The hump – Gianluigi Arduini

The hump affects luminosity performance due to blow-up (particularly at 450 GeV). In collision it can excite beam-beam coherent modes or generate tails and therefore losses. The main mitigation measure is the use of low noise TFB at maximum gain.

Since middle of November turn-by-turn/bunch-by-bunch position with damper pick-up has been available. Ion filling scheme with basic spacing of 500 ns gave the possibility of determining the frequency of the hump $\pm f_0 + n \times 2$ MHz with $0 < f_0 < 1$ MHz. The frequency of the hump is less than 10 MHz.

The identification (and possibly eradication) of the origin remains the (challenging) goal of the on-going analysis and measurements.

- The hump is there all the time. Use the hump buster.
- It causes emittance blow-up at injection and faster decrease in luminosity in collision. (Tails, beam loss – nice plots).
- It is a constant magnetic field effect – goes linear with energy
- Incoming: transverse feedback on in the squeeze next year (possibly); optimization of gain in collision; more noise reduction in the feedback system.

The hunt continues.

2011

Given the performance of 2010 it is reasonable to look forward to 2011 with some optimism. However, it should be bourn in mind that there are problems lurking out there. These include: electron cloud; UFOs; beam-beam; and R2E. Of these UFOs probably have the most potential to wreak havoc with operational efficiency.

Questions subsequently answered:

- Energy – 3.5 TeV
- Squeezing further - minimum beta* - 1.5 m. Collimation, aperture, orbit look OK
- LHCb "luminosity levelling" via separation at 3 m
- Beta* = 10 m. at Alice. Accept overhead of commissioning squeeze for ion run.
- Start with 75 ns. with 150 ns. as back-up
- No limit on beam intensity from collimation
- Bunch intensity at least nominal
- 1.2e11 with emittance of 2 micron – 75 ns – single batch definitely sounds interesting

Experiments requirements – Massi Ferro-Luzzi

- Rationalization of polarity reversal procedures
- Van der Meer scans as required for luminosity calibration accompanied by accurate BCTs
- Luminosity levelling for LHCb with a maximum luminosity of 3×10^{32} $cm^{-2}s^{-1}$, maximum pile-up (mu) of 2.5
- A multi fb^{-1} year is anticipated for Atlas and CMS
- Max 4×10^{32} $cm^{-2}s^{-1}$ for Alice (beta*, separation)
- Special runs will include intermediate energy, 90 m. etc.

50 and 75 ns (electron cloud) Gianluigi Arduini

Electron cloud was initially observed with 150 ns. in the common beam pipe where it was driven by near coincident beam crossings. However electron cloud really kicked off with 50 ns. It was also seen in single beam warm sections with 75 ns.

- The scrubbing time constant is around 8 hours with 50 ns.
- Scrubbing at smaller bunch spacing than operational required buys margin.
- Scrubbing should be performed with the experiments solenoids off
- Heat load observed in the arcs with 50 ns but not 75 ns.
- Scrubbing at 450 GeV in the arc is good for higher energy
- 50 ns: see instabilities developing along the trains – curable with high chromaticity.
- Possible coupled bunch modes with 75 ns plus head-tail. Transverse feedback, low chromaticity as cures.
- 75 ns: incoherent effects observed with low e-cloud density and 30-40% emittance blow-up of some bunches (with high chromaticity).

Ramping up in intensity

Strategy was reasonable in 2010 despite all the discussion. It should be pursued in 2011.

- Reviews and staged increase served us well in 2010
- “Just because we have a checklist doesn’t mean we’re safe”. Review the checklist.
- Review recommendations of the reviews – has everything been taken into account?

Re-commissioning in 2011 foresees:

- 3 to 4 weeks re-commissioning with a virgin set-up, new ramp, new squeeze, new beta*s, orbit, modified parameter space… it will be different.
- Full collimator set-up and full validation (loss maps, asynchronous dumps etc.)
- One would foresee a ramp backup to around 200 bunches in 50 bunch steps (with 75 ns. bunch spacing). In 2010 it took around 4 days (minimum) per 50 bunch step with most time lost to machine availability and lost fills (UFOs…). Thus it is reasonable to anticipate around 2 weeks to get back to 200 bunches
- After a 10 day scrubbing run larger steps of 100 bunches is foreseen driving through from 300 to a maximum of 900 bunches (for 75 ns.). This should take around 3 weeks.

It is important that a revised checklist and regular meetings of the rMPP are used to sign off each step up intensity. Regular beam-based checks should also be performed.

beta - how low can we go? Roderick Bruce*

Given that the measured aperture (at 450 GeV) is larger than expected and by scaling to 3.5 TeV and other assumptions (orbit uncertainty 3 mm, measured beam size…), the conclusion is that:

- Could go to 2.5 m without reducing present margins
- With decreased margins (TCT/triplet: 1.5 σ; reduce margin TCT-dump protection from 5.7 to 3.4 σ) and assuming:
  - nominal 0.7 mm separation – should bring it down in ramp;
  - using measured beating at injection and top energy with 5% reproducibility, 10% beating in n1 calculation;
  - 3mm orbit shift in pessimistic direction between measurement at injection and top energy;
  - 12 sigma beam-beam separation (larger than nominal);
  - triplet aperture at injection 2 sigma larger than global limit.

The proposal for 3.5 TeV running is a beta* of around 1.5 m.

Beam parameters from SPS – Elias Metral

Approximate beam parameters expected from injectors in 2011 (* indicates that the value has yet be established).

Bunch spacing [ns]	Batches from PSB	Bunch Intensity	Emittance [mm.mrad]
150	Single	1.1×10^{11}	< 2.0
75	Single	1.2×10^{11}	2
75	Double	1.2×10^{11}*	1.2*
50	Single	1.4×10^{11}	3.5
50	Double	1.2×10^{11}*	1.5*
25	Double	1.15×10^{11}	3.6

Luminosity estimates for 2011

A number of variations were shown. Typical assumptions were:

- 3.5 TeV
- 930 bunches (75 ns)
- 2.5 micron emittance
- 1.2×10^{11} protons/bunch
- beta* = 1.5 m
- Nominal crossing angle
- Hübner factor 0.2
- 130 days at peak luminosity

Given the above one should see a peak luminosity touch in the order of $1 \times 10^{33} cm^{-2}s^{-1}$ and an integrated for the year of 2 to 3 fb^{-1}.

CONCLUSIONS

2010 saw the LHC come a phenomenally long way in 9 months. Among the notable features is the remarkable maturity of some key systems after just a year. This hasn’t come for free; it’s been years in the preparation; and the devil is, as always, in the details. There is still lots to follow-up with possible improvements and consolidation detailed for all systems.

2011 clearly aims to leverage off of what’s been learnt this year and the potential is encouraging. However there are some known problems incoming (UFOs, electron cloud, R2E) which could impact operability. Perhaps most importantly, we will be pushing up Ralph's stored energy plot during the year and working almost from the start with destructive beams. Awareness of the risks must underpin our approach.

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An excellent job was done by the workshop secretariat (Sylvia Dubourg, Flora Meric): the web site was in place, we all got there, had somewhere to sleep and had plenty to eat. This was not obvious - there were many "requests".

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