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RLIUP: Review of LHC and Injector Upgrade Plans

Centre de Convention, Archamps, France, 29–31 October 2013

Proceedings

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Abstract

This report contains the Proceedings of the "Review of LHC and Injector Upgrade Plans" (RLIUP), held in the Centre de Convention, Archamps, France, 29–31 October 2013. The RLIUP examined the parameters of the LIU and HL-LHC projects following the experience and changes in the beam parameters experienced over the previous two years. It discussed which level of integrated luminosity will necessitate a replacement of the inner detectors and the insertions, the importance of reaching 3000 fb^{-1} or the minimum integrated luminosity which would be tolerated. The main outcome of RLIUP is a staged path from the LHC performance at the end of 2012 to the required performance for the HL-LHC, along with a number of important recommendations on the work organization of the coming years.

Preface

The "Review of LHC and Injector Upgrade Plans" (RLIUP) was held in the Centre de Convention, Archamps, France, 29–31 October 2013 (see http://indico.cern.ch/event/260492/). RLIUP was attended by 111 participants, coming mostly from the CERN Accelerators and Technology Sector. Also several representatives of the LHC experiments and all 9 members of the CERN Machine Advisory Committee (CMAC) had been invited (6 of the latter attended).

The workshop scope and programme had been drafted by an RLIUP Organizing Committee, comprising Gianluigi Arduini, Frederick Bordry (Co-Chair), Oliver Brüning, Paul Collier, Brennan Goddard (Deputy Scientific Secretary), Mike Lamont (Deputy Chair), Malika Meddahi, Steve Myers (Chair), Roland Garoby, Lucio Rossi, Roberto Saban, and Frank Zimmermann (Scientific Secretary).

The RLIUP examined the parameters of the LIU and HL-LHC projects following the experience and changes in the beam parameters experienced over the previous two years, according to which the LHC/HL-LHC luminosity performance will be determined by the event pile-up and pile-up density; by the bunch spacing, with electron cloud a possible issue for 25 ns, requiring scrubbing and a long-term solution; and by the machine availability, calling for a minimization of downtime and speeding up of the turnaround time. In addition, RLIUP discussed which level of integrated luminosity will necessitate a replacement of the inner detectors and the insertions, the importance of delivering 3000 fb^{-1} or the minimum integrated luminosity which would be tolerated instead.

RLIUP concluded that shutdowns have to be planned well in advance, including a global resources-loaded schedule; that the weaknesses in some expertise areas need to be rectified; and that any new designs should be based on the ALARA principle using the correct materials. As a primary outcome, RLIUP produced a staged path from the LHC performance at the end of 2012 to the required performance for the HL-LHC. RLIUP also suggested investigating an increase of the maximum beam energy, noting the planned installation of some 11-T magnets as part of the HL-LHC project.

Further information on the review can be accessed from its indico web site http://indico.cern.ch/event/260492/. The RLIUP was organized in 6 (or 7) plenary sessions, covering (1) experiments, (2) post-LS1 scenarios with and without Linac 4, (3a) PICs and upgrade scenario 1: adding performance improving consolidation, (3b) PICs and upgrade scenario 1: upgrade scenario 1, (4) upgrade scenario 2, (5) ions, and (6) close out. The proceedings are structured according to these plenary sessions:

- Session 1: experiments (conveners A. Ball and M. Lamont)
- Session 2: post-LS1 scenarios with and without Linac4 (conveners G. Arduni and S. Hancock)
- Session 3a: PICs and upgrade scenario 1: adding performance improving consolidation, (conveners M. Meddahi and L. Rossi)
- Session 3b: PICs and upgrade scenario 1: upgrade scenario 1 (conveners M. Meddahi and L. Rossi)
- Session 4: upgrade scenario 2 (conveners B. Goddard and R. Garoby)
- Session 5: ions (conveners O. Brüning and M. Ferro-Luzzi)
- Session 6: close out (conveners S. Myers and F. Zimmermann)

These proceedings have been published in paper and electronic form. Electronic copies can be retrieved through the CERN CDS pages.

The compilation of these proceedings would not have been possible without the help of the conveners and the excellent contributions from the speakers. The organizational support by the workshop secretary Shauna Dillon, technical support by Pierre Charrue, and indispensable editorial assistance in the preparation of the proceedings by Valeria Brancolini, Evelyne Delucinge, and Lucie Mainoli are also most gratefully acknowledged.

Finally, we would like to thank all the participants for the stimulating and lively discussions.

Geneva, 18 July 2014
B. Goddard and F. Zimmermann

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PERFORMANCE PARAMETERS – EXPERIMENTS PERSPECTIVE

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Abstract

In its physics program for the next two decades, the LHC foresees a series of upgrades to steadily increase the instantaneous luminosity of the accelerator. This paper describes the experimental challenges for the ATLAS and CMS detectors to operate and perform at increasing rates and occupancies. It focuses on the upgrades that will be implemented to maintain the physics acceptance in the trigger selection and the high efficiency and resolution in the reconstruction of the many interactions that will occur at each beam crossing.

INTRODUCTION

The upgrades of the ATLAS and CMS experiments will be accomplished in three stages during the long shutdowns foreseen for the upgrades of the LHC. In LS1, the CM energy will be increased to 13 TeV (or slightly higher), and it is expected that the bunch spacing will be reduced to 25 ns for future RUNs. It is anticipated that the peak luminosity can exceed the nominal value of $1x10^{34}$ Hz/cm^2 before LS2 and reach more than $2x10^{34}$ Hz/cm^2 after LS2. The experiment upgrades during LS1 will complete the original detector designs, consolidate operation and start to prepare for luminosities beyond the nominal value. In the period through LS2 (Phase 1) the upgrades will be completed for operation at a mean pile-up (PU) of ~50 proton-proton collisions per bunch crossing, with margin up to ~70. In LS3 the LHC itself will be upgraded to optimize the bunch overlap at the interaction region. It is foreseen that the peak luminosity, exceeding 10^{35} Hz/cm^2 at the beginning of the fills, will be leveled at ~5 x 10^{34} Hz/cm^2 to control the PU. The goal for the High Luminosity LHC (Phase 2) is to deliver a further 2500 fb^{-1} in the decade after LS3. ATLAS and CMS will need major upgrades during this shutdown to solve detector and system aging, high occupancy and radiation hardness issues, mitigate pile-up effects and enhance performance where statistics/systematics limited.

PHASE 1 UPGRADES

The phase 1 upgrades [1,2] are mainly driven by technical constraints of integration in the current detectors, in addition to the external constraints of schedule and funding. They essentially consist in: completing the original detector; increasing the readout granularity when possible without changing the detector themselves; and using new high power and large bandwidth FPGA and xTCA telecommunication standards for the data processing. These allow sufficient improvements of the trigger selection to maintain the performance of the present detectors.

The hardware trigger in ATLAS and CMS is limited to 100 kHZ and it is based on muon systems and calorimeters information. Events are selected when they contain individual or multiple particles with a momentum or energy above a threshold defining the rate allocate to each type of event. A simplified example of such a trigger menu and of the thresholds applied in CMS is presented in Fig. 1. For efficient selection of the interesting physics signals, the threshold must be maintained at low values. When luminosity and therefore rates increase, this can be achieved by improving the measurement precision and implementing more sophisticated selection algorithms, either at the level of individual detectors or in their combination.

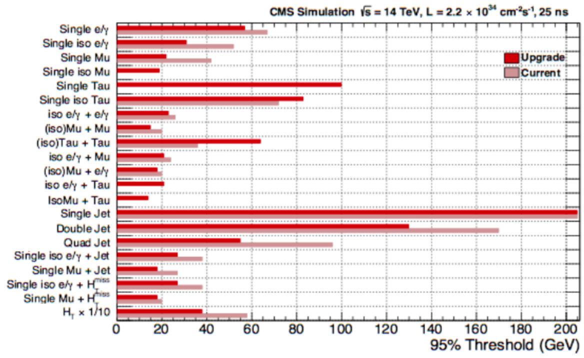

Figure 1: Example of a simplified CMS menu at 50 PU. The thresholds are adjusted to maintain the bandwidth of each trigger at similar levels for the upgraded and non-upgraded systems.

During Phase 1, the completion of the muon systems in the forward regions both in ATLAS and CMS, will allow improving the sharpness of the muon selection. Some upgrades of the calorimeter front-end and back-end electronics will allow finer granularity of the information available for the trigger. These improvements of the input data together with the additional processing power in the back-end electronics will result in better turn-on selection at the thresholds, more efficient subtraction of PU energy, better isolation of particles and identification of narrow τ-jets. New topological selection will also be introduced, based on particle masses or angular correlations. An example of the physics acceptance benefit provided by the CMS trigger upgrade is presented in Fig. 2.

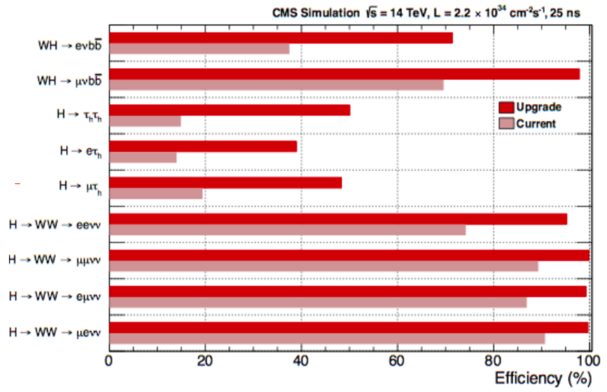

Figure 2: Trigger acceptance for few key physics channels with the upgraded and non-upgraded systems and for the menu presented in Fig. 1.

In addition to the trigger upgrades, ATLAS and CMS will upgrade their pixel detectors to measure one more space point at a lower radius of ~3 cm. In ATLAS this will be achieved by inserting a new long inner barrel layer, while CMS will replace the full pixel detector. These upgrades will allow improving the position precision on the origin of the charged tracks, with substantial gain in the efficiency to associate them to a primary vertex or to identify secondary vertices associated to the decay of light or heavy quarks. This is illustrated in Fig. 3, showing that an increase of 65% of the ZH → μμbb signal statistics can be reached with the CMS new pixel detector.

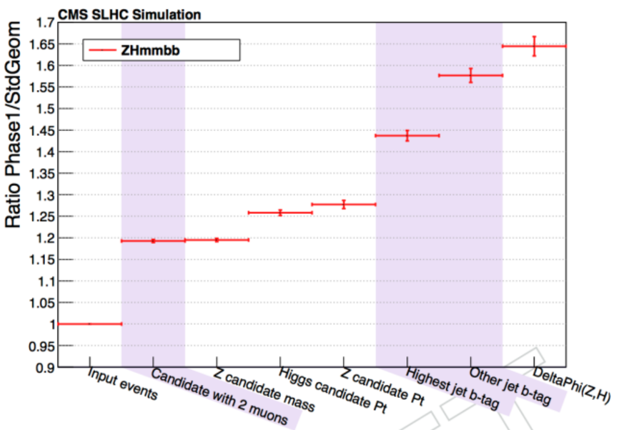

Figure 3: The ratio Phase-1 / current of events left after each selection cut at 50 PU. The cuts where the upgrade detector is expected to excel are highlighted.

PHASE 2 UPGRADES

The physics program at the HL-LHC aims at precise measurement of the Higgs couplings, as well as measurement of very low cross section processes and search and/or study of other new particles [3]. This imposes severe constraints on the detector acceptance in a challenging PU environment, especially in the forward region of the detectors that will become extremely important. The goal for the ATLAS and CMS upgrades [4, 5] is to maintain the present performance at least up to ~140 PU with a capability to take data up to ~200 PU. While the required replacement of some systems will allow performance enhancement to cope with the highest PU, assessing the best operation point of the full experiment will need thorough investigation and major work to tune the event selection, the data reconstruction and the physics analyses.

For both ATLAS and CMS, a major upgrade will be the replacement of the tracker motivated by longevity issues and the need for a higher granularity device, also implemented in the hardware trigger event selection. To cope with the increased readout bandwidth, significant amount of the other detector front-end electronics will need replacement, also accommodating the new specifications for the trigger system. This concerns all systems in ATLAS and the DT muon chambers and the electromagnetic calorimeter in the CMS barrel. In addition, CMS will have to replace the endcap calorimeters due to longevity issues, while only the most forward part of the detector could be affected by irradiation in ATLAS.

The main features for the new silicon trackers will be a strip length divided by about a factor 4 in the outer layers, and pixels with smaller size of about 25x100 μm^2. Thinner sensors will be used to accommodate the large radiation doses. The assembly will be lighter than in the present detectors, significantly reducing the γ conversions and the multiple scattering of charged particles. This will ensure high reconstruction efficiency and excellent association of tracks to the proper vertices. As an example, the expected b-quark tagging performance in the future ATLAS tracker is presented in Fig. 4.

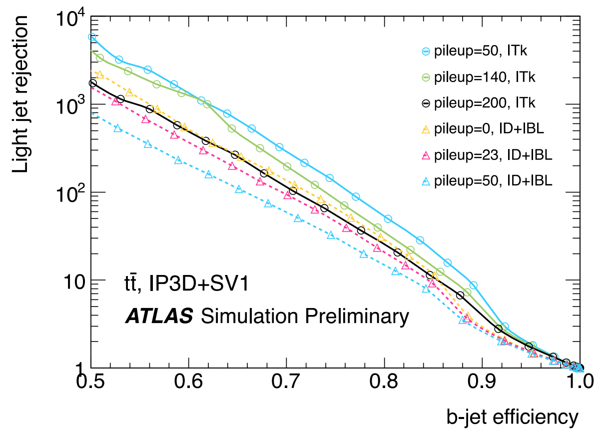

Figure 4: Performance of b-tagging with the ATLAS Phase1 (IBL) and Phase 2 (ITK) trackers.

A new feature of the future trackers could be an extension of the pixel systems in the region of pseudo-rapidity between 2.4 and 4 to cover the full range of the calorimeters. The association of charged tracks to their energy deposits will provide PU mitigation. This has been shown to be extremely powerful to reject fakes in the identification of jets from the Vector Boson Fusion or Scattering processes that will be of major importance in the HL-LHC physics program.

The configuration of the ATLAS and CMS trackers will essentially differ in their implementation for trigger purpose. While the ATLAS detector will be read-out in regions of interest at 500 kHz, based on a calorimeter and muon first-level trigger; the CMS tracker will implement an on-detector selective read-out to provide track-trigger stubs at 40 MHz. This will be achieved measuring the bending of the tracks in the high magnetic field, over the few mm separating two sensors connected to a same read-out chip. A cut on the distance between the strip hits will allow sending only the information for tracks of transverse momentum ≥ 2 GeV. Both in ATLAS and CMS, the hardware reconstruction of tracks in the back-end electronics could then be performed from the comparison of the hit map with a bank of patterns stored in Associative Memories. CMS is also investigating a propagation method using FPGAs. The track matching with the calorimeter and muon system objects, will provide high momentum resolution for leptons and photons, improved isolation, proper association of particles to a same vertex to reduce combinatorial background from the PU, especially in Jets, and improved total and missing transverse energy resolution. Preliminary studies indicate that the lepton trigger rates could be reduced by factors up to 10, for a given threshold (Fig. 5).

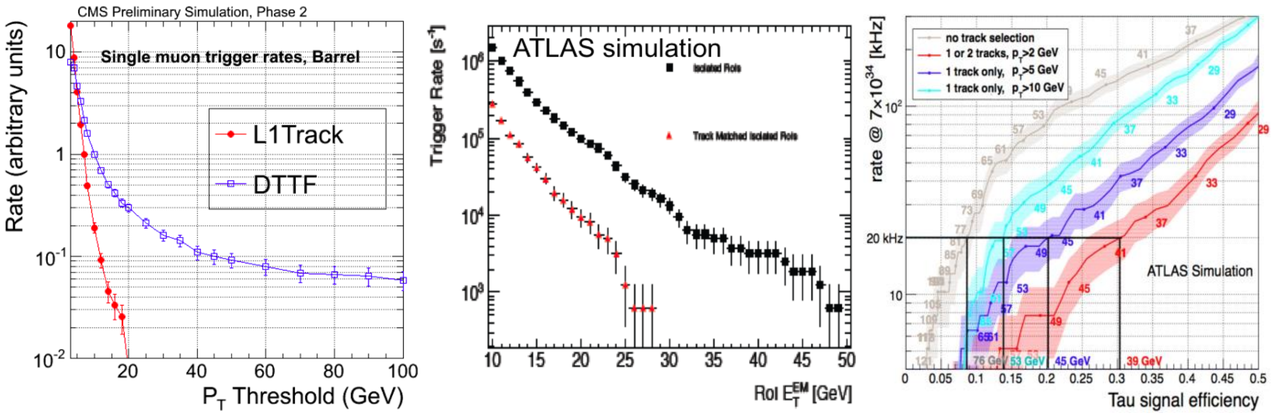

Figure 5: Single muon trigger rates in CMS with and without track matching as a function of transverse momentum threshold (left), single isolated e/γ rates in ATLAS with (red) and without (black) track information as a function of transverse energy (center), and τ signal efficiency versus rate and thresholds with and without track selection (right).

The new front-end electronics design, will also allow increasing the trigger read-out rate from the present 100 kHz up to ≥250 kHz in ATLAS and up to 0.5/1 MHz in CMS, depending in this latter case on the bandwidth sustainable in the pixel detector. The subsequent rise in the required computing power at the high-level trigger appears manageable within the expected progress of technologies in the timescale of the project.

As mentioned above, the potential to fully exploit the HL-LHC luminosity will be driven by the experiments performance. It has recently been shown that a new scheme of the beam crossings using a specific crab cavity configuration, could allow to lengthen the beam luminous region and to reduce the PU density. This could be a powerful mean to improve the charged tracks association to vertices to mitigate pile-up effects. However, demonstrating if it would be sufficient to allow operation at higher PU will need careful simulations and tuning of the reconstruction algorithms. Especially, the tracker doesn't allow mitigating the effect of neutral particles PU in the calorimeters. Experiments are in the process of evaluating these effects, as well as the possibility to mitigate the PU of neutrals through a precise time of flight measurement.

CONCLUSION

After the crucial discovery of a Higgs boson in 2012, the LHC has an extremely exciting and unique program to expand the physics reach through the next two decades. This requires major upgrades of the accelerator and of the ATLAS and CMS experiments. The first stage of these upgrades is already at construction level and studies and R&D for the High Luminosity LHC are ramping-up. Many exciting ideas are being discussed to meet the challenges of operation in the highest pile-up environment.

ACKNOWLEDGMENT

I wish to thank Pr. Philip Patrick Allport from the ATLAS collaboration for his help in preparing material for this paper.

REFERENCES

[1] ATLAS Phase 1 upgrades Technical Design Reports; CERN-LHCC-2013-018; ATLAS-TDR-023, CERN-LHCC-2013-017; ATLAS-TDR-022, CERN-LHCC-2013-007; ATLAS-TDR-021, CERN-LHCC-2013-006; ATLAS-TDR-020

[2] CMS Phase 1 upgrades Technical Design Reports: CERN-LHCC-2013-011; CMS-TDR-12, CERN-LHCC-2012-016; CMS-TDR-11, CERN-LHCC-2012-015; CMS-TDR-10

[3] ECFA HL-LHC Experiments Workshop agenda and summary report: https://cmsdocdb.cern.ch/cgibin/PublicDocDB//ShowDocument?docid=12141 https://indico.cern.ch/conferenceDisplay.py?confId=252045

[4] Letter of intent for the Phase II Upgrade of the ATLAS detector: CERN-LHCC-2012-022 ; LHCC-I-023

[5] CMS Phase 2 Upgrade: Preliminary Plan and Cost Estimate: https://cds.cern.ch/record/1605208/files/CERN-RRB-2013-124.pdf

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PLANS AND PHYSICS OUTLOOK FOR NON-HIGH LUMINOSITY EXPERIMENTS UNTIL AND AFTER LS3

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Abstract

Based on the current physics scene, the future holds more than ever a joint enterprise of precision measurements and direct searches. With its very broad scientific program of heavy flavour precision measurements both in the beauty and the charm sector, as well as forward electroweak precision physics, LHCb has demonstrated to be a powerful forward general purpose detector complementary to ATLAS and CMS. After the expected lifetime of 10 fb^{-1} for the current experiment, the precision of many measurements will still be limited by statistics. Experience from Run 1 shows that systematic uncertainties are not expected to limit the precision down to the theoretical uncertainties. LHCb will thus undergo one major upgrade in LS2 to the ultimate flexibility of a full software trigger, together with a sub-detector configuration which should allow improving the physics yield up to an instantaneous luminosity of $2x10^{33}$ $cm^{-2}s^{-1}$, with the goal of collecting an integrated luminosity of at least 50 fb^{-1} by 2028. The flexibility of the upgrade also prepares LHCb for any changes in the physics scene beyond LS2.

The ion program is an integral part of the LHC physics program. For the purpose of physics normalization, detector re-commissioning and calibrations, the ALICE experiment requires data taking during the nominal proton-proton physics and at nucleon-nucleon energies equivalent to the heavy ion collisions. This will evolve with the major upgrade of ALICE which is currently planned for LS2.

In view of the LHC and the injector upgrades, this paper reviews the physics motivations, the upgrade and consolidation programs, and the operational requirements and schedule for LHCb and for the ALICE proton-proton data taking into the HL-LHC era. For completeness, it also covers the relevant aspects of the LHC forward physics program and other special runs.

INTRODUCTION

The current physics scene after the LHC Run 1 in both proton-proton physics and in heavy ion physics is intriguing to say the least. While the discovery of the existence of a scalar in nature compatible with a 126 GeV/c^2 Standard Model Higgs boson is vital for the Standard Model (SM), direct searches did not reveal any signs of new particles beyond the Standard Model. Moreover, the Standard Model prevails in all the LHC precision measurements. In particular, the absence of a non-SM signal in precision tests in the heavy flavour sector have narrowed down the space for New Physics with flavour related couplings up to a mass scale of many tens of TeV. Nevertheless, New Physics is required to explain the neutrino oscillations and masses, and account for the cosmological observations of baryon asymmetry, the Dark Matter, and Dark Energy. However, while unitarity arguments allowed establishing an upper bound on the mass of the Higgs boson, there is no such trivial indication for the energy scale of this New Physics. Taken together, this indicates that precision measurements are likely to be the best compass at the LHC to suggest the direction on physics beyond the Standard Model. Clearly the nature of the newly found boson should be studied through precise measurements of the couplings to the vector bosons and the fermions, as well as of the Higgs self-interactions in order to reconstruct the scalar potential and establish its role in the electroweak symmetry breaking and mass generation. The general purpose nature of flavour physics together with the fact that one of the most fundamental unexplained question about the baryon asymmetry is of flavour nature show that continued precision measurements on rare heavy flavour decays and CP violation are of equal importance in the search for New Physics. Of course, the direct searches for on-shell production of new particles will continue to play an important role.

The LHC is also able to produce ultra-relativistic heavy ion physics at energies exceeding previous machines by more than an order of magnitude. The higher energy is expected to make the strongly interacting medium hotter and denser, and should increase significantly the cross-sections for the production of the hard objects which are used indirectly to probe the final state medium to quantify its density, temperature, and its transport properties. Theory and previous experiments predict that the formation of Quark Gluon Plasma (QGP) should leave distinct signatures on charged particle production, jets, heavy flavour of which quarkonia are of particular interest, and on the production of photons and low mass di-leptons.

With only a percent of the integrated luminosity currently foreseen for the entire LHC Pb-Pb operation and three weeks of p-Pb collisions in 2013 at around half the nominal LHC energy, the LHC has already produced a number of unexpected and important results [1][2]. While measurements of the elliptic flow in Pb-Pb collisions still show that the medium behaves like a very strongly interacting, almost perfect fluid, and most observables are at least in qualitative agreement with the 'Heavy Ion Standard Model' which emerged with RHIC, the big surprises showed up in the p-Pb and even in the p-p data. One of the most striking discoveries is the long-range two-particle correlations appearing as ridges in the rapidity-azimuthal plane in high multiplicity p-p interactions and even stronger in p-Pb. These observations are compatible with a collective hydrodynamic flow of a strongly coupled medium hinting

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at the formation of QGP fire balls even in p-p interactions. Another completely unexpected recent feature is the large enhancement at high Q^2 and x in the inclusive charged particle forward-backward asymmetry in p-Pb. Further findings in p-Pb collisions indicate a stronger than expected suppression of ψ(2S) relatively to J/ψ that cannot be explained by effects associated with Cold Nuclear Matter or energy loss, and that hint at final state effects. In the opposite sense, a very important result from Pb-Pb data seems to confirm the coalescence mechanism whereby the J/ψ suppression associated with QGP is compensated at higher energies by a subsequent charm recombination during hadronization. Currently many of the results are statistically insufficient to be used effectively for constraining theoretical models.

Taken together, the LHC has demonstrated the need for better understanding of p-p and p-Pb data in order to disentangle the many effects present in p-p, p-Pb, and Pb-Pb and improve the interpretation of QGP signatures. The results also show that p-Pb collisions are more than just a control experiment and that we can expect a wealth of interesting results to come.

LHCb PLANS AND PHYSICS OUTLOOK

LHCb Physics Objectives

The main objective of LHCb is measuring indirect effects of New Physics in heavy flavour processes with CP violation and strong suppressions in the Standard Model, such as those involving Flavour Changing Neutral Currents (FCNC) mediated by box and penguin diagrams. The new particles are expected to appear and contribute through virtual quantum fluctuations and produce discernible effects on measurable quantities which are well predicted in the Standard Model and which characterize the processes in a distinct fashion, such as decay rates, angular distributions, forward-backward (a)symmetries, etc. The access to virtual effects allows indirectly probing energies higher than the centre-of-mass energy of the LHC. Apart from assuming that the New Physics couples to flavour, this strategy to search for New Physics is largely model independent. The contribution from New Physics generally enters into the measurable quantities as a correction of order $\delta C^{NP} \propto \epsilon^{NP}/\Lambda_{NP}^2$, where ϵ^{NP} is the coupling and Λ_{NP} corresponds to the scale of masses of the new particles. Clearly, in order to discern the New Physics, the error on the measurement must be significantly smaller than the correction for New Physics. For a given resolution, a smaller coupling entails less reach in the mass scale. In practice this means to continually reduce the statistical error and manage extremely well the error from systematic effects. As an example, Fig. 1 shows the expected sensitivity for LHCb and Belle II on the zero-crossing of the forward-backward asymmetry in the $B_d \to K^*\mu^+\mu^-$ decay [3][4].

The LHC is to a large extent a charm and a beauty factory. LHCb and the upcoming upgrade aim at exploring fully the very rich repertoire of decays and topologies, and all the possible observables which are sensitive to New Physics. The theoretical understanding for many of these observables is very good within the framework of the SM, and the LHCb upgrade aims at reaching experimental sensitivities which are comparable to the theoretical uncertainties. In addition, LHCb has also demonstrated to be capable of making important measurements in electroweak physics, on Lepton Flavour Violation, and in QCD.

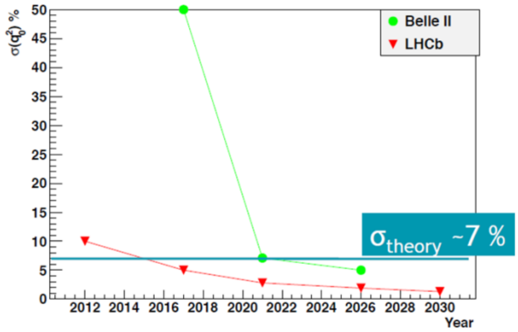

Figure 1: Expected evolution of the sensitivity for LHCb and Belle II on the zero-crossing of the forward-backward asymmetry in the $B_d \to K^*\mu^+\mu^-$ decay [4].

LHCb Run 1 Lesson and Run 2 Plans

With the impressive performance of LHC and the demonstration that LHCb can successfully perform forward precision measurements with event pileup, the operation and trigger strategy evolved significantly during the LHC Run 1 allowing LHCb to collect over 3 fb^{-1} at centre-of-mass energies of 7 TeV and 8 TeV [5]. Experience with the detector operation and with the analysis of the data show that systematic effects may be managed very well, and that the precisions in many measurements are not expected to be limited by systematic uncertainties. This also includes regular polarity switches of the LHCb spectrometer dipole which allows averaging out systematics from detector asymmetries. The large statistics and well managed systematic effects together with the stable trigger and data taking conditions have led to a very large number of world-class measurements and dominance in heavy flavour physics [6], in addition to a reputation of an excellent forward general purpose detector at the LHC. Long Shutdown (LS) 1 will allow LHCb to fully explore the large statistics collected and prepare LHCb for Run 2.

In Run 2 with 25 ns bunch spacing, the current LHCb baseline is to operate the detector at a levelled luminosity of 4×10^{32} $cm^{-2}s^{-1}$, i.e. at an average number of interactions per bunch crossing of around unity. The aim is to collect at least an additional 5-6 fb^{-1} by LS2. Since it seems likely that a virtually new LHC machine, the increase of beam energy and the shift to 25 ns operation may lead to a limited integrated luminosity in 2015, LHCb favours an extension of Run 2 by between six and twelve months. On the contrary, LHCb disfavours a delay of the start of LS2 beyond 2018. It should also be noted that the expected system lifetimes of the LHCb trackers is around 10 fb^{-1}. For the luminosity levelling, the $\beta*$ setting, or range in the case of levelling by $\beta*$, should be such that it allows LHCb to run at constant luminosity with a levelling lifetime which is of the order of the longest typical fill duration (10-15h).

LHCb Upgrade Strategy and Prospects

Even after an expected total integrated luminosity of 10 fb^{-1} in Run 2, many of the LHCb precision measurements will remain limited by statistics, and some exploratory physics modes will not even be accessible yet. A 5 to 10-fold, depending on the final state, increase in statistics will not only allow reaching the desired statistical power but would also allow opening the door to new physics modes both within the field of flavour physics but also in the other physics topics for which the LHCb acceptance is particularly interesting. With the encouraging experience of working in an environment with event pileup during Run 1, this large statistics can be achieved efficiently by firstly operating the experiment in Run 3, in Run 4 and beyond at a higher luminosity of up to $2x10^{33}$ $cm^{-2}s^{-1}$. Secondly, it requires a major change to the LHCb trigger architecture to remove the current limitations and increase the trigger efficiency, in particular for hadronic modes. Upgrades of some of the LHCb detectors are necessary as a consequence of the required radiation longevity. In addition, the upgrade provides an opportunity to re-optimize the experiment with new technologies to cope more efficiently with the higher occupancies and further improve the physics capabilities. The LHCb upgrade [7] strategy therefore consists of reading out the entire detector at 40 MHz, and performing solely the triggering based on the full event topology in software on a CPU farm. Several of the sub-detectors should be improved to provide the appropriate granularity to allow a fast full reconstruction, and to operate the detector at a luminosity up to $2x10^{33}$ $cm^{-2}s^{-1}$, ie. at an average number of interactions per crossing of close to five. Some sub-detector replacements are of course also needed as a result of the radiation effects up to 2018 and the higher integrated dose associated with the aim of collecting at least 50 fb^{-1}. In order to profit from the higher luminosity and the higher trigger efficiency, the physics output rate will need to be 20 kHz.

The consequence of the 40 MHz readout is that all the sub-detector Front-End and Back-End electronics must be redone. Secondly the detector and the readout upgrade must be done in one single Technical Shutdown. A single sub-detector operating in the old configuration will force LHCb to continue operating with the current limitations until it is upgraded.

In terms of sub-detector upgrades (Figure 2), the aim is to achieve the same performance as now but at significantly higher pileup and occupancy. The biggest detector replacement concerns the tracking system from the VErtex Locator (VELO) up to the main tracking stations. The aim is to optimize the upgraded tracking detectors to allow faster tracking and vertexing. For the Trigger Tracker (TT) the idea is to rebuild the detector with the same technology of silicon strips but with higher segmentation, improved sensor overlap, and better small-angle coverage.

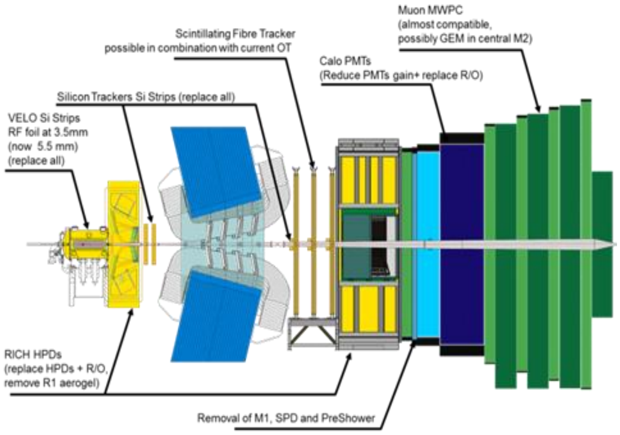

Figure 2: The LHCb sub-detector upgrades in LS2.

In the case of the main tracking stations, the Inner Tracker (IT) will be entirely replaced, either with a somewhat larger detector based on the same silicon strip technology, or with a large scintillating fibre tracker. In the case of the two RICHes, the hybrid photo-multipliers (HPD) will be replaced by multi-anode photo multipliers. This is also necessary since the FE electronics is integrated in the HPDs. In addition, the aerogel will be removed from RICH1 since the background due to the large number of tracks is too high in the upgrade to allow reconstructing the rings from the signal photons. The RICH1 optics will be re-optimized in order to allow operating at a luminosity of $2x10^{33}cm^{-2}s^{-1}$. In order to run at higher luminosity, the calorimeters will only reduce the gain on the photomultipliers and compensate with an increased electronics gain. The signal to noise has been demonstrated to be sufficient. As it stands currently, the muon detectors after the calorimeters will remain as they are.

The first muon detector layer (M1), and the scintillating pad detector (SPD) and preshowers used for e/γ separation with the calorimeter, will be entirely removed as they will not contribute at the expected very high occupancy.

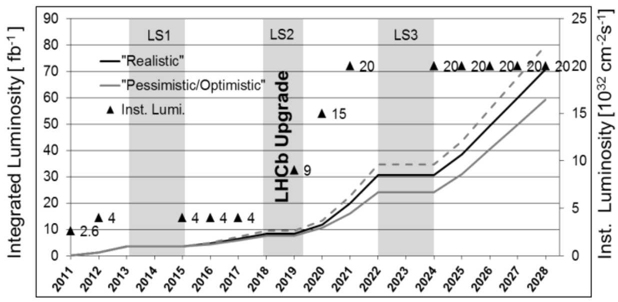

Figure 3: Example of the luminosity prospect up to 2028.

Currently LHCb is in the final phase of reviews and choice of technologies. The preparation of the Technical Design Reports and the prototype validation is starting now. Finally the full installation of the detector and the 40 MHz readout is scheduled for the LS2, expected to

Table 1: Expected statistical sensitivities after LHC Run 2 and after 50fb^{-1} with the LHCb Upgrade as compared to current theoretical uncertainties for a list of key observables [8].

Type	Observable	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	8 %	2.5 %	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.6°	0.2°	negligible
Charm	A_Γ	0.40×10^{-3}	0.07×10^{-3}	–
CP violation	ΔA_{CP}	0.65×10^{-3}	0.12×10^{-3}	–

take place in 2018-19, with the requirement of an 18-month access to the cavern. As mentioned above, LHCb believes an extension of Run 2 by between six and twelve months may be justified in order to increase significantly the integrated luminosity in Run 2. It is also clear that the preparation for the upgrade installation in LS2 would benefit from an extension of Run 2. On the contrary, an LS1.5 is of limited use and would not reduce the installation time needed for the upgrade in LS2.

Taking together the best of knowledge from LHCb and LHC during Run 1, the strategy of the LHCb upgrade and the future schedule, Figure 3 shows an example of a luminosity projection up to 2028 with the LHCb upgrade in 2018. Table 1 also shows the expected statistical precision for representative key physics channels after 50 fb^{-1} [8]. Generally speaking, nearly all the key measurements should have reached precisions close to the theoretical uncertainties. However, it should be stressed that the strength of the LHCb upgrade is only partly about satisfying the final precision for flavour physics. More importantly, the ultimate flexibility in the upgraded trigger and detector re-optimization allow adapting the LHCb physics program and running conditions to any signature which may come out of a changing physics scene after 2020.

ALICE UPGRADE PLANS AND NEEDS FOR REFERENCE DATA

Motivation for Reference Data

With the large statistics of heavy ion collisions which will be available at the LHC, and the complete detector coverage to low p_T and large rapidity to study with high precision all the different types of hard probes, it is becoming equally important to collect large statistics of reference data in p-p, and in p-Pb collisions. The p-p data is needed to normalize to the effects of soft and perturbative QCD and fragmentation in the vacuum, and p-Pb data allow factorizing out initial state effects and cold nuclear matter effects. The aim is to achieve an error on the reference data which is negligible compared to the heavy ion data. While scaling of the hard probe observables with the centre-of-mass energy is possible to some extent, in most cases it introduces unacceptably large errors. For this reason the reference data should be recorded at the equivalent nucleon-nucleon centre-of-mass energy.

The reference data is equally important for ALICE, ATLAS and CMS for physics normalization. In addition, ALICE requires p-p data for operational reasons to perform detector commissioning and calibrations. However, these may be done at the nominal beam energy for high-luminosity p-p operation.

The design choice of the detector configuration for heavy ion physics means that ALICE has readout limitations which translate into a relatively strong limitation on the luminosity at which the detector can collect p-p data. Currently, this is related to the electron drift time of 100μs in the TPC.

ALICE Run 2 Plans

In Run 2, ALICE aims at collecting up to ten times more statistics than in Run 1 and profiting from the detector improvements which are currently being implemented in LS1. The larger statistics will allow improving significantly on the precision of the measurements in Run 1 and exploring new observables. Run 2 will also extend the current measurements at $\sqrt{s_{NN}}$= 2.76 TeV up to 5.1 TeV (6.5Z TeV/beam with lead ions) to study the energy dependence.

ALICE is not requesting a special p-p reference run at equivalent energy in Run 2. For the physics normalization it is considered sufficient to apply energy scaling with the help of the p-p data recorded at 7 and 8 TeV, and the future data at 13 TeV. For this reason, ALICE is planning low luminosity operation throughout the nominal p-p runs (~24 weeks/year). The current plan is to collect minimum bias reference data in 2015 at a levelled instantaneous luminosity of 1-10x10^{29} $cm^{-2}s^{-1}$. With beam parameters expected from the Bunch Compression and Merging Scheme [9][10] in Run 2, this luminosity implies a separation of close to 5σ at the injection β^* of 10 m. The exact value of the luminosity will depend on the quality of the vacuum conditions in the ALICE Long Straight Section which already caused some difficulties in Run 1. In case of poor vacuum conditions, the optimal luminosity becomes a trade-off between minimizing the contamination of beam-gas events in the minimum-bias sample and minimizing the fraction of events with pile-up from multiple crossings in the 100µs TPC readout time.

In 2016 and 2017 ALICE expects to collect rare triggers at a levelled p-p luminosity of 5-10x$10^{30}$$cm^{-2}s^{-1}$.

It should be noted that ATLAS and CMS have a strong preference for an annual p-p reference sample at equivalent nucleon-nucleon centre-of-mass energy to follow the integrated luminosity of the heavy ion physics. Since they have no limitation on the instantaneous luminosity, the equivalent sample can be collected in the order of a day (e.g. 30 pb^{-1} at <10^{33} $cm^{-2}s^{-1}$> with 30% machine availability) plus the setup time. ALICE will participate in these runs but will not be able to collect sufficient statistics.

Since p-Pb measurements have yielded a number of surprising results which impact significantly the understanding of QGP signatures, it seems a strong motivation for operating also the p-Pb run at the expected Pb-Pb energy of $\sqrt{s_{NN}}$= 5.1 TeV (4.1Z TeV/beam with lead ions) instead of at the maximum p-Pb energy of $\sqrt{s_{NN}}$=8.2 TeV (6.5Z TeV/beam). This would also avoid requiring yet another p-p reference sample at the equivalent energy for the p-Pb run.

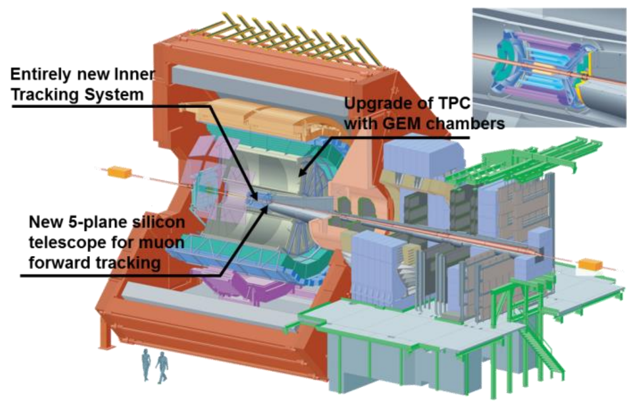

Figure 4: The major ALICE sub-detector upgrades in LS2.

ALICE Upgrade Strategy and Run Plan

The ALICE upgrade [11] is aimed at taking full advantage of the rare physics processes which allow probing the characteristics of the hot and dense QCD matter, such as quenching of jets, medium transport of heavy flavour and quarkonium, and photons and low-mass di-leptons as probes of the thermal history of the system. In particular, these probes require coverage to low transverse momentum, and very large statistics in order to perform multi-dimensional analysis. These goals may be achieved with ten times the integrated luminosity of Pb-Pb collisions collected in Run 1 and Run 2 (10 nb^{-1}) and by increasing the statistics of low-p_T events by a factor 100 (8x10^{10} events).

The ALICE strategy for Run 3 and Run 4 therefore consists of a major upgrade of the sub-detector readout electronics and the central readout system in order to be able to operate the detector at a levelled instantaneous luminosity of 6x$10^{27}$$cm^{-2}s^{-1}$ and to be able to accept a rate of 50 kHz of Pb-Pb interactions with only a minimum bias trigger, and perform the online data reduction based on an event reconstruction at the 50 kHz. A new Inner Tracking System is being built with an improved vertexing based on an ultra-low mass silicon tracker around a significantly smaller beam pipe and more efficient tracking at low p_T with increased granularity. In order to run at higher luminosity, the ion feedback problem in the TPC readout chambers is solved by replacing the MWPC by GEM chambers and by implementing a continuous un-gated readout. In addition, a new Muon Forward Tracker based on a 5-plane silicon telescope with the same rapidity coverage as the Muon Spectrometer is added in front of the hadron absorber in order to perform accurate muon tracking back to the vertex region.

Table 2: ALICE run plan for Run 3 and Run 4

Year	System	Luminosity
2019	Pb Pb (5.1* TeV) – 4 weeks	2.85 nb^{-1}
2020	Pb Pb (5.1 TeV) – 4 weeks	2.85 nb^{-1}, lower B field (0.2T)
2021	pp (5.1 TeV) – 8 weeks	ALICE: 6 pb^{-1} (4 x 10^{11} events)
2022	LS3	
2023	LS3	
2024	Pb Pb (5.1 TeV) – 4 weeks	2.85 nb^{-1}
2025	½ PbPb + ½ pPb	PbPb:1.42 nb^{-1}, pPb:50 nb^{-1}
2026	Pb Pb (5.1 TeV) – 4 weeks	2.85 nb^{-1}

The complete upgrade operation on the detector and the installation of the new readout is scheduled for the LS2, expected to take place in 2018-19, with the requirement of an 18-month access to the cavern. The intervention on the TPC itself requires 10 months on the surface. ALICE would not object to an extension of Run 2 by up to 12 months. On the contrary, in the current planning, an LS1.5 is of limited use and would not reduce the installation time needed for the upgrade in LS2.

The ALICE run plan for Run 3 and Run 4 is shown in Table 2. In terms of p-p reference data for ALICE at the corresponding nucleon-nucleon centre-of-mass energy, the 10 nb^{-1} of low-p_T Pb-Pb data is equivalent to about 6 pb^{-1} of p-p data. ALICE expects to be able to operate the detector at a levelled luminosity of 5-10x10^{30} $cm^{-2}s^{-1}$ which translates the data set into the equivalent of 1-2 months of gross running time. It is preferable to collect this data in one run period. In order to increase the acceptance towards low p_T for the low mass di-lepton studies, the Pb-Pb data taking plan includes a running period with a reduced solenoid field from 0.5 T to 0.2 T. This may also have to be complemented by a p-p run at reduced field to collect about 10^9 events, equivalent to a few hours of data taking. For the high p_T measurements and jets, the current ALICE baseline is to use the p-p data collected at 7, 8 and 13 (14) TeV and scale with the help of perturbative QCD.

As opposed to Run 1 and Run 2, ALICE will not participate in the nominal p-p run for the entire running year in Run 3 and Run 4. Instead, they need about 1-2 months of nominal p-p physics in the period before each heavy ion run in order to commission the detector and to perform detector calibrations.

In order to deduce the need for p-p reference data to match the ATLAS and CMS high p_T measurements in Pb-Pb collisions, the equivalent nucleon-nucleon luminosity should be scaled with the number of partons interacting. As a consequence, the 10 nb^{-1} of Pb-Pb data is equivalent to 300 pb^{-1}. Again ATLAS and CMS prefers that the p-p reference data taking follows the integrated luminosity of Pb-Pb. This is particularly important for CMS in order to calibrate the jet energy scale at the equivalent nucleon-nucleon centre-of-mass energy. Again, at essentially no limit on the instantaneous luminosity, this data may be collected in a few days plus the setup time.

FORWARD PHYSICS PLANS

The definition of forward physics here include those measurements with very forward detectors located outside of the experimental caverns and that typically perform tagging of leading protons or detection of showers from diffractive or electromagnetic processes. These physics measurements may be split into two types: those that are performed parasitically or in parallel with high luminosity operation and with a nominal machine configuration, and those which require a special setup of the machine. For the former type, all of the experiments have their programs, and TOTEM and LHCb are making upgrades currently in LS1. LHCb will have the ideal conditions for studying Central Exclusive Production in Run 2 [12]. TOTEM is implementing the capability of resolving event pileup and multiple tracks in the proton detectors, and aims at accommodating timing detectors for reconstructing the longitudinal vertex position of the leading protons in central diffractive events [13]. This type of physics measurements in nominal conditions will continue in Run 2 and Run 3. While there are no plans currently, it is possible that this type of forward detectors will also still exist beyond Run 3. It should of course not be forgotten that while the future forward physics in parallel with the high luminosity operation will not require a special configuration of the LHC, the forward detector may still require special commissioning runs, such as for instance the Roman Pot alignment runs.

For the TOTEM physics program, and ATLAS/ALFA, which involve the high β^* operation (2.5 km planned for Run 2) and that should be performed at each of the major LHC beam energies, the aim is to complete the data taking in Run 2. This assumes that the cables for the optics are installed for TOTEM. If this is not the case, the program may only be completed in Run 3. LHCf will complete their program in the very early stages of 2015.

There is clearly no plan for high β^* operation in the HL-LHC era.

ALICE & LHCB POLARITY SWITCHES

ALICE will only need infrequent polarity reversals in the future in order to keep control on the effects of space charge distortions in the TPC at high luminosity. As a rule of thumb, ALICE requires a polarity switch per running period with a new type of data set. Most likely ALICE will not request any polarity reversal during the nominal p-p runs at 13 TeV. As ALICE is not planning on running throughout the entire operational year with nominal p-p collisions in Run 3 and Run 4, the plan is to keep the solenoid off and the dipole permanently on to avoid machine re-commissioning before ALICE switches the detector on for the commissioning and calibration period, and the heavy ion run.

In order to maintain full control on systematics effects, LHCb is requiring annually as close as possible to equal statistics with both polarities, and polarity reversals at approximately bi-weekly frequency. For the tilted crossing angle, the relatively small number of analyses which have explored fully in detail the systematic effects in the 2011 data with a purely horizontal crossings and the 2012 data with the tilted crossing, have not yet observed a significant improvements with the tilted crossing scheme. For this reason it is not felt justified at this point to request this complicated scheme for Run 2. More information will come in the course of the next few months. Nevertheless, it is important to point out that it has been shown that there is clear benefit from reducing the asymmetry as much as possible by minimizing the difference between the overall crossing angle in the positive and negative polarity.

LUMINOSITY CALIBRATIONS

Luminosity calibrations are a special mode of operation involving a dedicated setup of the LHC machine which will continue to be mandatory into the HL-LHC era.

Obviously, a luminosity calibration is required at each major beam energy. It can also be expected that luminosity calibrations may be needed early in the run each year to recalibrate the luminosity monitors of the experiments. It is assumed that the goal on the accuracy of the calibrations will remain <2%.

As opposed to the luminosity calibrations in the past at ≤8 TeV, the calibrations at higher energy will require $\beta*$ values larger than the current injection values to compensate for the smaller beam size. For the van der Meer scan method, ATLAS and CMS require a $\beta*$ of 15-20 m. To exploit fully the beam gas imaging method in LHCb with the SMOG system [14], in addition to the vdM scan method, LHCb requires a $\beta*$ of 30-40 m. This will allow fully measuring the single beam shapes and tails, and map out x-y correlations. This information is used by all experiments to achieve the ultimate accuracy on the luminosity calibrations. On the other hand, increasing the emittance as compensatory measure against the smaller beam size is strongly disfavoured as it introduced strong effects on the bunch shape in the past and was difficult to control.

As previously, the luminosity calibrations will continue requiring reduced bunch intensity ($<8x10^{10}$ ppb) to avoid the effects of dynamic beta and beam-beam deflections, a normalized emittance of around 3μm, and filling schemes with well separated isolated bunches. If present, it may be advantageous to maintain crab cavities off during the calibration for stability reasons and there may also be special requirements on the crossing angle.

As stated above, the LHCb SMOG system will remain in the LHCb upgrade, and will be kept operational beyond LS3.

CONCLUSIONS

The impressive performance of the LHC accelerator in the first three years of operation has enabled the LHCb experiment to pave the way for heavy flavour physics at an entirely new level of precision which will be pursued further in Run 2 into the territory where small deviations from the SM may be expected with another 5-6 fb^{-1}. Nevertheless, the ultimate precision and the access to many physics modes may only be achieved with a 5 to 10-fold increase in statistics.

The astonishing flexibility of the LHC also allowed already re-examining the understanding in heavy ion collisions with the sequel of a number of surprising measurements and discoveries. In particular data from p-Pb collisions and even p-p reference exhibit some collective phenomena which require more understanding to interpret the strongly interacting medium and QCD effects in Pb-Pb collisions. Run 2 should produce a 5-, 10-fold increase in statistics at higher energy with the potential to produce measurements with sufficient precision to start constraining models.

In order to exploit at maximum the LHC capacity and physics potential, both ALICE and LHCb are each going through a major upgrade in LS2, both of which will require an 18 month access to the experimental cavern.

Both upgrades should allow collecting an order of magnitude more luminosity during Run 3 and Run 4 and beyond with the promise of a large number of results of fundamental importance.

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REFERENCES

[1] Talks at Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, November 4-8, 2013, Cape Town, South Africa.

[2] J. Schukraft, arXiv:1311.1429v1.

[3] LHCb Collaboration, JHEP 08 (2013) 131.

[4] LHCb Collaboration, LHCb-PUB-2013-015, October 9, 2013.

[5] R. Jacobsson, "Performance of the LHCb detector during the LHC proton runs 2010 - 2012", Proc. of the 2012 IEEE Nucl. Sci. Symposium, October 2012, California, USA.

[6] LHCb Collaboration, arXiv:1208.3355.

[7] LHCb Collaboration, "Letter of Intent for the LHCb upgrade", CERN-LHCC-2011-001.

[8] LHCb Collaboration, "Framework TDR for the LHCb upgrade", CERN-LHCC-2012-007.

[9] S.S. Gilardoni, "The high intensity/intensity brightness upgrade program at CERN: Status and challenges", Proceedings of the 52nd ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams, Beijing, China, September 17-21, 2012.

[10] R. Steerenberg et al., "Post-LS1 25 ns & 50 ns options from the injectors", Proceedings of the LHC Beam Operation Workshop, Evian, France, 17 – 20 December, 2012.

[11] ALICE Collaboration, "Letter of Intent for the upgrade of the ALICE experiment", CERN-LHCC-2012-012, 6 September 2012.

[12] R. McNulty, "Status and prospects for Central Exclusive Production at LHCb", LHC WG on Forward Physics and Diffraction, May 15-16, 2013, CERN.

[13] TOTEM Collaboration, "TOTEM Upgrade Proposal", CERN-LHCC-2013-009; LHCC-P-007, 12 June 2013.

[14] C. Barschel, Ph.D. Thesis, RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany, to be published.

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POST LS1 SCHEDULE

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Abstract

The scheduling limits for a typical long year taking into account technical stops, machine development, special physics runs are presented. An attempt is then made to outline a ten year post LS1 schedule taking into account the disparate requirements outlined in the previous talks in this session. The demands on the planned long shutdowns and the impact of these demands on their proposed length will be discussed. The option of using ion running as a pre-shutdown cool-down period will be addressed.

INTRODUCTION

The next 10 years or so will see the exploitation of the LHC at energies at, and above, 6.5 TeV. In parallel there will be preparation for the High Luminosity LHC (HL-LHC). The various demands on CERN's medium term and long term operations schedule are considered below. Open issues include the following.

- LHC Machine
  - For what length of contiguous time can the LHC operate for? Here one worries about cryogenics and maintenance of key technical infrastructure.
  - How long can the operations group and hardware support teams run for without impacting efficiency?
  - What are the requirements of the ion program in both the North Area and the LHC?
- Injectors
  - Are the risks of running with Linac2 until 2018/2019 acceptable?
  - What are the optimum timing of, and time required for, the Linac4 connection and another LIU upgrades?
- Experiments
  - Finalization the schedule for phase 1 of the detector upgrade program.
  - The need for an extended year end technical stop around 2017.
  - Developments and plans for phase 2 of the upgrade program.

Also to be taken into account in the longer-term strategy are: accelerator technology development time; detector technology development time; and funding profiles for the phase 2 upgrades. The corresponding implications of these issues for the schedule are necessary vague but indications are that there is a need to stretch the present temporal envelopes.

The present baseline schedule foresees:

- a 3 year Run 2 2015 through 2017;
- a 1 year LS2 in 2018;
- a 3 year Run 3 2019 through 2021;
- the start of a 2 year LS3 for HL-LHC upgrade in 2022.

The experiments have tentatively mapped the necessary stages for HL-LHC operation onto this schedule: R&D; engineering design; construction; production; installation and commissioning. These phases have been discussed in detail at a recent ECFA workshop [1]. Clear scheduling tensions exist which will be explored below.

NOMINAL YEAR

The longer term operational model appears to be settling into a series of three to four long years of operation interspersed with long shutdowns of order of a year or more. The long shutdowns are foreseen for essential plant maintenance, experiments' upgrades, injector upgrades (LS2) and LHC upgrades (LS3).

The approximate breakdown of a generic long year is:

- 13 weeks Christmas technical stop including 2 weeks hardware commissioning (this would count 3 weeks at the end of a year and 10 weeks at the start of the following year); Around 10 days are required before the CERN Christmas closure to secure the helium inventory (worth approximately 7 MCHF) and be protected again serious failure with only minimal "on-call" support [2].
- around 160 days of high luminosity proton-proton operation;
- three technical stops of 5 days duration during the year;
- a 4 week ion run;
- and time for special physics runs and machine development.

A more detailed breakdown is shown in table 1.

A longer period for scrubbing will be required after shutdowns during which a significant fraction of the machine will be warmed-up and vented to air.

When considering extended periods of operation it is interesting to consider the operational period 2009 to 2103

- 2009: 23rd November to 16th December
- 2010: 22nd February to 6th December with a special AMS run 4th to 9th February

http://dx.doi.org/10.5170/CERN-2014-006.13

Table 1: Potential breakdown of a standard HL-LHC year

Activity	Days
Christmas technical stop including HWC	91
Commissioning with beam	21
Machine development	22
Scrubbing	7 (to 14)
Technical stops	15
Technical stop recovery	6
Proton physics running including intensity ramp-up	160
Special physics runs	8
Ion run setup	4
Ion physics run	24
Contingency	7

- 2011: 21st February to 7th December
- 2012: 14th March to 17th December
- 2013: 14th January to 16th February

It should be noted that the injectors started around 2 weeks before these dates to have beam ready for the LHC. This represented an intense and prolonged running period with long operational years and short winter stops and certainly the strains on injectors, hardware, operations and support were at the limit at the end.

RUN 2

Extended Year End Technical Stop (EYETS)

The main motivation for an extended year end technical stop some time in 2017 is for CMS to install its new 4 layer pixel detector which will be ready at the end of 2016. CMS require 19 weeks beam to beam extending the normal winter technical stop by some 6 weeks. Some contingency should be foreseen.

ATLAS have stated that they do not need the EYETS. It is not of any significant benefit to ALICE and LHCb but, as will be discussed below, the extended stop would naturally push back the start of LS2 buying them useful time in their preparations for the planned upgrades in LS2.

During the EYETS cryogenics would plan to keep the magnets cold below 80K to ensure that conditioning is not lost. One could imagine some sectors being kept in nominal conditions for some training quenches in order to probe the requiring training for 7 TeV operation. The stop would also provide the opportunity for selective cryogenics maintenance [2].

Even sandwiching the extended stop between ion runs it would appear to be too short for a possible Linac4 connection. This has been estimated to required around 9.5 months [3]. However, the stop could be used to perform LIU preparation work, in particular cable clean-up in the Booster. This activity is very much on the critical path for the eventual Linac4 connection and the shift to H^- injection in the Booster.

Length of Run 2

The nominal run length is assumed to be 3 years. However, a reasonable question is: "could it be longer?". In the specific case of Run 2 the following options may be considered.

A four year run without an extended stop This is unacceptable for CMS.

A four year run with an extended stop Here we talk about the operation of LHC for 3.5 to 4 years with around 5 months out in the middle. This implies operation of injector complex for 4 to 4.5 years with around 5 months out in the middle. As mentioned above this option has the attraction of buying at least two LHC experiments important contingency in their preparation for major upgrades in LS2.

On the down side it extends the risk of running with Linac2 until 2018/2019.

The machinery and global cryogenics maintenance plan have periodicity of maximum 40,000 hours (5 years at 8'000 hours (or 11 months)) including cool-down, hardware commissioning before beams and warm-up before next long shut-down. This would give 1 year of technical set-up and 4 years of physics. Experience so far shows that some equipment reliability falls before these accumulated hours. Some effort is being brought to bear but limited extension in time can be expected. Bearing in mind that cryogenics starts operation mid 2014 for the cool-down of the LHC, cryogenics would not rule out either a four year run or a four year run with EYETS. The intermediate 5 months extended technical stop would give time to treat most sensitive machines and allow for another 1 or 2 years operations at hopefully something like full reliability [2].

To summarize the options for Run 2 are:

- Baseline: 3 years run 2015 through 2017;
- Slipped baseline plus 6 months: EYETS plus extended run through to the middle of 2018;
- Slipped baseline plus 12 months: EYETS plus extended run through to the end of 2018.

Options that are assumed to be ruled out are: a 4 year run straight through; extending EYETS to 9 months to allow the connection of Linac4.

LONG SHUTDOWN 2 (LS2)

A breakdown of the requirements of the LHC experiments, LHC machine and injectors regarding LS2 is shown below. The clear conclusion is that LS2 will need to be of the order of 18 months.

Experiments

ALICE foresee a major upgrade of their detector for installation in LS2 which they are assuming to be 18 months. They would not violently object if LS2 shifts to 2019 this would provide important contingency.

LHCb requires 18 months for the installation of their upgrade. A later start of LS2 at end 2018 would be advantageous for LHCb for similar reasons to ALICE. Further delay of the start of LS2 beyond 2018 would be disfavoured.

ATLAS are assuming the baseline i.e an LS2 of 14 months starting at the beginning of 2018.

CMS require an LS2 of 14 to 18 months and prefers that it starts towards the end of 2018 ("to collect sufficient data (with the upgraded tracker) LS2 must not start before summer 2018").

There is a concern about potential overheads that might be caused by radiation levels forcing potential constraints such as cool-down time.

Injectors

The baseline planning is for the Linac4 connection to the Booster to take place during LS2. Detailed planning is available elsewhere in these proceedings [3]. It is estimated that a total of 16 months is required for the Booster works including 1.5 months of cool-down. An additional 4 months of beam commissioning is foreseen. Cabling will be on the critical path and it might be possible to claw some time back in EYETS.

The PS upgrade is determined mainly by magnet program (replacement of the pole face windings etc.). The estimate is about 1 year plus 1 month cool-down.

The SPS foresees 12 months for the 200 MHz upgrade and 7 months for amorphous carbon coating of main bending magnets (to be confirmed).

It can be seen the key activity is the connection of Linac4 to the Booster with a total duration work required in LS2 of 20.5 months. Some co-commissioning of the injectors and the LHC might be necessary. This is certainly imaginable with the LHC only requiring limited beam during the initial commissioning phase foreseen to be about 2 months.

LHC

At present the main items planned for LS2 are:

- 16 months for cryogenics and cooling/ventilation maintenance (also required in LS4);
- installation of dispersion suppressor collimators;
- vacuum consolidation in IR2;
- installation of RF cryogenics plant;
- possible HL-LHC preparation (e.g. space for crab cavities, TAS aperture change).

There is apparently nothing which would push the required time beyond 18 months.

RUN 3

Given the EYETS and the extension of Run 2 into 2018, and the necessary extension of LS2 to 18 months, Run 3 necessarily gets pushed. Tentatively accepting a slip of the start of LS3 to the start of 2023 gives a Run 3 of 2.5 to 3 years spanning 2020 through 2022. (see figure 2). The exact length of Run 3 can, of course, be better optimized nearer the time.

LONG SHUTDOWN 3 (LS3)

Regarding the length of LS3, for the experiments 30 months seems feasible for CMS while ATLAS estimate 27 months (with an outside possibility for 35 months). Again there are concerns that LS3 could become longer due to activation aspects, infrastructure increase and maintenance, longevity issues still to discover and "our usual packing in of whatever we can".

For the LHC this is the HL-LHC upgrade and there are major infrastructure implications which include:

- 20 months for cryogenics and cooling/ventilation maintenance;
- major upgrades of insertion regions: new triplets, 11 T dipoles, collimators, cryogenics, crab-cavities, cold powering;
- possible civil engineering in the tunnel (crab-cavities);
- possible civil engineering on surface.

Clearly it is too soon to give a detailed breakdown but 2.5 years seems a reasonable working hypothesis.

For completeness it is noted that 16 months is foreseen for LS4 and 20 months for LS5 - essentially driven by cryogenics and CV.

IONS

Ions are an integral part of the HL-LHC program. Extended periods of running greater than 1 to 2 months have been ruled out as an option. The scheduling of longer ion run before LS3 ($\approx$2 months) plus any other low luminosity running such as proton-proton reference data, high β^*, MD etc. before a long shutdown is clearly a possibility.

CONCLUSIONS

Given the above, three main variations seem possible.

Firstly a modified baseline would exclude EYETS, accept an extended LS2 of 18 months and keep the LS3 start in 2022. This is clearly disfavours CMS, and given upgrade development and funding considerations unrealistically forces the pace.

The second option which we call "Slipped baseline+6" sees:

- a EYETS in 2017;
- an extended Run 2 to mid-2018;
- a 3 year Run 3 with LS3 starting in 2023.

The third option which we call "Slipped baseline+12" sees:

- a EYETS in 2017;
- an extended Run 2 to end-2018;
- a slightly shortened Run 3 with LS3 starting in 2023.

The three options are detailed in Figs. 1,2 and 3.

ACKNOWLEDGEMENTS

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REFERENCES

[1] ECFA High Luminosity LHC Experiments Workshop, http://indico.cern.ch/conferenceDisplay.py?confId=252045, Aix-les-Bains, October 2013.

[2] S.Claudet, private communication.

[3] B. Mikulec, J-B. Lallement, Work Effort in the LHC Injector Complex, including Linac4 connection, for the Upgrade Scenarios, these proceedings.

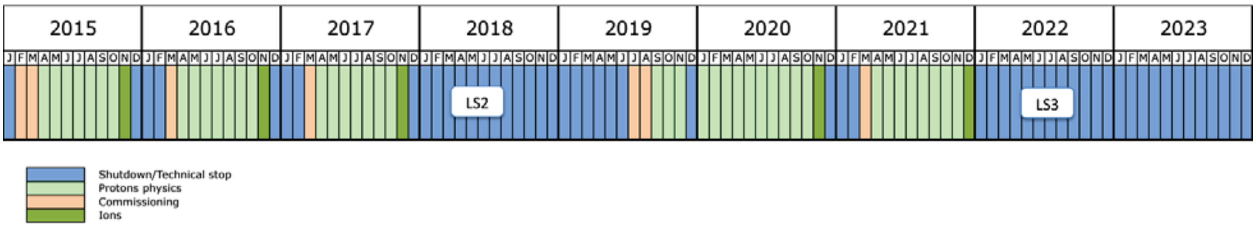

Figure 1: Baseline with LS2 extended to 18 months

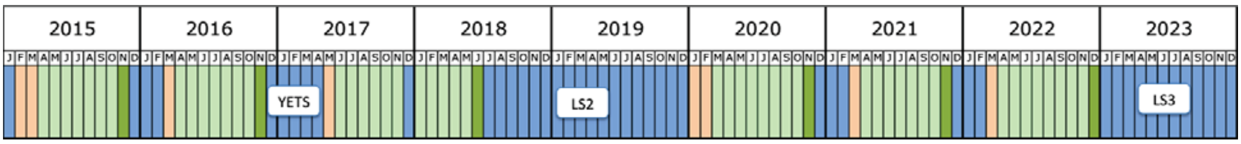

Figure 2: Slipped baseline plus 6 months

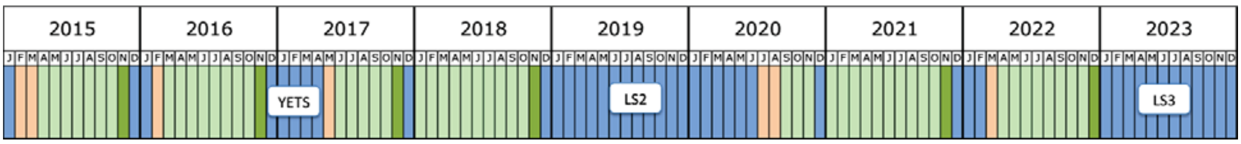

Figure 3: Slipped baseline plus 12 months

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EXPECTED PERFORMANCE IN THE INJECTORS AT 25 ns WITHOUT AND WITH LINAC4

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Abstract

The quality of the 25ns beams that can be delivered at the LHC injection is determined by the injection process into the PSB, as well as by space charge, collective interactions, electron cloud and RF power limitations in the PS and SPS. Using the information available from our present experience, the main goal of this paper is twofold: (1) to assess the intensity and brightness reach of the 25ns beams produced by the LHC injector chain with the two main schemes, before and after the connection of the PSB to Linac 4; and (2) to identify which bottlenecks will be likely to limit the performance with Linac 4. A few options to maximize the potential of the increased brightness provided by Linac 4, based on flattened bunch profiles at the PS injection or the use of alternative optics configurations, will be included in the analysis.

INTRODUCTION

During the 2011 and 2012 runs, the LHC physics production mainly made use of 50 ns beam, while the 25 ns beams were only injected into LHC on few occasions for injection tests, Machine Development (MD) sessions, an extended scrubbing run and a short pilot physics run [1, 2]. Furthermore, several MD sessions making use of 25 ns beams also took place in the SPS, during which the set up of this type of beams was optimized throughout the whole LHC injector chain even prior to their use in LHC [3]. Nowadays, thanks to a vast experience and several important improvements carried out over the years over all the accelerators of the LHC injection chain, the nominal 25 ns beam is produced well within specifications [4] and its transport through the different accelerators hardly exceeds the allocated beam loss and emittance blow up loss budgets (i.e. 5% intensity loss and emittance growth in the PSB and PS, and 10% in the SPS). For example, one of the essential ingredients that contributed to limit the degradation of the 25 ns beams along their transport to the LHC was the accumulated scrubbing of the SPS over the years, which has eventually made the amount of electron cloud in the ring acceptable to produce 25 ns beams within specifications [5]. It is also important to recollect at this stage that in 2012 a new scheme for the production of 25 ns beams was developed and applied. This scheme, called BCMS (Batch Compression and bunch Merging and Splitting), is described in [6, 7]. By reducing the splitting factor in the PS from 12 to 6 (at the expense of producing trains of 48 instead of 72 bunches at the PS exit), these beams can in principle reach double brightness with respect to those produced with the standard scheme.

After Long Shutdown 1 (LS1), the LHC will run with 25 ns beams for physics production. Therefore, the goal of this paper will be to analyze the possible future scenarios with 25 ns beams and provide the beam characteristics that can be expected at the different stages of the LHC injection chain for each scenario. In particular, after summarizing the achieved performance of the injectors with 25 ns beams, Section 1 will focus on the potential improvements that can be implemented after LS1, providing also the achievable beam parameters. Section 2 will describe the expected performance improvement after the connection of Linac 4 to the PSB and how this can translate into an increased brightness of the beam delivered to the LHC even in absence of any other upgrade throughout the injector chain. In this framework, some exotic ideas to beat the space charge limit at the PS injection will be briefly discussed, like the use of hollow bunches at the PSB-PS transfer or the implementation of alternative optics configurations at the PS injection. Finally, the possible advantages of the single batch PSB-PS transfer will be also addressed.

PRE-LINAC4 ERA

Achieved performance

An upper limit for the brightness of the LHC-type beams is determined at the PSB injection, because of the efficiency of the multi-turn injection process as well as the effects of space charge during injection. To obtain bunches with 1.2 eVs longitudinal emittance (resulting in 180 ns total bunch length with the maximum 8 kV voltage on h=1) at the PSB extraction, as required for the following RF manipulations at 1.4 GeV in the PS, the transverse emittance versus extracted intensity curve has been measured at the PSB with careful optimization of the injection settings for all measurement points (lower line in Fig. 1) [8]. The brightness is actually already defined at capture of the beam in the h=1 bucket, because intensity and emittance measurements along the PSB cycle reveal that no significant beam loss or emittance blow up takes place after capture for any of the measured points. In the case of the BCMS beams, due to the injection into h=9 in the PS, the total bunch length at PSB extraction cannot exceed 150 ns, which limits the value of longitudinal emittance for the PSB bunches to 0.9 eVs. To achieve this value of longitudinal emittance at extraction, it is necessary to produce it already at injection by means of longitudinal shaving and conserve it along the cycle. This makes the achievable brightness of

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the BCMS beams lower than that of standard LHC beams, so that the resulting curve transverse emittance versus extracted intensity moves to the upper line of Fig. 1.

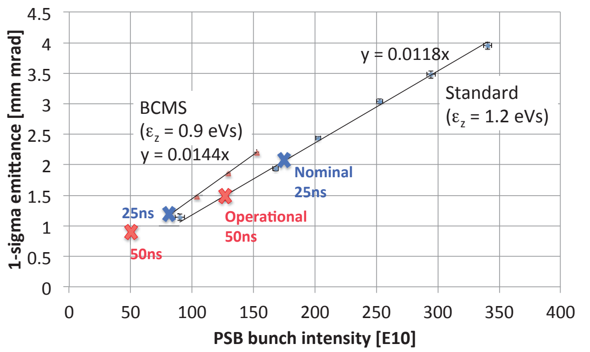

Figure 1: Performance at the PSB extraction with LHC-type beams. The two lines correspond to standard and BCMS production schemes, as labeled.

The measurement points displayed in Fig. 2 refer to 25 ns beams at the SPS extraction and were taken after the low gamma transition optics Q20 became operational in the SPS [9]. The transverse emittances shown in this plot are deduced from combined wire-scans at the end of the SPS flat bottom and the values were cross-checked with measurements in the LHC. The error bars include the spread over several measurements as well as a systematic uncertainty of 10%. The bunch intensity is measured at the SPS flat top after the scraping of the beam tails, as required prior to extraction into LHC. From these measurements, two important considerations can be made. First, the 25 ns beams produced with the standard production scheme are well within the original specifications (i.e. 1.15×10^{11} ppb and 3.5 μm transverse emittance [4]) and the BCMS scheme can achieve much higher brightness (in trains of 48 bunches). Second, the same figure shows not only the measurement points but also the projected lines from the PSB brightness (i.e. the measured PSB brigthness lines are translated into protons per SPS bunch applying 5% and 10% intensity loss and emittance growth in the PS and SPS, respectively). Therefore, one can see that the standard 25 ns beam goes through the injector chain with an additional 15% emittance blow up (or intensity loss) compared to the allocated budget, while the BCMS beam performs within the expected budgets. Possible reasons for the worse performance of the standard 25 ns beams could be the slow losses at the SPS flat bottom or space charge effects at the PS injection, which, combined with the larger transverse emittances, may potentially lead to increased fast losses.

The space charge induced tune spread can be evaluated at each stage of the injection chain (relativistic factors β, γ) from the measured values of bunch peak density $\lambda_{\max}$, transverse emittances $\epsilon_{x,y}$, and momentum spread δ as well as from the knowledge of the machine optics (beta functions, $\beta_{x,y}(s)$, and dispersion functions, $D_{x,y}(s)$), using

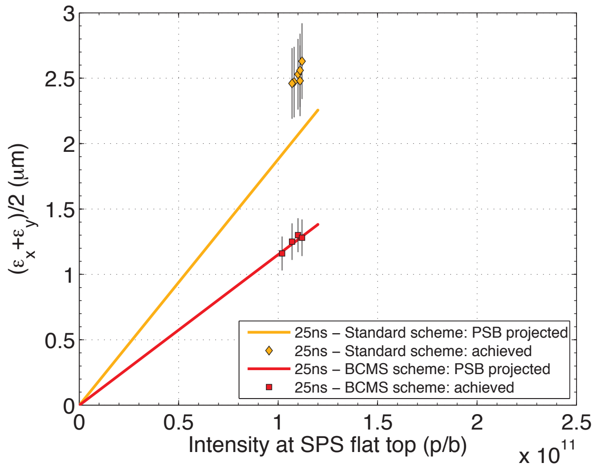

Figure 2: Performance at the SPS extraction with 25 ns beams. The projected lines from the PSB perfomance are also plotted, after applying the expected intensity loss and emittance growth budgets throughout the injector chain.

the following formula:

$$\Delta Q_{x,y} = \frac{\lambda_{\max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_{x,y}(s)ds}{\sigma_{x,y}(s)\left[\sigma_x(s)+\sigma_y(s)\right]} \qquad (1)$$

with r_p being the classical proton radius and

$$\sigma_{x,y}(s) = \sqrt{\epsilon_{x,y}\beta_{x,y}(s) + D^2_{x,y}(s)\delta^2}\ .$$

Calculating the tune spread values achieved at the PS and SPS injections for both the 25 ns beams, with parameters reviewed here above, and the 50 ns beams (standard and BCMS) [10], and from the experience accumulated in dedicated space charge MDs throughout 2012 and 2013 [12], the maximum values of ΔQ considered acceptable at the PS and SPS injection have been set to 0.31 and 0.21, respectively.

Expected post-LS1 performance

The 25 ns beams (both standard production and BCMS) in the 2012/13 run were already at the limits of what the LHC injectors can produce. In terms of intensity per bunch, the intensity reached at the exit of the SPS is only 10% lower than what is achievable within the present limitations due to the RF power and the longitudinal instabilities in the SPS [5, 11]. Actually, during one MD session at the end of 2012, an intensity of about 1.35×10^{11} ppb could be successfully accelerated to 450 GeV/c, but the beam was found to be degraded in all planes probably due to a combination of longitudinal instabilities and revived electron cloud effects. In terms of brightness, both the standard production scheme and the BCMS rely on bunches that are already at, or very close to, the limit of space charge at the PS injection ($\Delta Q_y = 0.31$).

The possibility to improve the performance after LS1 rests therefore on the perspectives of increasing the bunch intensity by 10% and improving the brightness by circumventing the space charge limit at the PS injection. To explain then which improvements could be envisioned, we first need to clarify the reasons limiting the longitudinal parameters of the bunches at the PSB extraction:

- For the standard production scheme (injection into PS h=7), the longitudinal emittance is limited to 1.2–1.3 eVs to ensure the quality of the triple splitting at 1.4 GeV before acceleration in the PS. As a consequence, the bunches cannot be longer than 180 ns, which is the matched value for the required longitudinal emittance in the PSB h=1 bucket with 8 kV at 1.4 GeV. In reality, the acceptable bunch length could have been as much as 220 ns in order to be compatible with the rise time of the recombination kicker in the transfer line (105 ns) and provide the correct bunch spacing to fit into the PS h=7 (327 ns).

- For the BCMS scheme (injection into h=9), the bunch length is limited to 150 ns to allow for the 105 ns rise time of the recombination kicker and obtain the 255 ns spacing of the PS h=9. The maximum longitudinal emittance allowing for this bunch length at the PSB extraction is 0.9 eVs.

The first condition to improve the situation above is to allow for larger longitudinal emittances to be transferred from the PSB to the PS. This is possible if triple splitting in the PS are made at 2.5 GeV instead of the injection energy. Second, the PSB should be able to provide bunches at 1.4 GeV with total length of 220 ns or 150 ns for the standard production scheme or the BCMS, respectively, and longitudinal emittances larger than the matched values on h=1 alone with 8 kV. This is possible with a controlled longitudinal blow up made with C16 along the ramp and with additional 8 kV on h=2 used in phase with h=1 at 1.4 GeV (instead of being reduced to 1 kV as in standard operation). The longitudinal emittance of a bunch at the PS injection should not exceed:

- 3 eVs (h=7)/2 eVs (h=9) due to the acceptance bottleneck at the start of acceleration from 1.4 to 2.5 GeV;

- (Total Split Factor $\times 0.35$ eVs)/1.1, as bunches at the PS extraction must have longitudinal emittance of 0.35 eVs with 10% blow up allowed in the PS;

- Flat Bottom Split Factor $\times 1$ eVs for transition crossing on h=21, as bunches go smoothly through transition if their longitudinal emittance is below 1 eVs;

- The matched value in the PSB with h=1+2 with available voltage and desired bunch length at extraction.

Considering all the constraints, bunches with 2.8 eVs longitudinal emittance can be transferred with the standard scheme, while 1.5 eVs is the maximum tolerable with the BCMS scheme. The overall performance of standard and BCMS 25 ns beams at the SPS extraction is illustrated in Figs. 3.

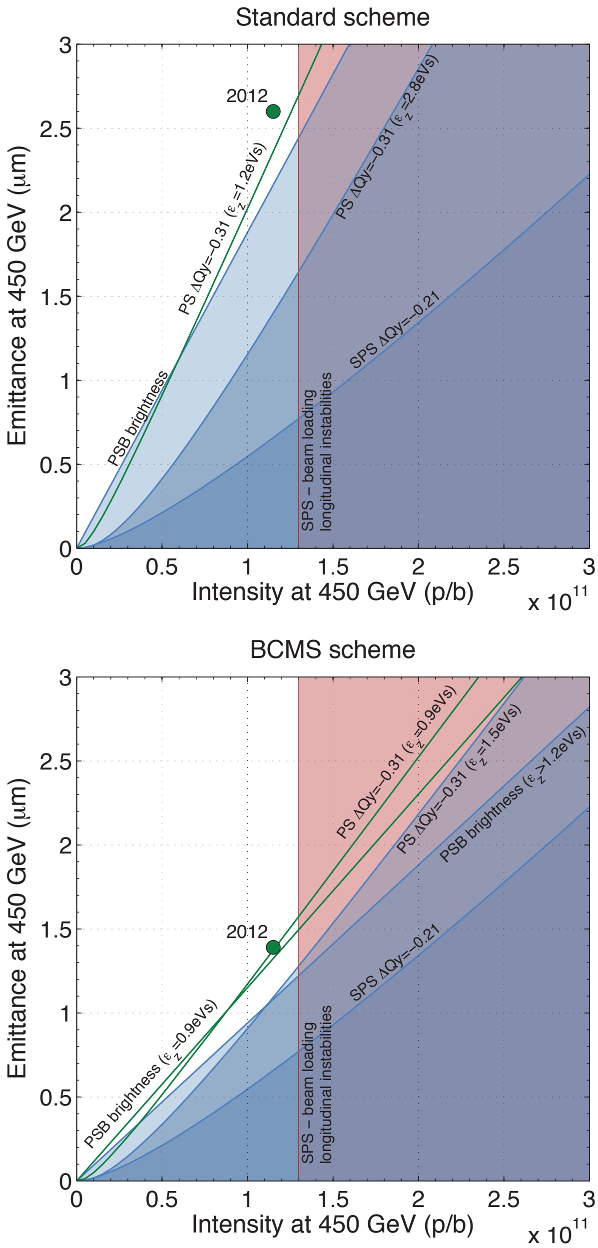

Figure 3: Limitation diagrams for the standard production (top) and BCMS scheme (bottom).

In these figures, the emittance vs. intensity curves corresponding to the known performance limitations (i.e. PSB brightness, PS and SPS space charge) are plotted at the SPS extraction both without (green curves) and with (blue curves) the relaxed longitudinal parameters at the PSB-PS transfer. The intensity limitation of 1.3×10^{11} ppb due to the SPS RF power and longitudinal instabilities limitation is also displayed as a vertical red line. Since these

		PSB						
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Post-LS1	Standard	19.21	2.02	0.05	1.0	1100	$2.4 \cdot 10^{-3}$	(0.58, 0.67)
	BCMS	9.60	1.06	0.05	1.0	1100	$2.4 \cdot 10^{-3}$	(0.48, 0.61)
	PBC	6.40	0.78	0.05	1.0	1100	$2.4 \cdot 10^{-3}$	(0.40, 0.53)
	8b⊕4e	17.73	1.86	0.05	1.0	1100	$2.4 \cdot 10^{-3}$	(0.57, 0.67)

		PS (double injection)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Post LS1	Standard	18.25	2.12	1.4	2.79	220	$1.8 \cdot 10^{-3}$	(0.14, 0.23)
	BCMS	9.12	1.11	1.4	1.48	150	$1.4 \cdot 10^{-3}$	(0.18, 0.31)
	PBC	6.08	0.72	1.4	1.0	150	$0.9 \cdot 10^{-3}$	(0.21, 0.31)
	8b⊕4e	16.84	1.96	1.4	2.0	220	$1.3 \cdot 10^{-3}$	(0.18, 0.25)

		SPS (several injections)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Post-LS1	Standard	1.44	2.22	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.05, 0.08)
	BCMS	1.44	1.16	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.08, 0.14)
	PBC	1.44	0.86	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.10, 0.18)
	8b⊕4e	2.00	2.05	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.08, 0.13)

		LHC					
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	bunches/train
Post-LS1	Standard	1.30	2.44	450	0.47	1.63	4×(72b+8e)
	BCMS	1.30	1.28	450	0.47	1.63	6×(48b+8e)
	PBC	1.30	0.95	450	0.47	1.63	6×(32b+8e)
	8b⊕4e	1.80	2.26	450	0.60	1.67	4×(7×(8b+4e))

Table 1: This table summarizes all achievable parameters with 25 ns beams after LS1. The performances of two new schemes with Pure Batch Compressions (PBC) and production of "standard" trains alternating 8 bunches and 4 gaps (8b⊕4e) are also included.

curves also represent the borders between areas of reachable and unreachable parameter ranges, the latter ones have been shown as shaded regions. Obviously, the larger longitudinal emittances at the PSB injection result in longer bunches and/or larger momentum spreads, which reduce the slope of the curve $\Delta Q_y = 0.31$ in the emittance vs. intensity plane. It is clear that the possibility to transfer bunches with larger longitudinal emittance from the PSB to the PS results into a higher achievable brightness, only limited by the PSB brightness for the standard production scheme and by the PS space charge for the BMCS scheme. It should be noted that relaxing the longitudinal parameters at the PSB extraction also results into a more favorable PSB brightness line for BCMS beams, because the 1.2 eVs line of Fig. 1 can also be assumed for this type of beams.

Table 1 summarizes all the achievable parameters after LS1. For sake of completeness, it includes not only the 25 ns beams produced with the standard and BCMS schemes, discussed above, but also the Pure Batch Compression (PBC) scheme [13] and the (8b⊕4e) scheme described in references [13, 14]. To be noticed that the sub-μm emittance values of the PBC scheme are in principle achievable in the PSB by means of transverse shaving, although the emittance preservation all through the injection chain has not yet been demonstrated for this type of beams and could prove not to be trivial.

PERFORMANCE WITH LINAC 4

After the connection to Linac 4, the main assumption is that beams out of the PSB will have double brightness with respect to the value achieved currently with Linac 2. In practice, the PSB performance with Linac 4 can be assumed to be represented by two lines with half slope compared to those shown in Fig. 1. In Fig. 4 the limitation diagrams with Linac 4 (as described in the previous section) are diplayed. Beams produced with the standard scheme can reach 1.3×10^{11} ppb within 1.65 μm, which is a significant improvement compared with the 2.44 μm achievable with Linac 2 (see Fig. 1). This improvement basically relies on the margin on the PS space charge provided by the new longitudinal parameters in the PSB-PS transfer (see Fig. 3, top plot). Beams produced with the BCMS scheme will have 1.3×10^{11} ppb within 1.28 μm, which equals the achievable performance with Linac 2. This is not surprising, because the BCMS beams, even with the new lon-

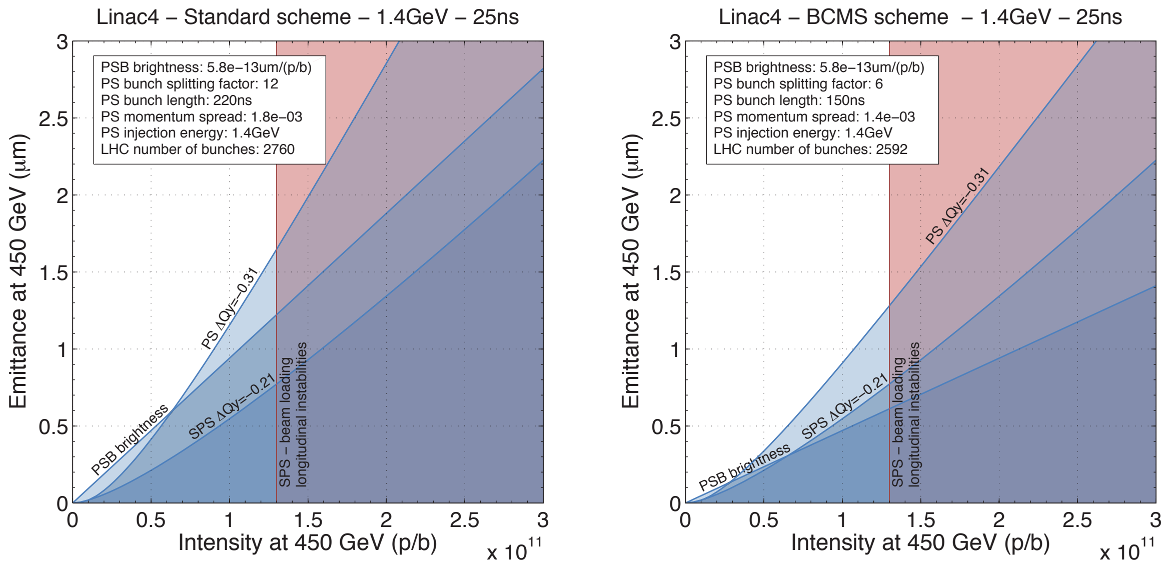

Figure 4: Limitation diagrams for the 25 ns beam (standard and BCMS production scheme) after the connection to Linac 4.

gitudinal parameters for the PSB-PS transfer, will be still limited by the space charge in the PS. As a consequence, with no other upgrades downstream, this type of beam will not be able to benefit from the increased brightness from the Linac 4.

Figure 4 also reveals that, if we could find a means to lower the curve of the PS space charge below the one of the PSB brightness, Linac 4 would provide the potential to increase the brightness of both the standard and the BCMS beams by as much as 20–30%. From the tune spread formula Eq. (1), it is clear that, assuming that the PSB-PS transfer energy will remain 1.4 GeV, the only knobs to achieve this brightness gain lie in either decreasing the bunch peak density (i.e. flattening the bunch), or increasing the momentum spread, or both. Some ideas are presented in the following subsections.

Hollow bunches

To flatten the bunch profile, the first option is to use the second harmonic in counterphase with the main harmonic in both the PSB and the PS, and then transfer matched flat bunches. This manipulation only distributes the core particles over a larger longitudinal phase space area, but the core remains the most highly populated region. However, this solution does not offer a large gain potential and would also pose technical problems of synchronization between the two accelerators. Consequently, we will mainly focus on another option to flatten the bunch profile, i.e. creating a hollow bunch in the longitudinal phase space. Unlike the first option, in this case the bunch distribution in the longitudinal phase space is changed and the core is depleted, with most particles being moved to large synchrotron amplitudes. Hollow bunches can be produced in several different manners:

1. By using a second harmonic with tailor-made voltage and phase programs on both main and second harmonic. This allows redistributing the particles in the longitudinal phase space and folding the highly populated core into a large synchrotron amplitude ring. Two possible techniques are considered, which were already proposed and discussed in [15]. The overall manipulation needs a few synchrotron periods and would require an extended flat top of few tens of milliseconds in the PSB.

2. By shaking the beam by means of an RF phase modulation close to the synchrotron frequency and then applying a higher harmonic sweeping excitation to smear the particles into a ring-like distribution. First tests were already successfully conducted at both the PSB and PS [16, 17]. This technique can be applied in the PSB while accelerating.

3. By injecting the hollow distribution directly in the PSB by means of longitudinal painting and controlled chopping (after the connection of the PSB to Linac 4). Since one full cycle for longitudinal painting needs 40 injected turns, while the 25 ns beam only needs the injection of about 7 turns, a large fraction of the beam will have to be chopped out. With this scheme, the hollow bunch will then have to be stably accelerated through all the PSB cycle, preserving its longitudinal structure.

The phase space distributions before and after the hollow bunch creation (compatible with the transfer constraint of a full bunch length below 220 ns) using the technique 1) are sketched in Fig. 5. Comparing the top and bottom plots, a depression of peak density by about 40% as well as a broadening of the momentum spread, both potentially contributing to a relaxation of the space charge, are visible.

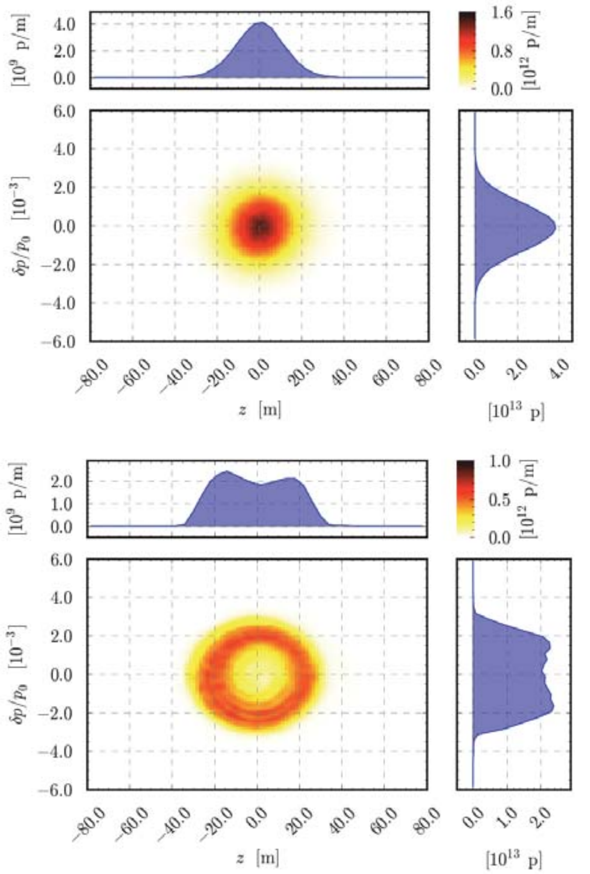

Figure 5: Longitudinal phase space density plots before and after the RF gymnastics to create a hollow bunch. Beside, the projections in the two dimensions are also plotted.

In this case, the estimated gain also depends on the larger bunch length allowed for the hollow bunch compared to the initial bunch.

Techniques 1) and 2) have been already experimentally tested (as shown in the relative references), but they have never been used for the production of operational beams. Although promising because of the potential space charge reduction they offer, stability and operational reliability of hollow bunches is yet to be demonstrated. For example, a possible practical problem could be encountered with the triple splitting, because this type of manipulation applied to a hollow bunch could lead to daughter bunches unbalanced in intensity. Another issue could be linked to the different location and density of the tune footprint of a hollow bunch, which is being investigated via long term tracking simulations including space charge.

Alternative optics configurations

Another idea that is currently under investigation to ease space charge at the PS injection is the possible change of the injection optics to enhance the horizontal dispersion or to create vertical dispersion via coupling [18]. Both possibilities are in principle viable thanks to the horizontal and vertical acceptances of the PS, which are sufficient to accommodate the low emittance LHC beams, even with enlarged transverse sizes. The option of distorting the optics to enhance the horizontal dispersion could potentially lead to a reduction of the tune spread by 10–15% and was already tested on a few Machine Development (MD) sessions during the 2012-13 run, although no conclusion on its efficiency can be drawn yet. The option of creating vertical dispersion is based on the use of the existing skew quadrupoles and could yield a 30% reduction of the space charge tune spread with the existing magnets, while new hardware should be installed to increase its efficiency. MDs aiming at testing the coupled optics are planned to take place after LS1.

Single batch PSB-PS transfer

The last point we want to discuss in this analysis is the production of LHC beams with single batch PSB-PS transfer and which advantages this might entail. For all the schemes discussed so far in this paper, we have always implicitly assumed two consecutive injections from the PSB to the PS, i.e. 4+2 bunches for the standard scheme and 4+4 bunches for the BCMS (in the so-called double batch PSB-PS transfer). The reason is that this way of producing LHC beams naturally allows increasing their brightness (as prescribed by the PSB brightness line, Fig. 1). An alternative scheme, already used operationally in the past for the production of 50 ns beams, relies on one single PSB-PS transfer by extracting two bunches per ring from the PSB. This would make the LHC injection process shorter at the expense of a net loss of initial brightness related to the higher intensity per ring that needs to be injected.

In a simplified view, as it provides LHC beams with double brightness compared to the present, Linac 4 would in principle also enable the production of all the present LHC beams with a single batch PSB-PS transfer. In practice, since the bunches should be transferred from h=2 in the PSB, they would be shorter (about 140 ns) and consequently feel more space charge for the same brightness in the PS (defined as intensity over transverse emittance ratio). On the positive side, these beams would be accelerated immediately after injection and the 1.2 s flat bottom, deleterious for long term space charge effects, would be removed. As a consequence, a larger tune spread than $\Delta Q = 0.31$ at the PS injection could be probably acceptable for beams transferred in single batch. However, due to lack of experience, it is difficult to estimate to which extent this value can be exceeded. Table 2 summarizes the parameters achieved in the past with the 50 ns beams (the only ones to have been produced and used operationally for LHC physics using this scheme) [19] as well as the parameters achievable in the future with Linac 4 in both the standard and the BCMS production schemes. It is clear that the beams produced with the standard scheme would need to stand a tune spread at PS injection that is 25% beyond

		PSB (1 b after capture, c=285 ms)						
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Achieved	50 ns	17.47	2.19	0.05	—	—	—	—
	25 ns	—	—	—	—	—	—	—
Linac4 (25 ns)	Standard	38.41	2.22	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.54, 0.62)
	BCMS	19.21	1.37	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.40, 0.48)

		PS (6 – 8 b/inj)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Achieved	50 ns	8.30	2.30	1.4	1.0	145	$1.07 \cdot 10^{-3}$	(0.14, 0.17)
	25 ns	—	—	—	—	—	—	—
Linac4 (25 ns)	Standard	18.25	2.34	1.4	0.9	140	10^{-3}	(0.32, 0.39)
	BCMS	9.12	1.44	1.4	0.9	140	10^{-3}	(0.23, 0.31)

		SPS (4 – 6 × 36-72 b/inj)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Achieved	50 ns	1.32	2.42	26	0.42	3	$1.5 \cdot 10^{-3}$	(0.04, 0.06)
	25 ns	—	—	—	—	—	—	—
Linac4 (25 ns)	Standard	1.44	2.45	26	0.42	3	$1.5 \cdot 10^{-3}$	(0.04, 0.07)
	BCMS	1.44	1.51	26	0.42	3	$1.5 \cdot 10^{-3}$	(0.06, 0.11)

		LHC (n ×144-288 b/inj)				
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)
Achieved	50 ns	1.20	2.70	450	0.60	1.65
	25 ns	—	—	—	—	—
Linac4 (25 ns)	Standard	1.30	2.70	450	0.45	1.55
	BCMS	1.30	1.66	450	0.45	1.55

Table 2: Table showing the achieved beam parameters for 50 ns beams and parameters in reach with 25 ns beams using a single batch transfer scheme between PSB and PS.

the limit from last year's operational experience.

By allowing four injections into the SPS in 7.2 s instead of the present 10.8 s, the length of the SPS flat bottom could be reduced by 33%, which results in an overall reduction of the SPS filling cycle by 17% (half of the cycle is taken by acceleration and flat top, whose lengths do not change with single or double batch beams). In the best case of dedicated LHC filling, this would translate into a reduction of the minimum waiting time of the LHC beams at 450 GeV by 17%. Given the emittance growth measured in the LHC between injection and collision, this potential reduction of the time at injection could have a beneficial impact on the attainable luminosity (especially in the case of strong electron cloud degradation of the 25 ns beams at 450 GeV), although it is very unlikely to lead to a better performance than the twice brighter double batch variants discussed in the previous part of this paper.

CONCLUSIONS

In summary, the present 25 ns beams can be delivered to the LHC well within specifications. The BCMS beams perform within emittance growth and intensity loss budgets throughout the injector chain, while the standard ones exhibit 15% larger emittance values at the exit of the SPS. These beams were successfully used at the end of 2012 for the LHC scrubbing run and a short pilot physics run. After LS1, due to the RF power limitations in the SPS, the intensity per bunch of the 25 ns beam can only be increased up to 1.3×10^{11} ppb out of the SPS. The possibility to further improve the performance reach of the injectors will then mainly rely on the potential brightness increase attainable from the relaxation of the longitudinal parameters at the PSB-PS transfer. This will be made possible by making all the RF manipulations in the PS at 2.5 GeV (as opposed to the present 1.4 GeV) and will play a major role in relaxing the space charge constraint at the PS injection thanks to the longer bunches and/or broadened momentum spread. In particular, standard and BCMS beams will be transferred to the PS with longitudinal emittances of up to 2.8 and 1.5 eVs, respectively, (compared to the present 1.2 and 0.9 eVs) leading to potentially 15–20% brighter beams at the SPS extraction.

After the PSB connection to Linac 4, beams with double brightness with respect to present beams will be delivered by the PSB. In absence of any other upgrade within the LHC injection chain, this will entail 33% brighter beams from the standard production scheme (which were originally limited by the PSB brightness), but no gain for the BCMS beams, which were already limited by the PS space charge. The space charge at the PS injection can actually be reduced by either flattening the bunch profile at the PSB-PS transfer (e.g. creating hollow bunches) or by changing the PS injection optics to enhance dispersion. These schemes, though promising and tested in MDs, have never been validated in standard operation. The PSB-PS single batch transfer scheme has the potential to decrease the minumum LHC injection time by 17% for the same initial brightness beams as with Linac 2.

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REFERENCES

[1] G. Rumolo, *et al.*, "E-cloud effects", in Proceedings of the LHC Beam Operation Workshop, Evian, France, 12–14 December, 2011

[2] G. Iadarola, *et al.*, "Electron Cloud and Scrubbing", in Proceedings of the LHC Beam Operation Workshop, Evian, France, 17–20 December, 2012

[3] H. Bartosik, *et al.*, "Electron Cloud and Scrubbing Studies for the SPS in 2012", CERN-ATS-Note-2013-019 MD

[4] LHC Design Report, edited by O. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, CERN-2004-003-V-1

[5] H. Bartosik, *et al.*, "Can we ever reach the HL-LHC requirements with the injectors?", elsewhere these proceedings

[6] R. Garoby, "New RF Exercises Envisaged in the CERN-PS for the Antiprotons Production Beam of the ACOL Machine", IEEE Transactions on Nuclear Science. **Vol. NS-32. No. 5**, October 1985

[7] C. Carli *et al.*, "Complementary/alternative possibilities", in Proceedings of the LHC Performance Workshop Chamonix 2011, Chamonix, France, 24–28 January, 2011

[8] B. Mikulec, "Performance reach of LHC beams", in LIU Beam Studies Review, CERN, Geneva, Switzerland, 28 August 2012

[9] H. Bartosik, *et al.*, "Increasing instability thresholds in the SPS by lowering transition energy", CERN-ATS-2012-177

[10] V. Kain, *et al.*, "50 ns back-up scenario", elsewhere these proceedings

[11] E. Shaposhnikova, "Intensity limit in the SPS without and with the 200 MHz RF upgrade", in 2nd LIU Technical Meeting, CERN, 12 July, 2013

[12] H. Bartosik, R. Wasef, in Space Charge 2013, CERN, Geneva, Switzerland, 16–19 April, 2013

[13] H. Damerau, *et al.*, "LIU: Exploring alternative ideas", elsewhere these proceedings

[14] R. Tomás, *et al.*, "HL-LHC: Exploring alternative ideas", elsewhere these proceedings

[15] C. Carli, "Creation of Hollow Bunches using a double harmonic RF system", CERN-PS-2001-073

[16] R. Cappi, et al., "Measurement and Reduction of Transverse Emittance Blow-up Induced by Space Charge Effects", CERN/PS 93-18

[17] R. Garoby, S. Hancock, J.L. Vallet, "Production of flat-topped bunches", CERN/PS/RF Note 92-8

[18] S. Gilardoni, Y. Papaphilippou, private communication.

[19] A. Findlay, *et al.* "Single batch transfer studies", in MSWG Meeting, CERN, 4 September, 2009

Published by CERN in the Proceedings of RLIUP: Review of LHC and Injector Upgrade Plans, Centre de Convention, Archamps, France, 29–31 October 2013, edited by B. Goddard and F. Zimmermann, CERN–2014–006 (CERN, Geneva, 2014)

INTEGRATED PERFORMANCE OF THE LHC AT 25 ns WITHOUT AND WITH LINAC4

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Abstract

The performance of the LHC above 6.5 TeV will depend on many factors. The available beams and their brightness defines together with achievable beta* the potential peak luminosity. For some cases the peak luminosity and the associated event pile-up may degrade the quality of the data recorded by the experiments. Such cases will require luminosity leveling for which a number of options are available. The peak performance may also be limited by cooling capacities and other equipment related issues, including machine protection as well as UFOs. The 25 ns beams require in addition substantial periods of scrubbing. The performance of the LHC in terms of integrated luminosity will be evaluated for various scenarios involving 25 ns beams, taking into account potential limitations from the various sources.

25 NS BEAMS IN THE INJECTORS

The expected performance of 25 ns beams in the injectors is discussed in detail by G. Rumolo in another contribution to this workshop [1]. A summary of the expected beam parameters at extraction from the SPS is given in Table 1. The bunch population is in all cases limited to 1.3×10^{11} ppb by the SPS RF system.

Between extraction from the SPS and start of collisions (stable beams) in the LHC, the following changes are considered:

- The intensity transmission is assumed to be 96% as achieved in 2012 with tight collimator settings,

Table 1: Achieved (in 2012) and expected beam parameters of 25 ns beams in the injectors for the standard and the BCMS production schemes. The scenario 'LS1' corresponds to the situation without Linac4, while the scenario 'L4' corresponds to the case with Linac4. N is the bunch population, ε^* is the normalized emittance.

Beam type	Scenario	N (10^{11})	ε^* (μm)	Limited by
Standard	Achieved	1.2	2.6	–
Standard	LS1	1.3	2.44	SPS
Standard	L4	1.3	1.65	SPS
BCMS	Achieved	1.15	1.4	–
BCMS	LS1	1.3	1.3	PS+SPS
BCMS	L4	1.3	1.3	PS+SPS

Table 2: Expected beam parameters of 25 ns beams at start of collisions after LS1 for the BCMS beam, the standard 25 ns beam and the standard beam with Linac4. For the BCMS beam there is no difference with or without Linac4. k is represents the number of colliding bunch pairs in ATLAS/CMS, θ is the half-crossing angle.

Beam type	N (10^{11})	ε^* (μm)	k	β^* (m)	θ (μrad)
BCMS	1.25	1.65	2590	40/50	150/140
Standard	1.25	2.9	2740	50	190
Standard+L4	1.25	2.0	2740	40/50	150/140

- An emittance blow-up of 15% is assumed in addition to the unavoidable blow-up from IBS. This is optimistic as compared to 2012 where the additional blow-up was typically 30%. It is also assumed that the blow-up from electron cloud, that is mainly observed at injection, is completely controlled.

The possible β^* values and the corresponding crossing angles were evaluated by R. Bruce [2]. Table 2 presents the beam parameters at start of stable beams, the number of colliding bunch pairs in IR1/IR5 (k), β^* and the half crossing angles θ. Filling scheme variations may affect k at the level of around 5%.

LHC PERFORMANCE LIMITATIONS

The maximum average pile-up is assumed to be limited to 45 events per bunch crossing. This value is also given as rough guideline for maximum acceptable pile-up in 2015. The pile-up is obtained from the luminosity assuming a visible cross-section of 85 mb at 6.5 TeV. For simplicity it is assumed in this document that it is also possible to level the luminosity at a pile-up of 45 events per bunch crossing, which is not (yet) guaranteed.

The cooling of the triplet magnets sets a limit to the maximum achievable luminosity of $1.75 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with an uncertainty of 10 to 20% [3]. This limit will have to be explored in 2015 and beyond. A study will be launched to analyze all possible limitations in the triplet (starting with the limiting heat-exchanger) to evaluate possible actions during LS2.

The intensity and/or brightness of the beams may be limited by instabilities, even though the 25 ns beam may be just stable up to 1.3×10^{11} ppb. In case of problems the beams may be stabilized at high energy by head-on beam-beam (squeeze in collision), but this makes operation more

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complex [4]. Other possible limitations to intensity are beam induced heating of equipment, electron cloud and UFOs. More experience must be collected on those item in 2015 and beyond.

UFOs

Between 2010 and 2013, 58 beams were dumped in the LHC due to UFO events [5]. An extrapolation of the UFO loss spectrum to 6.5 TeV using the currently accepted quench levels predicts around 100 beam dumps per year from UFOs after LS1. From the current status of the quench test analysis [6] there may be an extra margin on quench level for millisecond timescales (factor 2) at 4 TeV. This result must still be confirmed and extrapolated to 6.5 TeV. If this factor also applies at 6.5 TeV, the number of dumps would be reduced by a factor 2-3. The UFO rate depends on the bunch spacing, and it is stronger with 25 ns, but a fast conditioning was observed over a few fills in 2012. Based on the experience from the startup in 2012, one has to expect serious deconditioning after LS1, it will probably take 2-3 months to recover a lower UFO rate.

Electron cloud

Scrubbing was demonstrated to be efficient at 450 GeV [7]. It lowers the electron cloud in dipoles, a reduction that is less evident in the quadrupoles (due to a significantly lower SEY thresholds). Despite high intensity two-beam operation in the triplets for around 2 years (high electron dose), the electron cloud still present in the triplets. The SEY in the triplet is estimated to be around 1.2-1.3, the value being deduced from observed heat-load and simulations. A significant increase of the heat load (by a factor 4) is observed in the arcs during the ramp due to electron cloud in the dipoles. No change in heat load is observed in the quadrupoles. The underlying mechanism is not yet understood.

The available cooling power in the arcs (around 250 W per half-cell) will possibly limit initial operation at 6.5 TeV with 25 ns beams. The limitations observed in the standalone magnets (SAMs) will be lifted during LS1. A projection of the current situation to 2015 yields a limitation to 50% of the total number of bunches at 25 ns (≈1400 bunches).

Ideas have been put forward to enhance scrubbing at 450 GeV with dedicated scrubbing beams. To enhance the electron cloud doublet beams with bunch spacings alternating 5 and 20 ns or 2.5 and 22.5 ns have been proposed. The implications and issues (for BI, RF, ADT) are under investigation [8].

CONDITIONS

The performance predictions for 25 ns beams after LS1 are based on a high intensity proton run length of 160 days per year. It must be noted that periods of reduced luminosity (and intensity) are embedded in our runs. Such periods include initial intensity ramp up (up to a few weeks) and fast intensity ramp up after technical stops (around two

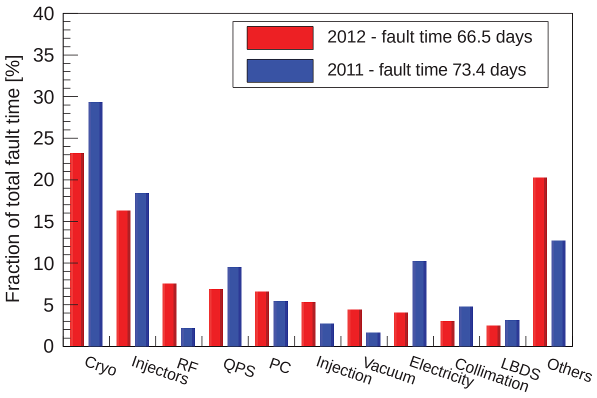

Figure 1: Relative contribution of the top-ten 2012 systems to the fault time. Courtesy A. Macpherson.

days). One should also not forget all the special runs like high-beta, LHCf, luminosity calibrations etc that are also embedded in the proton run and that cost a few percent of the running time.

Depending on the final performance and actual pile-up limitations, β^* leveling may be required for some time in each fill. To ease the setup and maximize efficiency it is important to train β^* leveling as soon as possible. A proposal to apply this technique for LHCb is under evaluation.

Machine Availability

The past 2012 run can be split into three blocks in terms of machine availability. On a per-physics-fill basis the time can be split up into:

- 6.1 hours of stable beams,
- 4.8 hours of faults,
- 5.5 hours of turn-around ('the rest').

This results in a 36% stable beams fraction / physics efficiency. The turn-around block also accounts for test cycles (Q/Q measurements, feedback tests, loss maps, high beta setup etc), lost cycles, short tests that were inserted in a standard cycles as well as a certain number of pre-cycles. The minimum turn-around time was 2.2 hours.

A break-down of the failures is shown in Figure 1. The cryogenic system and the injectors account for roughly 1/3 of fault time in 2012. One should also note that the long term average SPS (injector) efficiency is 85 ± 5%.

In comparison LEP1 reached physics efficiencies of over 50% in the period 1992-1994, see Figure 2. But the machine was much simpler and its fills were long. LEP2 had short(er) fills and an efficiency that is similar to LHC. A look at the weekly LHC stable beams efficiency in Figure 3 shows that with one exception in 2011, in the best weeks the LHC physics efficiency reached 45%.

The current accounting of faults and turn-around at the LHC is rather coarse. There is an ongoing effort between the AWG (Availability WG) and operation to improve the

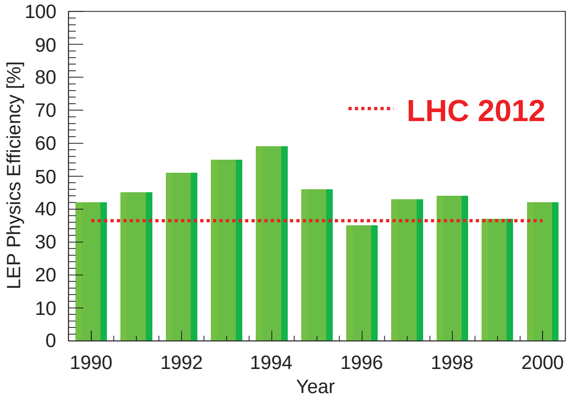

Figure 2: LEP yearly physics efficiency. Up to 1995 LEP ran around 45 GeV, from 1996 on it ran above 80 GeV.

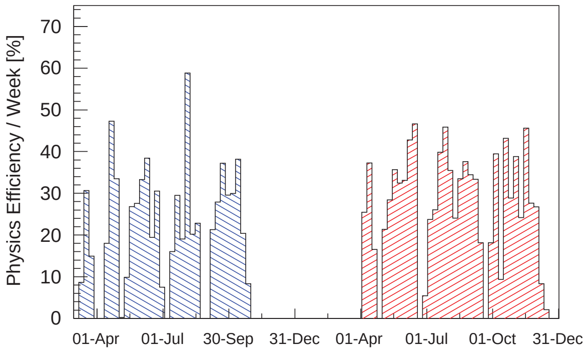

Figure 3: Weekly LHC physics efficiency in 2011 (blue) and 2012 (red).

modeling and information on the different phases. The aim is to build a tool that combines cycle information (beam modes, intensity, energy), Post-mortem information and fault information to provide a better model for faults and for the break-down of the 'turn-around time'.

After LS1 the cycle length will increase by ≈20 minutes. The baseline assumption for performance used here is that everything else remains the same except for the cycle length (same length of stable beams and of faults), and it is assumed that the turn-around time block includes two machine cycles for a total of 40 minutes. This leads to a stable beams efficiency of 35% which is used as a baseline for the performance evaluation. There are obviously many uncertainties, and such assumptions may be rather optimistic for a learning year like 2015.

LUMINOSITY MODEL

To asses the performance a simple luminosity model is used for 6.5 TeV, based on 2012 observations during collisions. The ingredients are:

- Luminosity burn-off with a total cross-section of σ = 105 mb,

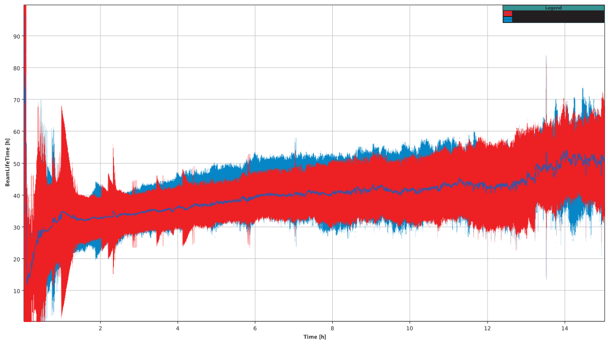

Figure 4: Evolution of the lifetime of the beams in collision as a function of the time spent in stable beams. The data corresponds to the average over all high intensity fills recorded after the octupole polarity reversal in August 2012. Courtesy A. Gorzawski.

- Single beam lifetimes as observed in 2012 at 4 TeV,
- Emittance growth as observed during physics fills in 2012, corrected for the synchrotron radiation damping (time constant of ≈ 30 hours.

The model tracks the intensity, emittances and luminosity along a fill by updating the parameters at intervals of 30 seconds based on finite differences. The model is cross-checked with a simple analytic approach (simple closed formula) for exponential fill length distribution and constant averaged luminosity lifetime [9] and with a Monte-Carlo approach (courtesy A. Apollonio).

Lifetime

Figure 4 displays the average intensity lifetime as a function of the time in stable beams for 2012 fills recorded after the octupole polarity reversal in August 2012. The lifetime including burn-off is in the range of 25 to 50 hours. It is assumed for this analysis that the single beam lifetime in the absence of collisions and burn-off is 60 hours.

Emittance growth

A significant effective emittance growth was observed in collision (from the luminosity evolution) at 3.5 and 4 TeV. The effective growth (assuming equal growth in both planes) extracted from the luminosity of ATLAS and CMS is shown in Figure 5. The origin of the growth is not understood. IBS is not sufficient to explain the growth, an extra contribution with growth time around 40 h is required. It is also noteworthy that the growth in 2011 was significantly steeper than in 2012. A parametrization of the 2012 emittance evolution using a second order polynomial is used to model the luminosity at 6.5 TeV. The growth is corrected for radiation damping (damping time ≈ 30 hours).

When the luminosity model using the ingredients discussed just before are applied to 2012 conditions at 4 TeV, the luminosity evolution can be reproduced well [10]: in

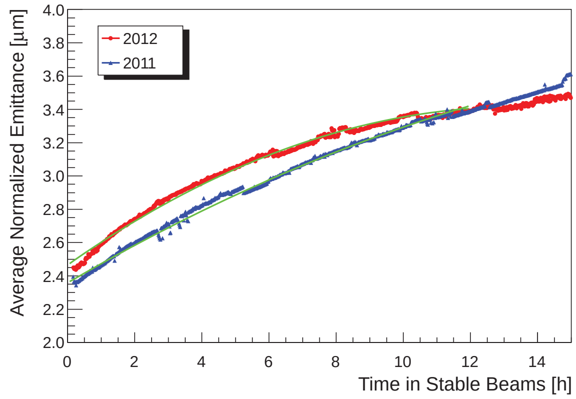

Figure 5: Evolution of the average emittance extracted from the luminosity of ATLAS and CMS in collision. The 2011 data is obtained from an average of the period with β^* 1 m (October-November 2011). The 2012 data is averaged over the period after the octupole polarity change in August 2012.Courtesy A. Gorzawski.

the first hour of stable beams, the luminosity lifetime is 6-8 hours, after 8 hours the luminosity lifetime has increased to 12-15 hours.

At 6.5 TeV the luminosity lifetime from burn-off alone at a luminosity of $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is $\approx$ 12 hours.

Fill length distribution

The fill length distributions shown in Figure 6 are very similar in 2011 and 2012 and can be approximated by simple exponential distributions. Typically 30% of the fills are dumped by the operation crews, the rest is dumped by the MPS.

An exponential fill length distribution is used for the performance figures quoted in the next section. The influence of the fill length distribution can be estimated by comparing the average integrated luminosity per fill for different fill length distributions, see Figure 7: exponential (truncated at 20 hours), flat and delta function centred at the mean value. In all cases the mean fill length is set to 6.5 hours. The results depend on the lifetime assumptions, but for the model used here, the luminosity increases by 10% for a flat distribution and by 20% for a delta function (with respect to the exponential distribution). The fill length distribution for 2012 is in fact a combonation of an exponential distribution driven by faults (2/3 of the fills) and of mixture of a flat distribution and a smeared delta functions (from fills dumped by the operation crews, 1/3 of the fills). The change in integrated luminosity as compared to a pure exponential is around 5-10%. Am analysis of the optimum dump time shows that a 6.5 hours dump time is not too far from the optimum of 8-10 hours for the assumed length of turn-around and fault times.

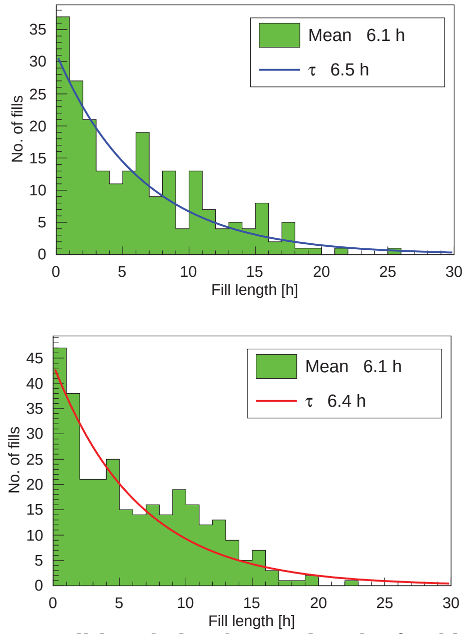

Figure 6: Fill length distribution (length of stable beams) in 2011 (top) and 2012 (bottom).

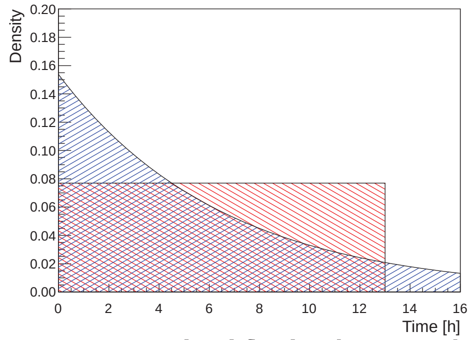

Figure 7: Exponential and flat distributions with the same mean fill length of 6.5 hours.

PERFORMANCE ESTIMATES

With Linac4 the performance of BCMS and standard 25 ns beams is very similar. The higher leveled luminosity of the standard beam (due to the larger number of bunches) is compensated by a longer leveling time with BMCS beams. The integrated luminosity is in the range of 48-53 fb^{-1}/year for a stable beams efficiency of 35% as shown in Figure 8. The potential peak luminosity $\mathcal{L}_p$, leveled luminosity $\mathcal{L}_l$ and leveling times are indicated in Table 3. It must be noted that the leveled luminosities are at the triplet cooling limit, and that the peak luminosities of the BCMS beams and of the standard beam with Linac4 are well above the estimated limit. If the 2011 effective emittance growth is used in the model, the integrated luminosities increase by approximately 2%. The values increase by 5-10% for a mixed 2012-like fill length distribution (see previous section).

If no leveling is used there is a modest gain of a few fb^{-1}

Table 3: Peak ($\mathcal{L}_p$) and leveled luminosity ($\mathcal{L}_l$) after LS1 for the various 25 ns beams in collision at the LHC.

Beam type	β^* (m)	$\mathcal{L}_l/10^{34}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$\mathcal{L}_p/10^{34}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Leveling time (h)
Standard+L4	0.4	1.65	2.1	1.6
BCMS	0.4	1.54	2.2	2.5
Standard+L4	0.5	1.65	1.9	0.7
BCMS	0.5	1.54	2.0	1.6
Standard	0.5	1.65	1.2	–

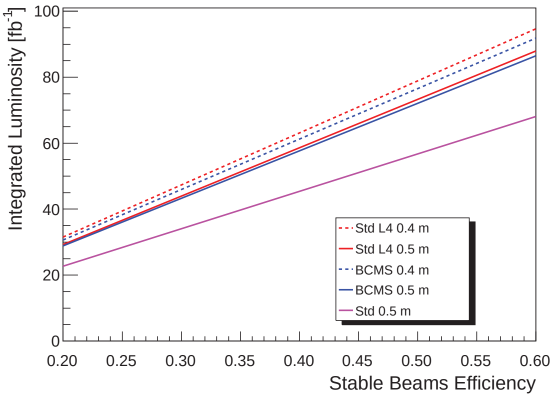

Figure 8: Integrated performance per year for the different beams as a function of the stable beams efficiency in case the luminosity is leveled according to Table 3.

due to the short leveling time and low(er) initial lifetime, see Figure 9. The BCMS and standard beams have again similar performance with Linac4, but the pile-up is higher with BCMS beams. The peak pile-up is around 66 events per bunch crossing for the BCMS beam with β^* of 0.4 m. The integrated luminosity increases to 50-55 fb^{-1}/year for a stable beams efficiency of 35% without leveling.

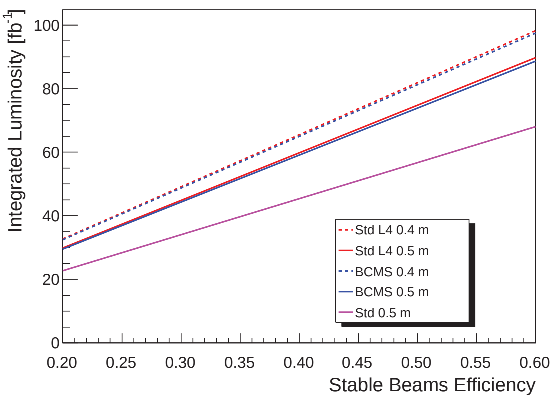

Figure 9: Integrated performance per year for the different beams as a function of the stable beams efficiency in case the luminosity is NOT leveled.

Monte-Carlo Model

A Monte-Carlo model had been developed by A. Apollonio for HL-LHC [11] to model luminosity (simplified), failures and turn-around and provide an as realistic as possible handling of the machine phases. If this model is applied to 25 ns operation post-LS1 assuming:

- 30% fills dumped by operation (the other following the exponential distribution),
- 6.2 hours of mean turn-around time,
- a fault time modeled by 4 LogNormal distributions,

then the results are consistent with the values quoted above, in the range of $\approx 45\mathrm{fb}^{-1}$. With this model it is also possible to evaluate the impact of UFO dumps: in the pessimistic scenario of ≈100 dumps/year, the yearly integrated luminosity is lowered by 15%.

SUMMARY

The expected integrated luminosity per year for 25 ns operation is in the range of 45-55 fb^{-1} for an efficiency similar to 2012. Over 5 and 1/2 years of operation until LS3 around 250-300 fb^{-1} would be collected. Without Linac4 it is recommended to use the BCMS beam, with Linac4 the standard 25 ns beam. There are currently many unknowns on the limitations, emittance, efficiency etc, but the situation should be clearer end 2015. It must be noted that the peak luminosity is always close to or above the expected triplet limitation. To reach luminosities of $2.5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ as quoted in many reference plots and documents, the performance must be boosted further (lower β^*, smaller emittances etc) and the triplet limitation must be lifted.

With Linac4 the standard 25 ns beams and the BCMS beams have very similar performance. A small bonus for the standard 25 ns is a lower pile-up (by 10%). The emittances that are eventually achieved may make the difference between standard and BCMS schemes. It may be easier with the standard beam due to the larger emittance. To be sure to reach or exceed 300 fb^{-1} by LS3 one should aim to improve the average physics efficiency of the LHC from 35% to at least 40%. This requires a concerted long term effort on the availability of equipment.

REFERENCES

[1] G. Rumolo, *Expected performance in the injectors at 25 ns without and with LINAC4*, these proceedings.

[2] R. Bruce, *Collimation after LS1: Cleaning and β^* Reach*, LBOC meeting of 11.12.2012, https://lhc-beam-operation-committee.web.cern.ch/lhc-beam-operation-committee/

[3] L. Tavian, *Cryogenics*, LHC Beam Operation workshop - Evian 2012, Evian, December 2012, https://indico.cern.ch/conferenceDisplay.py?confId=211614

[4] X. Buffat *et al.*, *MD on squeeze with colliding beams*, CERN-ATS-Note-2013-002 MD.

[5] T. Baer *et al.*, *UFOs*, LHC Beam Operation workshop - Evian 2012, Evian, December 2012, https://indico.cern.ch/conferenceDisplay.py?confId=211614

[6] M. Sapinski, *Status of quench tests analysis*, LBOC meeting of 22.10.2013, https://indico.cern.ch/conferenceDisplay.py?confId=276512

[7] G. Rumolo, *Maximum heat load expected in the arcs/SAM/triplets during scrubbing/operation*, LBOC meeting of 8.10.2013, https://indico.cern.ch/conferenceDisplay.py?confId=275930

[8] LBOC meeting of 5.11.2013, https://indico.cern.ch/conferenceDisplay.py?confId=277528

[9] J. Wenninger, *Simple models for the integrated luminosity*, CERN-ATS-Note-2013-033 PERF.

[10] M. Hostettler *et al.*, *Luminosity Lifetime at the LHC in 2012 Proton Physics Operation*, CERN-ACC-2013-0032. M. Hostettler et al, *Observations on bunch length histogram splitting and selective emittance blow-up in LHC Beam 1*, CERN-ATS-Note-2013-003 PERF.

[11] A. Apollonio *et al.*, *HL-LHC: integrated luminosity and availability*, TUPFI012, Proceedings of IPAC13.

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WHAT ARE THE REQUIRED MAINTENANCE AND CONSOLIDATION ACTIVITIES TO RUN AT DESIGN PERFORMANCE LEVELS (INJECTORS AND LHC) UNTIL 2035?

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Abstract

Assuming that Linac4 is connected to the PSB in LS2, we will outline the maintenance and basic consolidation works that will be needed to maintain design performance of the LHC and its Injector chain until 2035, with an overall reliability as good as that achieved in the first LHC operation period 2009 to 2013. Using these data we will estimate the shutdown schedule needed throughout this period to complete these maintenance and consolidation works. These estimates will also include the required radiation cool-down periods, time for system re-commissioning and testing as well as the time needed to restart the accelerator chain for LHC colliding beam operation. As some of the consolidation activities needed for the PS and SPS machines are related to the radiation dose taken by the machine equipment (e.g., irradiated cable replacement and magnet renovation) the variation of these time estimates as a function of beam losses in the Injector chain will also be covered.

INTRODUCTION

In order to compare the different upgrade scenarios, all over the accelerator complex, it is essential to set a solid frame, by establishing a baseline scenario, taking into account the optimum periodicity and length of Technical Stops, end of the year technical stops and Long Shut-downs.

The study presented includes only maintenance and consolidation needed to maintain 2012 performance and reliability levels, taking into account the resources availability as well as the cool-down periods with respect to the ALARA principle. It does not include the upgrade of PSB to 2 GeV, the upgrade of the SPS RF system, or the HL-LHC program. The possible time-slots for the connection of Linac 4 to PSB are also presented.

TECHNICAL STOPS

Technical Stops are needed regularly in order to perform the minimum preventive and corrective maintenance. It is estimated that a Technical Stop of 5 days, each 10 weeks is needed to maintain good level of performance and reliability.

END OF THE YEAR TECHNICAL STOPS (YETS)

In addition to the Technical Stops, a minimum time window of 10 weeks is needed in order to perform the legal and necessary annual maintenance of the different systems: cooling and ventilation, cryogenics, 400 kV electrical sub-station, kickers and beam dumping systems, access systems, RF, vacuum, beam instrumentation, power converters, safety systems... (the maintenance of the cooling and ventilation systems, as well as cryogenics installations are the time drivers).

In order to optimize this period, all the maintenance works preventing access to the underground infrastructures (i.e. test of the alarms, maintenance of the Jura sub-stations, …) will be done during the Christmas holidays.

The authors would like to emphasize the necessity of optimizing the cool-down period in the different facilities. This implies not to run with protons in the injectors and the LHC, for at least one month prior to the End of the Years Stops.

LONG SHUTDOWNS

After 3 years of operation in the LHC, each system needs to be stopped and be fully overhauled. The Long Shut-down program includes these recurrent activities as well as the necessary consolidation works.

“Recurrent” activities

In the LHC, the core of the “recurrent “activities are the maintenance of the different systems, and they will last a minimum of 16 months (beam to beam). The Cooling and Ventilation system as well as Cryogenic systems are again the time drivers, while all the other systems will be maintained in the shadow of these operations. These other activities include:

- Septa and kickers systems maintenance, which will last 6 months (but will need a 6 months cool-down period with respect to ALARA principles);
- RF maintenance, which will last 6 months;
- Electrical systems, collimation, vacuum, beam instrumentation…;
- Depending on the performance of cryo-magnets during beam operation, it is certain that a number of magnets will need to be exchanged. The current estimation is that some 20 magnets will need to be exchanges in each Long Shut-down. This will take 6 months (excluding warm-up and cool-down).

In the injectors, the 12 months needed for the maintenance of the cooling and ventilation system will drive the length of the “recurrent” activities. As in the LHC, the other maintenance activities will be performed in the shadow of these operations.

It is already foreseen to replace regularly the irradiated cables in the SPS, to clean-up the cable trays of unused cables, to renovate the SPS surface buildings (as included in the CERN consolidation plan). A roadmap for the preventive maintenance of the injectors magnets has been

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set up: it includes exchange of SPS magnets and renovation of PS magnets.

Long shut-down 2 – LS2

In the LHC, in addition to the "recurrent" activities, compensatory measures are required for the MBW and MQW (installation of shielding and absorbers), and will cause significant work for the magnet group. In the injectors, in order to keep a good reliability level, the following consolidation works are needed on top of the "recurrent" activities:

- The connection of LINAC4 to the PS Booster - 9 months;
- The power converters of TT2 will arrive to their end of life. Their replacement will last 9 months;
- The SPS evacuation systems, the Beam Imminent Warning will have to be renewed– 1 year;
- The fire detection cables, which are made of PVC will have to be exchanged – 1 year;
- The replacement of the SPS access system in order to be compliant with the rest of the chain.

Long-Shut-Down 3 (LS3)

In the LHC, assuming the forecast of integrated luminosity obtained by 2022, some equipment will have to be replaced:

- Inner Triplets at points 1 and 5 which will take 20 months (beam to beam);
- The pumping groups of the arcs which will take 6 months;
- It is also likely that we will have to replace some of the collimators.

It is also assumed that the cryogenic compressors, after 15 years of operation, will need replacing, but this will be transparent for the schedule as it will be done in the shadow of the cryogenic maintenance.

In the injectors, we only consider, for the time being to perform a full survey of the SPS, which is done systematically every 10 years.

Long-Shut-Downs program 4 & 5 (LS4 & LS5)

The current plan for LS4 includes the replacement of the Septa in the LHC (end of life), the continuation of the collimator replacement program, as well as the arc pumping replacement program, and potential replacement of a number of cryo-magnets. No additional activities are foreseen, in the injectors, except than the "recurrent" ones. The consolidation program of LS5, which will take place around 2035 is very hard to even guess, as it is linked to the integrated luminosity and the equipment performance. Nevertheless, we estimate a duration of 20 months for the LHC and 1 year for the injectors.

Overall plan – scenario 1

Scenario 1 includes the connection of LINAC to PS Booster during LS2, and the subsequent overall plan up to 2035. It should be remembered that scenario 1 includes no upgrade in the injectors or in the LHC. Scenario 1 is presented in Fig. 1.

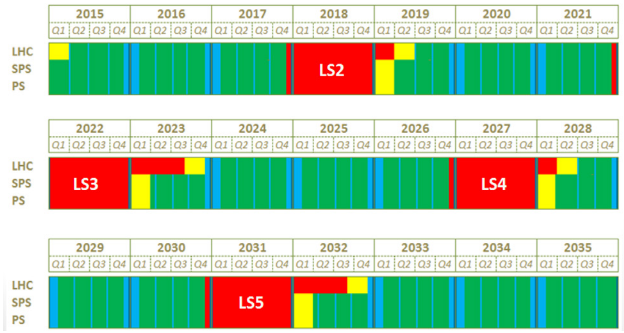

Figure 1: Scenario 1 up to 2035

This scenario results in a beam time fraction of 58% over the 21 years.

LINAC 4 CONNECTION TO PSB

A second scenario was studied with the connection of LINAC4 to PS Booster taking place during an additional Long Shut-down (LS1.5) in 2017. This scenario will push back the subsequent Long Shut-downs.

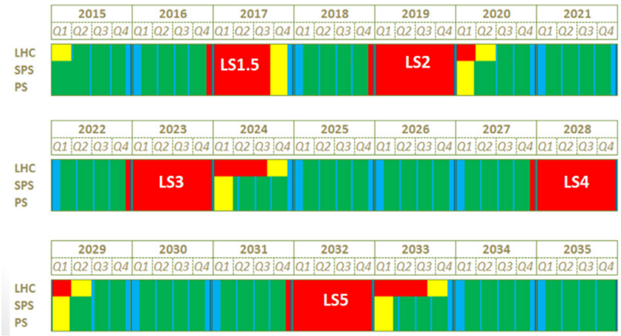

Figure 2: Scenario 2 up to 2035

This scenario is considered to have the following advantages:

- Mitigation of the risk of LINAC2 failure before LS2;
- LINAC4 is connected to the PSB immediately after commissioning in 2016 and is not left idle for 2 years;
- A reduction in the workload at the PSB during LS2;
- A reduction in the workload of general infrastructure services, as part of the LS2 consolidation programs could be done during this LS1.5.

On the other hand, a 9 months stop in the LHC is not sufficient to perform the full maintenance of the cryogenic systems, and will, thus not reduce the length of LS2. LS2 will have to start in 2019, to keep a good level of reliability. As a result, Scenario 2 reduces the potential physics output by one year, between 2015 and 2035.

CONCLUSIONS

Two baseline scenarios have been established, considering the essential maintenance and consolidation works, which are needed to maintain design performance of the LHC and its Injector chain until 2035. These scenarios are established as baselines to be compared with the various upgrade scenarios being considered at this workshop. It should be remembered that they will have to be updated, as decisions are taken concerning the upgrade programs, and the potential additional consolidation activities, which might be needed.

ACKNOWLEDGEMENTS

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WHAT COULD STOP US AND WHEN

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Abstract

The LHC magnet system, as any other electrical machine, could suffer from electromechanical faults that may reduce operability, decrease performance, or, in the worst case, require an intervention and time-consuming exchange of components. Radiation-induced degradation of the mechanical properties of the insulating materials will increase the fault rate. In this report we consider the origins of faults, and attempt a quantitative estimate of the lifetime of the most critical components, the triplet and the resistive magnets around the collimator region.

INTRODUCTION

After the successful operation of the LHC during the period of run I, and the consolidation that will be completed in 2014, a vital question in preparation to long-term exploitation of the accelerator is to understand the limits of the lifetime of the overall technical installation, and especially of the superconducting and normal conducting magnets.

The concept of lifetime, and specific indicators such as the Mean Time Between Failures (MTBF), are a part of well-established engineering practice for components produced in series and operated over sufficiently long time to accumulate relevant statistics and allow analysis such as Weibull plots. Unfortunately, this is not the case for a large part of the magnetic system of the LHC, and especially for the superconducting magnets. These are in several cases first-of-kin productions, barely beyond the prototyping stage (e.g. inner triplet), or the accumulated statistics on failure rate and failure consequence is not appropriate to allow for a meaningful extrapolation (e.g. MB and MQ). An estimate, as attempted here, must hence be based on a one-by-one analysis of the most critical situations identified, and forcibly requires some guesswork.

In this report we recall the most common magnet failure modes, with special accent to superconducting magnets. We then recall the non-conformities and faults experienced in the LHC magnet system, and the limits to radiation dose on its various elements, and especially on the IR triplet and the magnets in vicinity of the collimator regions. These elements are taken as a basis for an extrapolation of the lifetime of the magnets, and a forecast, to the best of the accumulated knowledge, on when LHC operation may be interrupted by a magnet fault requiring a lengthy magnet exchange. This analysis does not cover the LHC injector chain, and is limited to hardware failures, i.e. does not consider performance limitations that are either expected (e.g. maximum energy from practical limits on magnet training, or cooling capacity in the inner triplet) or may be found when re-commissioning the machine after the LS1.

SUPERCONDUCTING MAGNETS FAILURE MODES

A number of papers have been dedicated to the analysis of the reasons for failures of superconducting magnet systems. References [1-3] provide a good summary and basis for statistics. A much-simplified overview of the catalogs reported in the references quoted is given in Fig. 1. In essence, the causes of highest incidence are insulation and mechanical failures, accounting for about 50 % of all recorded failures. It is interesting to note that under-performing superconductor, possibly the most difficult technology of the magnet, is rarely an issue (less than 20 % of recorded failures).

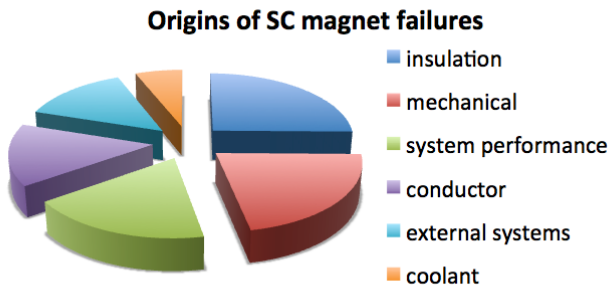

Figure 1. Distribution of failure modes, as recorded on various types of superconducting magnets systems, compiled from data in [2].

In the perspective of the above summary, we can compile the following list of potential trigger mechanisms for mechanical and electrical failures of the LHC magnets:

- Mechanical loading and fatigue on coil, structure, busses. These are associated with magnet powering, where the number of cycles during the machine lifetime is $O(10^4)$ per magnet, and thermal cycles, which are expected to be a few for the whole LHC;
- Singular events and associated thermal and electrical stress. These are essentially natural quenches, typically expected to be of the O(10) per magnet, as well as quenches induced by heater firing, with a somewhat larger total number of events in the range of O(100) per magnet, including commissioning and diagnostics;
- Radiation and associated degradation of mechanical and electrical strength. Doses in the range of O(10) MGy, as expected on the magnets in the triplet region of the LHC P1 and P5, and in the collimator regions of the LHC P3 and P7, are known to affect adversely insulators. We will discuss later these figures, in more detail.

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ELECTROMECHANICAL FAILURES

We consider under this chapter failures such as insulation degradation or shorts induced by mechanical or thermal stress, movements, electrical stress, loss of continuity on vital diagnostics, or degraded continuity (splice resistance) in the electrical circuit.

As mentioned earlier, the statistics on failure modes in the LHC is extremely limited, and, if we try to put it in the framework of a Failure Mode and Effect Analysis (FMEA) the LHC may still be in the "infant mortality" regime of the bathtub curve describing failure rate vs. time. On the other hand, with the energy limitation or Run I, electromagnetic loads have only reached a third of those expected at nominal operation. Finally, it is difficult to provide a strict definition of a failure of electromechanical nature in an LHC cryomagnet. Indeed, many electrical failures may simply lead to a degraded performance (e.g. loss of a corrector magnet), which may be accepted, mitigated or completely compensated.

In spite of the above caveats, we decided to use the present statistics on electrical non-conformities, which provides a record of all faults of electro-mechanical origin, to attempt an extrapolation of the rate of occurrence of such events for the duration of the LHC lifetime, essentially computing a Mean Time Between Failure (MTBF) for the instrumented cryomagnet. By assuming that this rate is identical on all magnet types, we can use this extrapolation to evaluate the probability of a failure of electromechanical origin in any circuit. It should be understood that one such failure does not necessarily entail the complete loss of performance. It is however the experience in LS1 that one such event will eventually call for a maintenance operation at the level of the cold mass, or a magnet exchange, during a technical stop or shutdown period. As we will discuss later, depending on the magnet in question, this may entail long times for the warm-up, radiation cooling and operation that will impact on the integrated luminosity delivered by the LHC.

At the moment of the analysis reported in [4], and excluding the September 2008 incident and consequences, a total of 35 Non-Conformities (NCs) of electromechanical nature were initiated since the beginning of the commissioning of the LHC. Limiting to the cold part of the cryomagnets, 12 were known before the beginning of the electrical quality assurance (ELQA) campaign performed at the beginning of LS1, and 7 additional were discovered during the ELQA campaign. This has led to the exchange of 21 cryomagnets since the beginning of hardware commissioning, 1 in 2007 (suspect of developing inter-turn short), 2 in 2008 (high internal splice resistance), and 18 in 2013 (various issues of excessive internal splice resistance, quench heater performance and insulation, coil insulation).

If we consider each of these NC as a failure. resulting in the exchange of a cryomagnet assembly, we can determine a failure rate (normalized to the total population of cryomagnets, i.e. approximately 1700), and estimate the MTBF [5]. The standard technique to produce stable extrapolations is to fit the failure rate in a Weibull plot, and use the parameters of the fit to compute the normalized failure rate and MTBF of the cryomagnet assembly. Applying one such process we obtain a MTBF in the range of 400 to 500 years, a first guess to be taken cautiously in the light of the various qualifying remarks made earlier.

This MTBF estimate translates in approximately 3 to 4 cryomagnet electrical NCs per year of operation, and at least 10 to 15 magnets exchanges every long shutdown. In particular, the probability of electrical failure of one of the triplet magnets within the next 10 years of operation is 3 %, i.e. 1 magnet. We recall here that while a magnet exchange in the arc is possible within 3 months, for the IR quadrupoles a magnet exchange requires removal of the DFBX and triplet up to the magnet to be exchanged, an operation that may require as long as 1 year.

RADIATION INDUCED FAILURES

This chapter covers electrical and mechanical failures that can be induced by degraded mechanical and dielectric properties, mainly in the coil insulation. A subtle point of radiation degradation is that failure may be gradual, and very localized in space (e.g. reduction of the crack threshold for resins), causing e.g. premature quenches and de-training. At this stage, however, this is only a conjecture, without supporting experimental or evidence.

In accordance to the measurements and projection reported in [6], and the analyses performed in [7] and [8], the hot spots in the LHC will be in the triplet region of P1 and P5, and in the magnets around the collimator region of P7.

In the triplet magnets at P1 and P5, the most critical locations are projected at the IP side of the Q2, and in the MCBX orbit corrector located at the non-IP side of the Q3. The expected dose [7] by LS3 (for an integrated luminosity of 300 fb^{-1}), taking into account a relatively comfortable but realistic 50 % uncertainty, is in the range of 18 to 40 MGy in the worst location of the Q2, and in the range of 13 to 30 MGy in the MCBX. For the magnets around the collimators at P7 [8], and specifically in the D3/D4 (MBW) and Q4/Q5 (MQW), the expected dose, based on dosimetry and simulations, is more than a factor two higher, i.e. from 80 to 90 MGy.

The above dose levels are high. Although it is not possible to provide a deterministic estimate of the failure, which depends much on the local details of material quality, quantity and geometry, values in the range of 20 to 50 MGy are typical for onset of brittle fracture and significant loss of mechanical properties for thermosetting resins, such as those used in the triplet magnets [9-12]. To give useful comparative values, after an irradiation to 20 MGy the bonding strength of the epoxies used in the G11 spacers of the quadrupoles, or to glue the layers of the MCBX, is reduced to 20 % of the value before irradiation. Fracture strength of insulators degrades to 50 % of the value before irradiation, after 20 MGy (G11) to 50 MGy (polyimide). These values suggest that the triplet magnets may experience a failure, possibly initiated by a gradual performance degradation (premature quenches), at a dose level expected for a total integrated luminosity of 300 fb^{-1}. These are values consistent with the initial specification and analysis of the magnet design as described in [13] that was giving a triplet lifetime of 7 years of continuous operation.

Two different resins are used in the normal conducting coils of the magnets around the collimators [8]. While the MBW resin, especially thanks to the presence of fibers, is expected to maintain a significant strength up to a dose in the range of 70 MGy, the conventional resin used in the MQW may no withstand doses in excess of 50 MGy. This is especially true for filler and spacer pieces, whose failure may result in undesirable movements during powering, and induce further electrical faults. In both cases, we see that the expected radiation resistance limits fall short of the projected irradiation dose. It is for this reason that partial protective measures are proposed already during LS1 [14]. A plan has been proposed for LS2 and LS3 to modify this region of the LHC allowing efficient and rapid maintenance (see later), prepare radiation hard spares, and modify the layout to introduce redundancy.

MATTERS OF PERSONNEL DOSE

Reference [6] gives an analysis of the ambient dose measurements performed during LS1, and the extrapolation to the conditions expected at the time of an LS3. The results indicate that the ambient dose in the zone of the normal conducting magnets next to the collimators region may reach values in the range of 1 mSv/h after 6 months cool-down time (obviously higher ambient doses will be registered close to the collimators themselves). The zone of the triplet magnets at P1 and P5 have less severe conditions, with values around 0.1 mSv/h after a 4 months cool-down time.

At the time of LS3, these zones will be classified as limited stay area, requiring at least ALARA level II preparation of interventions. To date, none of these regions is ready for rapid, partially automated maintenance that would allow for distant operation (e.g. from a nearby shielded area). It is hence urgent to envisage scenarios for the disconnection of the magnets, to prepare for the period after LS2 when radiation levels will increased significantly with respect to the present, rather bland situation. At the same time, it is important that spares and upgrades are designed taking into account considerations of dose limitations during magnet installation and removal.

CONCLUSIONS

On the time scale of LS3, and provided the integrated luminosity scales as projected, we should expect aging-related electromechanical and/or radiation induced failures in the triplet magnets (most critical are the Q2 and MCBX) at Points 1 and 5. This projection is coherent with the expected lifetime of the triplet, as defined by the magnet design and construction. By that time, a magnet exchange in the triplet may require a time of the order of 1 year (4 to 6 months cooling time, 6 to 8 months of work, with a scenario that requires to be defined to satisfy the dose limitations and the ALARA principles).

Magnet faults in the collimation region of Point 7, which may be induced by the relatively high level of coil irradiation, can be avoided by a number of protective actions. Partial protection is on-going on the most exposed MBW and MQW, to be continued during LS2 and complemented by radiation-hard spare coils.

It is also clear that selected area of the LHC (triplet, collimators) need to be prepared so that later interventions are possible (repairs, consolidation) in a reasonable time and personnel exposure. This consideration also applies to design of spare components and upgrades, where focus should be on radiation hardness, redundancy and maintainability.

REFERENCES

[1] D.B. Montgomery, Review of Fusion Magnets System Problems, Proc. 13th IEEE Symp. Fus. Eng., 27, 1989.

[2] Y. Iwasa, Case Studies in Superconducting Magnets, Plenum Press, 1994.

[3] J.H. Schultz, in Engineering Superconductivity, J. Wiley & Sons, 2001.

[4] M. Bednarek, Status and first results of the LS1 ELQA campaign, presentation at LSC 31.5.2013.

[5] Nelson, Wayne, Applied Life Data Analysis, Addison-Wesley, 1982.

[6] S. Roesler, The Panorama of the Future Radioactive Zones from Now to 2020, May 2013, https://indico.cern.ch/conferenceDisplay.py?confId=233480.

[7] F. Cerutti, et al., WP10: Energy Deposition and Radiation Damage in Triplet Magnets, April 2013, https://indico.fnal.gov/conferenceDisplay.py?confId=6164.

[8] P. Fessia, MBW-MQW in the LHC, Considerations on expected life and available options, 2013

[9] M. Tavlet, et al., Compilation of Radiation Damage Data, CERN 98-01, 1998

[10] D.J.T. Hill, Radiat. Phys. Chem., 48 (5), 533-537, 1996

[11] E.R.Long, S.A.T. Long, NASA Technical Paper 2429, 1985

[12] R.R. Colman, C.E. Klabunde, The Strength of G-10CR and G-11CR epoxies after Irradiation at 5 K by Gamma Rays, J. Nucl. Mat., 113, 268-272, 1983

[13] J. Kerby, M. Lamm, “INNER TRIPLET QUADRUPOLE MQXB”, LHC-LQX-ES-0002 rev 1.1, EDMS 256806, 2001

[14] TETM 67, 8th October 2013, LSC 24, 11th October 2013.

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PICS IN THE INJECTOR COMPLEX – WHAT ARE WE TALKING ABOUT?

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Abstract

This presentation will identify PIC activities for the LHC injector chain, and point out borderline cases to pure consolidation and upgrade. The most important PIC items will be listed for each LIU project (PSB, PS, SPS) and categorized by a) the risk if not performed and b) the implications of doing them. This will in particular address the consequences on performance, schedule, reliability, commissioning time, operational complexity etc. The additional cost of PICs with regard to pure consolidation will be estimated and possible time lines for the implementation of the PICs will be discussed. In this context, it will be evaluated if the PICs can be implemented over several machine stops.

ASSUMPTIONS

We do not treat in this paper Linac4 and the modifications in the PSB required for the connection of Linac4. Ions will not be treated in this paper either; we refer to the session dedicated on ions.

DEFINITION OF PICS

In this section we will attempt a definition of Performance Improving Consolidation (PIC) items in comparison with pure Consolidation and Upgrade.

Consolidation refers to partial or complete replacement of a system to be performed in order to maintain the present level of performance/availability. Such a 25-year consolidation program was put in place at CERN before the LIU project was launched, and there are numerous items which need to be consolidated in order to ensure reliable operation of the LHC injectors throughout the life time of the LHC, regardless of upgrade scenarios. A typical example is the replacement of the PSB multipole power converters.

Pure upgrade refers to the replacement or addition of a system to improve the performance, which would otherwise not be necessary. Examples are the H^- injection equipment in the PSB, or the modifications of the PS injection for 2 GeV.

Performance improving consolidation (PIC) terms the replacement or upgrade of a system justified by consolidation but with the goal of improving performance. An example would be the change of an ageing PSB power supply by a new one which is more reliable and which can also operate at 2 GeV beam energy.

Using this definition of PICs, there is significant overlap both towards consolidation and upgrade. Items which fall in these grey areas will be highlighted in the following sections.

LIU-PSB

In the following sections we list the PIC items of the LIU-PSB project, we address the risks and give a cost and time estimate.

Magnets

While the modification of the main dipoles (improved water cooling, shimming, retaining plates) is only required for the 2 GeV upgrade and hence a pure upgrade item, some of the magnets in the injection line and in the transfer line to the PS can be considered PIC items. A number of quadrupoles in the BI line are pure consolidation items which need to be changed in all possible scenarios. The partial replacement of magnets in the transfer line to the PS is a combination of consolidation and upgrade and hence a PIC item. The risk of not doing the consolidation consists in magnet failure and unsatisfactory spare situation, in particular for BT.BHZ10. The risks associated with changing the magnets are related to the transport and handling. Presently there is no lifting equipment which can access and handle the heavy dipole magnets. A study is in progress to assess this issue.

RF Systems

The low-level RF of the PSB is at the same time obsolete and inappropriate for future operation with Linac4 and the new high-level RF system. Re-commissioning of the new system will be needed.

The renovation of the high-level RF system consists in replacing the C02 and C04 cavities by new Finemet cavities. The old system is obsolete and will not work with Linac4 intensities and 2 GeV. The new RF system can partially be tested before full installation (prototype cavities in ring 3), but since installation of all required cavities will require removal of the present system, a full test cannot be done beforehand. Further to that technical issues need still to be addressed, e.g. impedance.

Power Converters

The replacement of power converters in the injection line is purely related to Linac4 connection and hence not considered a PIC. However a number of power converters in the rings and notably in the extraction and transfer line can be considered PIC items. Also the main power supply (MPS) can be considered a PIC item, since partial consolidation of the existing MPS would be necessary if it was to continue operation. In particular consolidation of the static VAR compensators (SVC) had been budgeted before the energy upgrade was discussed. Obviously the consolidation part of the budget is small w.r.t. the overall

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cost of a new MPS (3 MCHF compared to a total of 15 MCHF, see section *Cost*).

Beam Instrumentation

Beam instrumentation is also widely a PIC item, since consolidation needs and increased requirements in the frame of the upgrade project are almost inseparable. Main items are the new wire scanners, the new orbit system and replacement/increased number of BLMs. The shortcomings of the present systems are the insufficient transverse emittance diagnostics (improved precision needed for future high brightness LHC beams) and insufficient BLM coverage for operation with Linac4. As any new development the new systems need to be commissioned and tested, where possible before Linac4 connection. The main risk is that this will not be fully possible, which can impact the commissioning time after LS2.

PSB Dump

While the injection dumps are only required for Linac4, and therefore a pure upgrade item, the main dump of the PSB can be considered a PIC. The old dump was in place since the construction of the Booster, and is inappropriate for the intensities expected with Linac4 and 2 GeV beam energy. The dump was replaced by a new one during LS1, this item is therefore completed. There is no risk identified for the operation with the new dump.

Extraction and Transfer

There are reliability and spare issues with some of the extraction and transfer line equipment. This will be addressed at the same time as doing the upgrade to 2 GeV beam energy. The new systems will need to be commissioned, and potential issues with the rise time of the extraction kickers are being addressed.

Cooling and Ventilation

The present system is obsolete and a complete renovation is planned, taking into account the new requirements of an upgraded Booster. This comprises cooling for the new MPS, the new dump, and increased cooling of the main magnets. The CV system is also closely related to RP issues (evacuation of irradiated air). The renovation of the cooling and ventilation system is a potential time driver for LS2.

Transport and Handling Equipment

The entire transport and handling equipment must be renovated in order for it to be ready for the upgrade work planned in the PSB. If the renovation is not done, delays are to be expected for LS2. Studies are needed for removal/installation of the new dump (completed), and for the lifting of some equipment e.g. the large bending magnets in the BTM and BT line. In particular for these dipole magnets presently no handling equipment exists, and studies are underway.

Cost

Table 1 shows the cost overview of the beforehand mentioned LIU-PSB PIC items.

Table 1: Cost of LIU-PSB PIC items

PIC	**Cost [kCHF]**
Magnets	2696
LL RF	1566
HL RF	11732
Power Converters	18451
Beam Instrumentation	2954
Dump	460
Extraction and Transfer	3515
Cooling and Ventilation	6994
Transport and Handling	644 t.b.c.
Total	49012

It is interesting to note that the total cost of PIC items equals approximately the budget of LIU-PSB without the Linac4 related items (total budget 60.8 MCHF). In other words almost all items addressed in the frame of LIU-PSB can be considered PICs. The weighting of what fraction of these items can be associated to consolidation, and which fraction is associated to performance improvement has been done based on the budget figures. The result is that 50% of the total cost can be considered the consolidation part, and the remaining 50% is related to performance improvement. This result is in agreement with the budget estimate performed in the frame of the feasibility study [1], where a total cost of 53502 kCHF was estimated with 27320 kCHF already budgeted in the existing CONS project and 26182 kCHF to be added for the 2 GeV upgrade. The modifications related to the connection of Linac4 were not included at the time.

Time Lines and Increments

In this section we attempt to estimate the time needed to implement the PICs. The implementation of PIC items is constrained by the LHC shutdowns. It is therefore important to assess whether the time needed to implement a given item is needed as a single block, or whether it can be broken up and distributed over several shutdowns. Wherever that is the case, intermediate, shorter shutdowns could be used to advance work and release some pressure from LS2. In Table 2 we summarise the total duration needed to implement each item, the possibility to break up the activity, the minimum single block needed and the earliest start date.

Table 2: Time lines for PSB PIC items

PIC	total duration [m]	split (y/n)	minimum single block [m]	earliest start date
Magnets	4-5	y	3	partly before LS2
LL RF	7	n	7	LS2 digital RF control compl.
HL RF	10.5	n	10.5	LS2
Power Converters	MPS: 1/8.5/2 TL: 12	n	12	LS2
Beam Instr.	9	y	3.5	LS1
Dump	compl.	n		compl.
Extraction and Transfer	7	n	7	LS2
Cooling and Ventilation	7 exclusive +12	n	7/12	LS2
Transport and Handling		y		LS1

The largest time increments are needed by Cooling/Ventilation, Power Converters and RF. The time estimate for CV assumes that the present cooling equipment is dismantled and the new equipment is installed in the same location. As a consequence, during an estimated duration of seven months, no cooling would be available. Therefore presently plans are being worked out to include the CV equipment in the building for the new MPS, which would allow installation while the old system is still operational. The time estimate for the commissioning of the new MPS is composed of one month installation work, 8.5 months of commissioning in the new building (parallel to other work) and two months of final commissioning. The overall duration cannot simply be derived from Table 2. It is not driven by a single intervention, but by the combination of CV, cabling and RF work.

LIU-PS

In the following sections we list the PIC items of the LIU-PS project, we address the risks and give a cost and time estimate.

Magnets

In the frame of the energy upgrade new low-energy correctors are needed. This concerns vertical steerers, quadrupoles and skew quadrupoles. The magnets are considered PIC items. In particular the skew quadrupoles suffer from low reliability due to large thermal heating. The new magnets will need to be recommissioned.

RF Systems

The low-level RF renovation consists in an upgrade of the transverse feed-back amplifiers, in new 1-turn delay feedbacks for the 10, 40 and 80 MHz systems and in a new digital beam control.

On the high-level RF side the renovation of the 10 MHz system is planned. The limitations of the present RF system result in insufficient longitudinal beam stability and degradation of the beam quality. Recommissioning of the new hardware is the only risk identified.

Power Converters

The power converters of the low-energy quadrupoles are planned to be renovated, as well as the ones of the orbit correctors and skew quadrupoles. The same type will be used for newly installed skew sextupoles. Another item is the power amplifiers of the 40/80 MHz RF systems. The present system needs to be consolidated as the number of failures due to large RMS current and old thermal protections is increasing. The new power converters will require recommissioning.

Beam Instrumentation

Items to be renovated are the wire scanners and the BLMs. The present wire scanners are inappropriate for the emittance diagnostics of future high brightness beams. The BLM system is obsolete and a longstanding consolidation item. The new systems will need to be recommissioned.

PS Dumps

The internal dumps of the PS will be exchanged, as the present mechanics is prone to vacuum leaks. Furthermore the precision with which it acts on the trigger is insufficient. The new dumps will need to be recommissioned.

Transverse Damper

The transverse damper of the PS needs new power amplifiers in order to function up to specifications, and eventually a second kicker to separate the function for the two transverse planes. The present system is limited in DC power and bandwidth. No risk has been identified for the new system.

Longitudinal Damper

It is planned to install a Finemet cavity to damp longitudinal and coupled-bunch instabilities. Presently the bunch intensity is limited and incompatible with the HL-LHC parameters. No risk has been identified for the new system.

Radiation Shielding

It is planned to increase shielding on top of extraction septum in straight section 16 and above the route Goward. The situation is already at present not conforming to radiation protection standards. No risk has been identified for the new installation.

Cost

Table 3 shows the cost overview of the beforehand mentioned LIU-PS PIC items.

Table 3: Cost of LIU-PS PIC items

PIC	Cost [kCHF]
Magnets	1000
LL RF	900
HL RF	4200
Power Converters	3065
Beam Instrumentation	1062
Dumps	850
Transv. Damper	350
Long. Damper	1500
Rad. Shielding	3150
Total	16077

The cost drivers of the project are the RF and Power supplies. Radiation shielding is a cost driver as well, but it may be considered a 100% consolidation item. The overall split between what is pure consolidation and what is performance improvement is more difficult than in the case of LIU-PSB. An approach based on weighting yields approximately 40% consolidation and 60% for the performance part.

Time Lines and Increments

Table 4 summarises the time needed to implement the PICs as far as they are known.

Table 4: Time lines for PS PIC items

PIC	total duration [m]	split (y/n)	minimum single block [m]	earliest start date
Magnets	12	y		LS2
LL RF	parallel	y		LS2
HL RF	3	n		LS2
Power Converters	3	n	3	end 2015
Beam Instr.	5	y	1	LS2
Dumps	1	y	0.5	LS2
Transv. Damper	not critical	n		ongoing
Long. Damper				completed
Rad. Shielding				completed

Not all time lines for the PS PIC items are fully defined, but none of them is a time driver. As we will see in the summary, the intervention times are entirely driven by the PSB.

LIU-SPS

In the following sections we list the PIC items of the LIU-SPS project, we address the risks and give a cost and time estimate.

800 MHz Upgrade

The upgrade of the 800 MHz RF system consists in the replacement of the analogue control with a digital one, in a new 1-turn feedback and feed-forward (essential for beam control) in the low level and in the consolidation of the existing power system and the doubling of the available power (needed to match the 200 MHz upgrade). The shortcomings of the present 800 MHz system result in beam instabilities at higher intensity. The voltage is considered insufficient, there is a reliability risk and extra resources are needed to keep obsolete low-level running. The risk of implementing the upgrade lies in the readiness for operation end 2014.

200 MHz Low-level Improvement

The upgrade of the 200 MHz RF system is considered a pure upgrade item, while the improvement of the low-level is a PIC. The present 200 MHz RF system causes extra cost, resources and reliability risk to keep the obsolete systems running. The beam control is performing insufficiently. No risk has been identified for the case that the PIC is implemented.

Beam Instrumentation

Items to be consolidated are the replacement of the obsolete MOPOS electronics and adding a new fibre backbone, the replacement of obsolete BLM electronics using MOPOS fibres, the replacement of the existing wire scanners with new devices and the improvement of the BGI, BSRT, IMM and Head-Tail monitors. The existing systems cause extra cost, resources and reliability risk to keep obsolete systems running. There is presently no reliable transverse beam size measurement, the resolution is insufficient and there is no bunch-by-bunch capability for LHC beams. While no risk has been identified for MOPOS and BLM (deployment in parallel with existing system), HOM heating could be an issue for the new wire scanners.

Dumps

The TIDVG core needs to be replaced with an improved version in order to make it robust against present and future LHC beams. If not done, there is potential damage to the TIDVG for repeated dumping of intense/bright LHC beams. This would result in long (months) recovery in order to condition it with beam. Upgrading the dump will also require a long beam conditioning time.

Scrapers

Construction of additional spares and improvements to local shielding are planned. The present system suffers from insufficient spares, and a breakdown could cause reduced LHC performance (unable to clean transverse tails in SPS). No risk has been identified in case the improvements are done.

ZS Improvement

In order to consolidate the electrostatic septum ZS it is planned to improve the pumping, to reduce the impedance, to improve the ion trap connections and to short-circuit the anodes. The present ZS suffers from sparking, it imposes limitations on other beams and requires longer switch to an LHC cycle. No risk has been identified for the case that the renovation is done.

Kicker Impedance Reduction

The addition of transition pieces in the MKD kickers and a serigraphy of the MKQ kickers are planned. Presently the intensity is limited with high duty cycle beams. This imposes also a limitation on the scrubbing beam time. No risk has been identified for the case that the renovation is done.

Transverse Damper Improvement

The planned renovation of the transverse damper consists in the improvement of the low-level control, in the addition of dedicated pickups and in the consolidation of damper cables. The present system features extra cost and resources to keep obsolete systems running and represents a reliability risk. Furthermore it is not able to properly damp Pb ion beams. No risk has been identified for the case that the renovation is done.

Machine Interlocks (WIC)

It is planned to replace the obsolete electromechanical relays with a PLC solution compatible with the other SPS TL and CERN systems. The aim of the renovation is better reliability and easier maintenance, as well as standard supervision and diagnostics. If not done there is a possible reliability issue, extra maintenance costs, and need for extra resources for keeping obsolete system operational. No risk has been identified for the case that the renovation is done.

LSS1 Vacuum Sectorisation

It is planned to add sector valves around the TIDVG and MKP/D in order to reduce the personnel dose, to protect sensitive equipment and to reduce the pump-down time. Present risks are venting and damage to sensitive or very radioactive equipment, and an increased radiation dose to personnel. No risk has been identified for the case that the renovation is done.

Arc Vacuum Sectorisation

The aim is to reduce the length of the arc sectors by a factor of 2 in order to reduce pumping times. This would also improve the protection against loss of electron cloud scrubbing. If not done the scrubbing times for electron cloud mitigation are longer. No risk has been identified for the case that the renovation is done.

Cost

Table 5 shows the cost overview of the beforehand mentioned LIU-SPS PIC items.

Table 5: Cost of LIU-SPS PIC items (on LIU budget)

PIC	**Cost [kCHF]**
800 MHz Upgrade	
200 MHz Low Level Consolidation	3700
Beam Instrumentation	5600
Dumps	2900
Scrapers	200
ZS Improvement	1000
Kicker Impedance Reduction	4100
Transv. Damper Improvement	1300
Machine Interlocks (WIC)	600
LSS1 Vacuum Sectorisation	800
Arc Vacuum Sectorisation	2500
Total	22700

A tentative split up in “consolidation” and “performance” part of the PIC items has been done on a basis of weighting (not on pure budget figures as in the case of LIU-PSB) and interestingly yields a ratio of 50%/50%.

Time Lines and Increments

Table 6 summarises the time needed to implement the SPS PICs as far as they are known.

Table 6: Time lines for SPS PIC items

PIC	total duration [m]	split (y/n)	minimum single block [m]	earliest start date
800 MHz Upgrade	12	n/a	n/a	Completed in LS1
200 MHz Low Level Cons.	6	y	3	2016/17
Beam Instr.	24	y	3	LS1
Dumps	3	n	3	LS2
Scrapers	0			
ZS Impr.	3	y	2	2015/16
Kicker Impedance Reduction	3	y	2	2015/16
Transv. Damper Improvement	9	y	6	Completed in LS1
Machine Interlocks (WIC)	6	n/a	n/a	Completed in LS1
LSS1 Vacuum Sectorisation	6	n/a	n/a	Completed in LS1
Arc Vacuum Sectorisation	6	y	3	2015/16

As compared to Table 2, it becomes apparent that none of the interventions is exceeding in length the ones imposed by the PSB upgrade.

CONCLUSION

The classification of what is considered a PIC item is often ambiguous, and there are many borderline cases. The same is true for the accounting of what the "performance improvement" part and what the "consolidation" part in a PIC item is. However it is interesting to notice that a 50%/50% split seems to be the average across all machines. It has to be said that this split has been calculated strictly based on the budget figures for the PSB, but it has been estimated for PS and SPS. This estimate tries to weight what the performance and what the consolidation part in each item is, which is not necessarily reflected in the budget figures of the LIU-PS and LIU-SPS projects.

The time lines to implement the PIC items have been analysed with the goal of determining the minimum shutdown length needed for their implementation. The LIU-PSB project includes the time drivers with a minimum shutdown increment of 12 months, determined by CV, Power and RF in combination with the related cabling. The time estimates of PS and SPS are fully in the shadow of the PSB interventions. All time estimates depend strongly on available resources (manpower).

The cost of the PIC items can be summarised as

- LIU-PSB: 50'000 (total budget 60.8 MCHF)
- LIU-PS: 16'000 (total budget 20 MCHF baseline, including all options 32 MCHF)
- LIU-SPS: 23'000 (total budget 77 MCHF)

This corresponds to almost the entire budget of LIU-PSB (without the Linac4 related items), for the PS it corresponds to 80% and for the SPS to 30% of the respective total budgets.

Several items (e.g. beam instrumentation) need to be done in all possible scenarios in order not to compromise performance over the coming years.

REFERENCES

[1] K. Hanke et al, "PS Booster Energy Upgrade Feasibility Study", CERN EDMS 1082646 v.3 (2010).

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LHC PICS: WHAT ARE WE TALKING ABOUT?

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Abstract

This paper will provide an overview of the PICs (Performance Improving Consolidation) providing a brief description of the system.

The contribution of the PICs to the machine reliability will be underlined as this is one of the key parameter to reach the HL-LHC target.

PIC TARGET

The target of the PICs intervention [1] on the LHC machine is to make possible achieve an accumulated integrated luminosity of at least 1000 fb^{-1} in the year 2035, assuming 10 years of operation and starting from an integrated luminosity of 300 fb^{-1}. Other assumptions are 160 days of physics per year and a minimum performance goal of 70 fb^{-1}/year. The different systems to be upgraded will be reviewed listing the necessary equipment and where, along the LHC ring, shall be installed.

INTERACTION REGION IR1, IR5

The interaction region will need to be consolidated because of the accumulated radiation damage [2] and the improvement target is to equip these area with units that would stand higher radiation dose, exploiting the advancement of superconducting technology in order to provide aperture and gradient to achieve stronger focussing.

The main equipment that will be improved are described in the followings paragraphs.

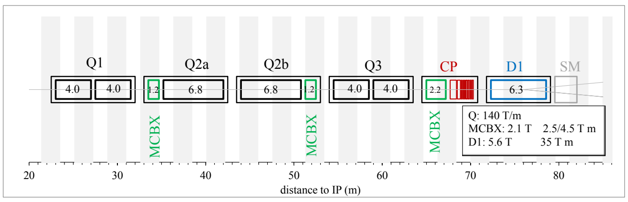

Figure 1: Magnet Layout for the HL-LHC upgrade from Q1 to D1.

The magnet system. The Q1 to D1 lay-out is shown in Fig. 1 [3, 4]. The present low-β quadrupoles in Nb-Ti will be replaced with Nb_3Sn based units. This new magnet (MQXF [5]) will have a coil aperture of 150 mm with an operational gradient of 140 T/m. They are based on the technologies and concepts developed in the past by the US LARP program (i.e. the HQ magnet, see Fig. 2). This unit is presently being designed in a collaboration between CERN (Fig. 3) and the US-LARP.

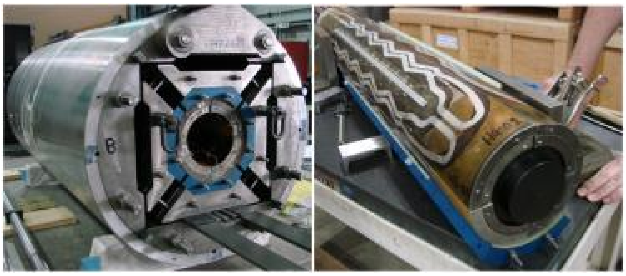

Figure 2: HQ magnet (on the left) and coils (on right) produced and assembled by LARP.

The present LHC uses normal conducting separation dipole D1. These elements will become superconductive in the new HL-LHC PIC configuration. The new D1 will be Nb-Ti based, with an operational field of 5.6 T and a magnetic length of 6.3 m. KEK in Japan is has taken the responsibility to develop the design of this type of magnet.

Figure 3: MQXF dummy coil wound at CERN.

The nonlinear corrector family (b_2, b_3, b_4, b_5, b_6, a_2, a_3, a_4, a_5, $a_{6)}$ will be installed in one cold mass that will be called corrector package and it will be placed between the Q3 and the D1. They will superconductive, using Nb-Ti conductors and they will be based on the superferric technology tested by CIEMAT and CERN during the SLHC-PP program. INFN is presently involved in the design of these units.

The orbit correctors will be also Nb-Ti based. The central field will be 2.1 T and will be produced in two different lengths (1.2 m and 2.2 m) featuring an integrated strengths of 2.5 T·m and 4.5 T·m.

As mentioned the present LHC triplet has lifetime limited by his radiation hardness. In order to increase the radiation hardness [6] of the future units and to cope therefore with the debris of such high integrated luminosity, the magnet will be equipped with beam screens that will present a thick shielding very probably in

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tungsten alloy. The screen is designed to limit the absorbed dose on the coil to 10 MGy for the foreseen 1000 fb^{-1} and to reduce the heat deposition in the superconductor to a safe value of 1.5 mW/cm^3 for a peak luminosity of 3×10^{34} cm^{-2} s^{-1}.

The beam diagnostic will need also to be upgraded in order to cope with the new operation condition of the machine. New cryogenic Beam Loss Monitors (BLMs Figure 4) will be installed on the front face of the cold magnets in order to provide accurate measurements of the losses that could impact the coils. New Beam Position Monitors (BPM) will be installed between Q1 and Q5. The will be designed to minimise transverse impedance and will be equipped with tungsten alloy shielding.

Figure 4: Prototypes of cryogenic BLM installed on the front face of an LHC MQ cold mass.

The powering will be guaranteed via a dedicated **superconducting link** that will connect the magnet in the tunnel with electrical distribution feed-boxes on surface. Here the power converter will be installed in radiation safe area providing quick access for intervention and guarantee that the equipment will be safe from Single Event Upset (SEE) and radiation damage.

The protection scheme will need to be reinforced with new **collimators** and **masks.** The absorber protecting the experiments (**TAS**), the **alignment system** and the **Quench Protection System** (QPS) will also need to be redesigned.

THE COLLIMATION

The upgrade of the collimation system is linked to the operational evidences that will be collected during the run 2 of LHC at 6.5 TeV. This is particularly important for the IR7 system consolidation. The main actions for the collimation are described in the following paragraphs.

New secondary collimators (TCS) built using a more robust material coated with a highly conductive Mo layer. These collimators will allow halving the overall machine impedance budget (linked to the collimator system) from frequencies of the order of 1 MHz. These collimators will be mainly installed in IR7. In IR 6 **new TCLAs** will need to be installed to protect Q4 and Q5, while for the same reasons in IR1 and 5 new **TCTP**s will be necessary.

In IR2, to protect the superconducting magnet in the Dispersion Suppression area during the ion run [7], it will be necessary to install new collimators (**TCLD** Figure 5) in the section presently occupied by the continuous cryostat. In order to do that Nb_3Sn based dipoles with higher central field will be used. This will provide the same integrated field over a shorter length. Replacing therefore 2 LHC MB with these new units it will be possible to free and area where a cryo-bypass will be inserted, providing continuity to the cryogenic and electrical services and allowing space to install warm collimators.

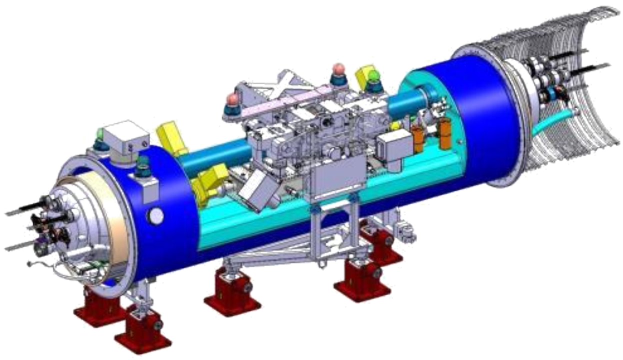

Figure 5: TCLD installed on its cryo-bypass dummy coil wound at CERN.

BEAM DIAGNOSTIC

The LHC beam instrumentation will need to be upgraded to face higher performance requirements and to stand the higher radiation dose

Radiation hard electronics will be installed in the IR3, IR7 and the LSS. Being radiation hard this electronics will be placed very near the measurement point, getting rid of the long cables that today collect severe noise. The present level of noise is such, that, today, it would be difficult to discriminate between it the signals to be read at 6.5/7 TeV.

The BLM electronics and the Synchrotron Light monitor will also need to be modified providing extra capabilities.

To enhance the emittance measurement capabilities, new Beam Gas Vertex detectors (**BGV**) and new **Fast Wire Scanner** will be installed in IR4.

SUPERCONDCUTING LINK

In addition to the superconducting link at IR1 and IR5, that will feed the magnet from Q1 to D1, a new superconducting link will need to be installed during LS2 in **IR7**. This will allow removing the 600 A power converters from the RR73 and RR77, placing them in the TZ76, a radiation safe area. This superconducting link will be only horizontal while the ones in IR1 and IT5 will be horizontal and vertical, but it will be installed already during the LS2.

CRYOGENIC SYSTEM

The first limitation of the present cryogenic system for the LHC will be encountered in sector 4-5, and in particular in the cooling capacity in the temperature range between 4.6 K and 20 K. This is due to the fact that the cryogenic installation of point 4 is also connected to the superconducting cavities that are installed there. Sector 4-5 will be therefore loaded not only with the power to be evacuated from the debris in the final focus in point 5, but also with the loads coming from the RadioFrequency system (RF). In addition, the two systems (magnets and superconducting cavities) are today strictly linked and warming, cooling and maintenance operation have to be performed on both large equipment at the same time. In order to get rid of this bottleneck in term of flexibility and installed cooling capacity, it has been decided to install a new cryogenic plant at point 4 to be connected only to the RF system that would be therefore separated from the other equipment. In addition, the two cryogenic plants would be provide extra redundancy the whole LHC system in case of malfunction of one of the two because the installation will be performed in order to allow connecting each of them to both the systems.

The next cryogenic limitations will be in the sector nearby the high luminosity experiments (IP1 and IP5) because the final focus will be loaded by the heat load coming from the collision point debris. As consequence the installation of two cryo-plants in these two locations to cool the two triplet is proposed. This will provide also easier operation thanks to increase flexibility and redundancy. It is also clear that HL-LHC (also including the three new cryo plants) will not have enough installed cryogenic capacity between 4.6 K and 20 K if the e-cloud effect in the dipoles of the arcs will not be suppressed.

WARM MAGNETS IN THE CLEANING INSERTION

In IR3 and IR7 the normal conducting magnets MQW and MBW will accumulate a very high level of radiation during the LHC and HL-LHC exploitation.

In order to guarantee the survival of these units till HL-LHC installation and beyond it has been decided to protect the most exposed units with tungsten alloy shielding to be installed during LS1. Thanks to this action only 4 MBW in IP7 and 4 MQW in IR3 will probably incur damaged before reaching the 3000 fb^{-1} foreseen by the full HL-LHC installation (US2 [8]) and they will be marginal for the PIC configuration. These units shall be changed with more radiation hard magnets during LS3. In addition it is important to remark that the activation of the equipment will increase while accumulating more integrated luminosity. For a total value of 1000 fb^{-1} and after 6 months of cooling we can still expect to have the magnets in IR7 emitting between 0.3 and 4 mS/h in IR7. These levels are 7 times more then what it was measured in LS1 and it will be about 3 times less (therefore ranges between 1 and 12 mSv/h) respect the values estimated for an integrated luminosity of 3000 fb^{-1} (HL-LHC US2 [7]).

CONCLUSIONS

The PICs, listed for the HL-LHC, target to substitute equipment that are not suitable to stand high radiation dose (i.e. the inner triplet) or would limit the machine operation capability (impedance budget due to TCS). Doing so the system will be upgraded in order to provide enhanced performance and the set of actions here described, is coherent with the objective to harvest 1000 fb^{-1} for 2035.

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- R2E: M. Brugger
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REFERENCES

[1] G. Arduini et al. "PICS: what do we gain in beam performance?", these proceedings.

[2] L. Bottura "What could stop us, when and how long?", these proceedings.

[2] E. Todesco, et al., "Design Studies for the Low-Beta Quadrupoles for the LHC Luminosity Upgrade," IEEE Trans. Appl. Supercond., vol. 23 no. 3, pp. 4002405, June 2013.

[3] E. Todesco, et al., "A first baseline for the magnets in the high luminosity LHC insertion regions," IEEE Trans. Appl. Supercond. 24, submitted for publication.

[4] P. Ferracin, et al., "Magnet Design of the 150 mm Aperture Low-β Quadrupoles for the High Luminosity LHC," IEEE Trans. Appl. Supercond. 24 submitted for publication.C. Petit-Jean-Genaz and J. Poole, "JACoW, A Service to the Accelerator Community," EPAC'04, Lucerne, July 2004, THZCH03, p. 249 (2004); http://www.JACoW.org.

[5] L. S. Esposito, F. Cerutti, E. Todesco, "FLUKA Energy Deposition Studies for the HL-LHC", TUPFI021, IPAC13 Proc., Shanghai, China.

[6] J. Jowett "Future heavy-ion performance of the LHC", these proceedings.

[7] L. Rossi "How to implement all the HL-LHC upgrades (HL-LHC)?", these proceedings.

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PICS: WHAT DO WE GAIN IN BEAM PERFORMANCE*

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Abstract

The beam parameters in the LHC resulting from the Performance Improvement Consolidation (PIC) activities presented in [1][2] will be briefly recalled and motivated assuming that LINAC4 will be operational as PS-Booster Injector. The corresponding limitations in the LHC are outlined. Based on the above performance an estimate of the LHC yearly integrated luminosity will be provided. The evaluation of the need and extent of the performance and reliability improvement for some of the PIC items might imply additional information: the necessary machine studies and the specific operational experience required during Run 2 will be summarized.

BEAM PARAMETERS IN THE INJECTORS AND LHC

The beam parameters expected at extraction from the SPS and at the LHC in collision as a result of the Performance Improvement Consolidation in the Injectors are summarized in Table 1. It is assumed that LINAC4 is connected to the PS-Booster with an H^- injection and that the SPS RF low level system is upgraded to modulate the RF power along the revolution period in order to allow an increase of the bunch population of the 25 ns LHC beam in the SPS. A further increase of the bunch population would require an upgrade of the RF power which is not considered as part of the PIC scenario [3][1].

Table 1: Beam parameters at SPS extraction and at the LHC in collision

	SPS Extraction		LHC collision (min. value – IBS)	LHC collision		
	Bunch population [10^{11}]	ε_n (H/V) [μm]	ε_n (H/V) [μm]	Bunch population [10^{11}]	$\varepsilon_{n\ coll.}$ (H/V) [μm]	Blow-up [%]
BCMS*	1.45	1.45/1.45	1.74/1.45	1.38	1.85/1.85	27
Standard†	1.45	1.85/1.85	2.09/1.85	1.38	2.25/2.25	21

* BCMS=Batch Compression Merging and Splitting scheme providing 48 bunches with 25 ns spacing per PS extraction.
† Standard production scheme providing 72 bunches with 25 ns spacing per PS extraction.

Experience during Run I has shown that beam intensity losses of few percents can be expected during the cycle. Losses are mostly occurring:

- At injection (e.g. satellite bunches preceding or following the main SPS bunch train bunches).
- During the injection plateau and at the start of the ramp (e.g. uncaptured particles or particles leaving the bucket because of large angle intra-beam scattering).
- During the ramp when the collimators are moved closer to the beam to their final settings.
- When the two beams are brought in collision.

An intensity loss of 5% distributed along the cycle is assumed during the LHC cycle from SPS extraction to collisions in the LHC. The losses at high energy are supposed to respect the minimum allowed lifetime of 0.2 h assumed for collimation and cleaning requirements.

A transverse emittance blow-up of 10 to 15 % on the average of the horizontal/vertical emittance has been considered in addition to that expected from Intra-Beam Scattering (IBS). The transverse emittances after injection, ramp and squeeze including IBS blow-up have been estimated and are listed in Table 1 assuming no coupling between the horizontal and vertical planes. This assumption is consistent with the observations made at the LHC at injection and during the cycle in 2012 after correction of the machine coupling. The IBS emittance blow-up has been estimated assuming that the r.m.s. bunch length is kept constant at 10 cm by means of a controlled longitudinal emittance blow-up during injection and ramp when the RF voltage is increasing linearly from 6 MV at injection to 16 MV at flat-top. The duration of the various phases of the LHC cycle used for the simulations is shown in Table 2.

The beam parameters in collision are listed in Table 1 together with the total emittance blow-up from SPS extraction.

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Table 2: Break-down of the turn-around time in the HL-LHC era (Courtesy of M. Lamont) [4].

Phase	Duration [min]
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	20
Ramp preparation	5
Ramp	25
Squeeze/Adjust	40
Total	180

The possible filling schemes in the LHC are presented in Table 3 where the total number of bunches and the corresponding number of colliding pairs is listed for the BCMS and Standard production schemes assuming 6 (respectively 4) PS injections per SPS cycle. 12 non-colliding bunches have been included on request of the experiments for providing beam-gas interaction data necessary for background evaluation.

Table 3: Filling schemes for 25 ns spacing beams (Courtesy of B. Gorini).

Filling scheme	Total	IP1-5	IP2	IP8
BCMS	2604	2592	2288	2396
Standard	2748	2736	2452	2524

Potential issues: electron cloud

Electron cloud is one of the main potential limitations expected for the operation with 25 ns beams. Electron cloud effects include emittance blow-up and heat-load on the beam screen. The experiments conducted in 2012 [5] have demonstrated that:

- Emittance blow-up occurs mainly when multipacting occurs in the main dipoles.
- A reduction of the Secondary Electron Yield (SEY) down to ~1.45 sufficient to reduce significantly the electron cloud build-up in the dipoles at injection can be achieved after a few days of scrubbing.
- The above value of the SEY is not sufficiently low to avoid multipacting in the main quadrupoles at injection and in the dipoles during the ramp.
- A SEY as low as 1.3 can be attained in the beam screen of the triplets indicating that low values of the secondary electron yield are within reach in cryogenic surfaces and in the presence of magnetic fields close to 2 T (magnetic field at the beam screen surface in correspondence of the triplet quadrupoles' poles at 4 TeV).
- No appreciable decrease of the SEY below 1.45 has been observed after scrubbing for several hours in the dipoles at 4 TeV in the presence of electron clouds.
- The maximum acceptable heat load in the Stand Alone Modules (SAM) was limiting the rate at which the beam could be injected while the maximum acceptable heat load in the Arc 34 beam screen was limiting the maximum number of bunches that could be accelerated taking into account the margin for the transients in the beam screen circuits temperature at the start of the ramp. Both these limitations will be relaxed for the 2015 start-up.

The possibility to inject and accelerate beams with the characteristics indicated in Tables 1 and 3 relies on the effectiveness of the scrubbing in reducing the SEY in the dipoles down to 1.4 or lower to avoid multipacting. According to the present experience it will not be possible to reach sufficiently low SEY to suppress multipacting in the main quadrupoles, for that reason an upgrade of the cryogenics is necessary [2].

The new HL-LHC triplets and the D1 separation dipoles in the Interaction Regions (IR) 1 and 5 will have beam screens coated with low SEY materials and, if necessary, they will be equipped with clearing electrodes to suppress multipacting. Similar countermeasures might have to be applied for the triplets and D1 in IR 2 and 8.

Potential issues: impedance

Collimators are the largest source of impedance in the LHC at high frequencies, this might limit their minimum opening and correspondingly the collimation efficiency and the minimum β* reach of the LHC. Interplay between impedance, transverse feedback and beam-beam effects are one of the possible origin of the instabilities observed in 2012 although this is not fully understood yet [6].

The single beam stability limit for the beam parameters corresponding to the various upgrade scenarios are shown in Fig. 1 for the present collimation system (blue line) and for Molybdenum secondary collimators (purple line) approximating the Molybdenum coated Molybdenum-graphite collimators. The collimator settings used for the calculation are presented in [7].

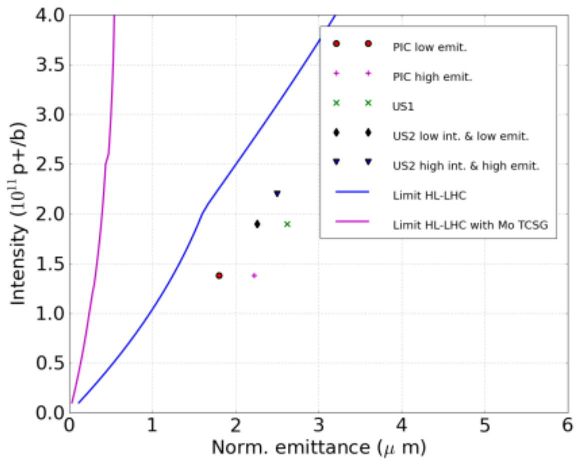

Figure 1: Single-beam stability limits for the present collimation system (blue line) and for the upgraded collimation system with Molybdenum collimators (purple line). PIC low-emit=BCMS beam parameters, PIC high emit.=Standard beam parameters.

The effects of chromaticity (assumed to be 15 units), Landau Octupoles (positive polarity - 550 A) and an ideal bunch-by-bunch transverse damper (50 turns damping time) are included [8].

The beam parameters for all the upgrade scenarios are quite close to the stability limit based on extrapolations from 2012 observations for the present collimation system while "metallic" collimators based on Molybdenum coated Molybdenum-graphite composites offer a comfortable margin and should be implemented already as part of PIC [2].

Potential issues: unknown sources of emittance blow-up

The values of the transverse emittance considered in collision (Table 1) are based on the assumption that the unknown sources of transverse emittance increase (in addition to IBS) can be kept under control so to have a relative emittance increase of less than 15% with respect to the injected beam transverse emittance.

The above goal has not been reached during Run I and emittance blow-up larger than 30% (see Fig. 2) has been observed in particular for one of the two beams (Beam 2) and for one plane (Horizontal). The proposed goal, although challenging, appears to be attainable taking into account the experience in the injectors and taking into account that this is mostly affecting one plane and one beam. The absolute value of the emittance increase seems to be constant irrespective of the initial emittance, pointing to an additive source of blow-up.

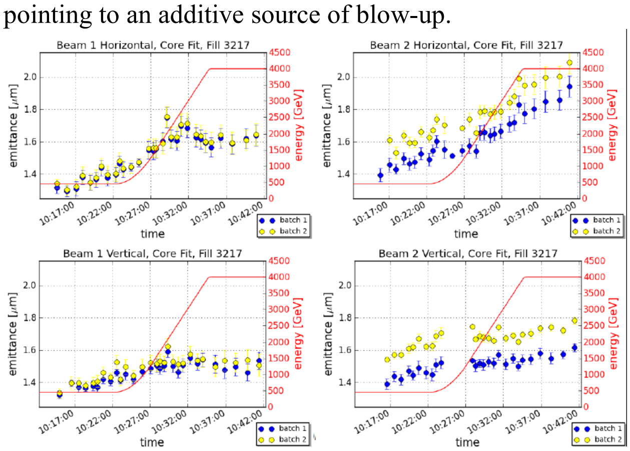

Figure 2: Transverse emittance evolution during a machine development session for Beam 1 (left) and Beam 2 (right) for the horizontal (top) and vertical (bottom) planes, respectively [9].

OPTICS

Given the large aperture of the HL-LHC triplets the minimum β* achievable in IP1 and IP5 is limited by the aperture in the matching section where TAN, Q5, Q4, D2 become aperture bottlenecks.

Two optics [10][11] have been considered for the estimate of the performance of the PIC scenario and adapted to the HL-LHC triplets and nominal LHC layout [12]. These optics configurations have different values of the beta functions at the IP in the crossing (β^*_{xing}) and in the separation plane (β^*_{sep}) so to have the possibility of reducing the crossing angle and reduce the pile-up density:

- β^*_{xing} = 40 cm/ β^*_{sep} = 20 cm.
- β^*_{xing} = 50 cm/ β^*_{sep} = 25 cm.

the latter providing more margin in aperture for a slightly reduced performance [13].

Flat beam optics likely require larger normalized beam-beam separations as compared to round beam optics (i.e. with $\beta^*_{xing} = \beta^*_{sep}$). Larger β* ratios (>2) might imply even larger normalized beam-beam separations although they could provide better performance (see Fig. 3) where the expected peak luminosity is plotted as a function of β^*_{xing} and β^*_{sep} . The lines corresponding to constant β^*_{xing} / β^*_{sep} ratios are indicated in yellow.

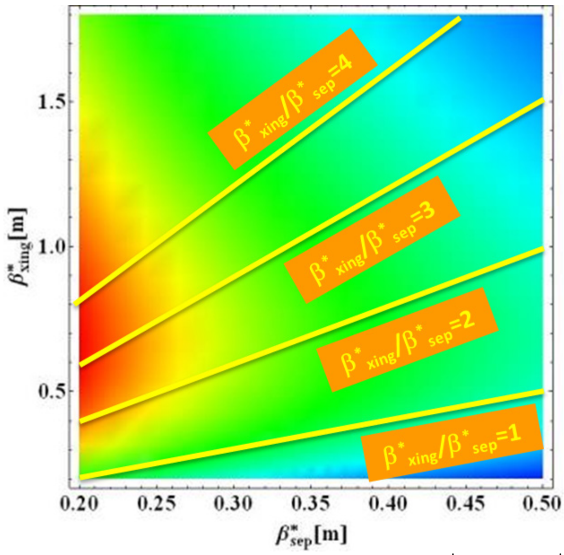

Figure 3: Peak luminosity as a function of β^*_{xing} and β^*_{sep}. The minimum value of the peak luminosity (1.2×10^{34} cm^{-2}s^{-1}) lies the blue area while the maximum value (2.6×10^{34} cm^{-2}s^{-1}) lies in the red area. A constant normalized beam-beam separation of 14 σ has been considered.

PERFORMANCE AT 6.5 TEV

Peak performance

The peak performance at 6.5 TeV has been estimated for the parameters listed in Tables 1, 3 and 4 and it is summarized in Table 5.

A normalized beam-beam separation of 14 σ has been assumed at the first parasitic encounter for the considered β* ratio of 2. This choice is supported by the preliminary results of weak-strong simulations for the beam parameters considered [14][15] but it will have to be validated by further studies and verifications.

Table 4: Longitudinal parameters in collision

Total RF Voltage [MV]	16
ε_L[eV.s] at start of fill	3.6
Bunch length (4 σ)[ns]/ (r.m.s.) [cm]	1.33/10

Table 5: Parameters and estimated peak performance for the two considered optics

	$\varepsilon^*_{n\ coll}$ [μm]	# Coll. Bunches IP1,5	Xing angle [μrad]	BB separation [σ]	L_{peak} [10^{34} cm^{-2}s^{-1}]
BCMS – 40/20	1.85	2592	364	14	2.9
Standard - 40/20	2.25	2736	400	14	2.5
BCMS – 50/25	1.85	2592	326	14	2.7
Standard – 50/25	2.25	2736	360	14	2.3

Integrated performance over one fill

The estimate of the integrated luminosity requires determining the luminosity evolution during a fill. The beam intensity evolution has been evaluated taking into account:

- Burn-off due to luminosity considering a total cross-section of 100-110 mb. The most pessimistic value of 110 mb has been retained for the estimations for the centre-of-mass energy of 13-14 TeV [16][17][18].
- An additional (unknown) source of intensity loss with a lifetime of 200 hours has been considered based on 2012 experience.

The emittance evolution has been determined including the following sources:

- Intra-Beam Scattering (IBS). No coupling has been assumed based on Run I experience;
- Radiation damping.
- An additional (unknown) source of vertical emittance blow-up with a lifetime of 40 hours has been added based on observations during Run I.

A finite difference method in steps of 5 minutes has been considered to properly account for the intensity evolution and of the evolution of the IBS lifetime as a function of the bunch population.

This method applied to 2012 fills with bunch populations comparable to those considered for the PIC scenarios represents fairly well the evolution of the bunch population, relative transverse beam sizes and ATLAS and CMS luminosities as indicated in Fig. 4, 5 and 6 for fill 2728 where no sign of beam instabilities have been observed at high energy.

The initial value of the transverse emittance (assumed to be equal for both beams and both planes) is estimated from the luminosities and average bunch populations measured at the beginning of the physics fill. The initial longitudinal emittance is estimated from the measured bunch length and RF voltage.

The relative beam size evolution is determined by normalizing the beam size measured by the synchrotron radiation beam profile monitor (BSRT) to the beam size measured at the beginning of the fill with the same monitor. Some visible beam size increase is observed for beam 2 only during the fill and immediately following a luminosity optimization scan when the separation of the two beams is varied in IP1 and IP5 to maximize the luminosity in these interaction points.

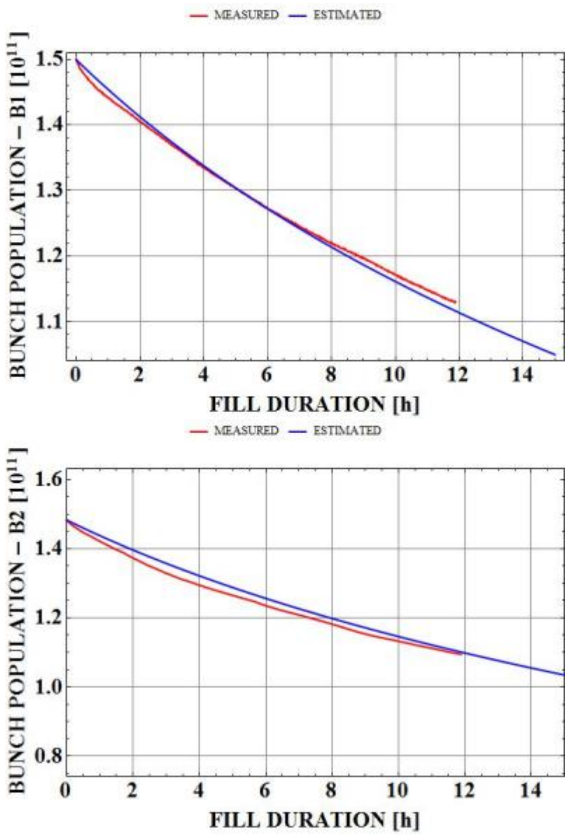

Figure 4. Average bunch population evolution measured (red) during fill 2728 for beam 1 (top) and beam 2 (bottom) compared with the evolution estimated with the model above described (blue).

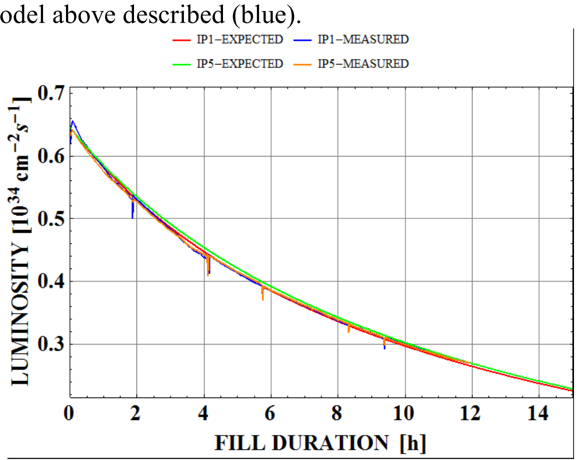

Figure 5. Luminosity evolution as measured in IP1 (blue) and IP5 (red) compared to those expected in IP1 (red) and IP5 (green).

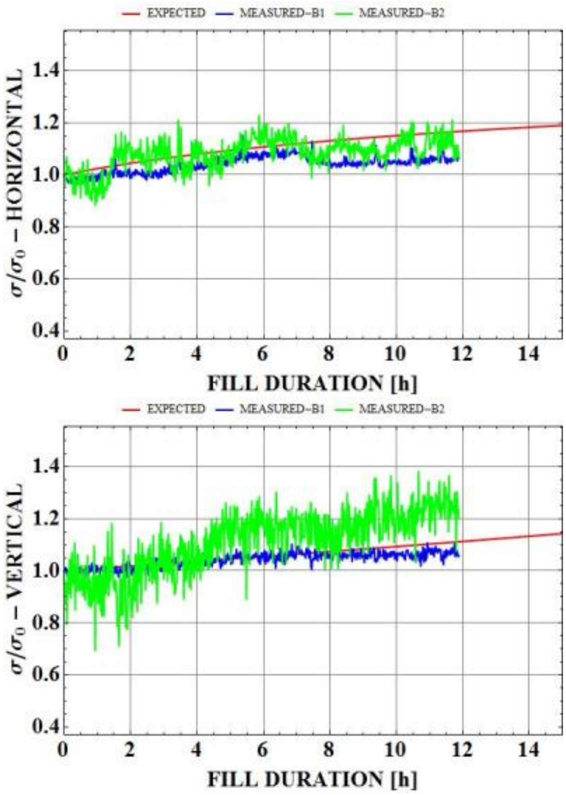

Figure 6. Relative beam size evolution measured by the BSRT in the horizontal (top) and vertical (bottom) planes for beam 1 (blue) and beam 2 (green) during fill 2728. The evolution estimated with the model above described is plotted in red.

Yearly integrated performance

The integrated luminosity targets for the PIC scenario are listed in Table 6.

Table 6: Integrated luminosity targets for the PIC scenario

Int. luminosity end 2021/end 2035 [ab^{-1}]	0.31[19]/1
Number of years of operation after 2021	10
Target luminosity/year [fb^{-1}]	70

Parameters defining the machine performance efficiency are required in order to determine the yearly integrated luminosity starting from the performance during a typical fill.

The *performance efficiency* (η) required to achieve the target yearly integrated luminosity L_{target} is the percentage of scheduled physics time spent for successful fills (including minimum turn-around) defined as:

$$\eta = \frac{L_{target}}{L_{fill}} \frac{T_{around-min} + T_{fill}}{T_{spt}} \times 100$$

where:

- L_{fill} = luminosity integrated during one fill of duration T_{fill}.
- $T_{around-min}$ = minimum turn-around time.
- T_{spt}=time spent in physics for luminosity production.

L_{target}/L_{fill} gives the number of successful fills per year. The performance efficiency (η_{6h}) for T_{fill}=6 h (average value in 2012) and for the optimum fill length based on the luminosity evolution and on the considered turn-around time (η_{opt}) will be evaluated.

We also define the *physics efficiency* (ϕ) as:

$$\phi = \frac{L_{target}}{L_{fill}} \frac{T_{fill}}{T_{spt}} \times 100$$

corresponding to the percentage of the scheduled physics operation time that the machine actually spends in physics. This parameter is particularly important for ALICE and LHCb which are constantly running in levelling mode.

The physics efficiency for T_{fill}=6 h (ϕ_{6h}) and for the optimum fill length (ϕ_{opt}) will be estimated.

Table 7 lists the values of the performance and physics efficiencies for the 2012 LHC run and a series of other parameters contributing to define the integrated performance.

Table 7: efficiency parameters for the LHC 2012 run

Scheduled Physics Time for p-p luminosity production (T_{spt}) [days]	190.5‡
Minimum Turn-Around Time ($T_{around-min}$) [h]	2.2
Average Fill length T_{fill}[h]	6.1
Integrated Luminosity (L_{int}) [fb^{-1}]	23.3
Physics efficiency ϕ [%]	36
Fills that made it to physics (N_{fill})	295
Performance efficiency η = N_{fill}*($T_{around-min}$+T_{fill})/T_{spt}*100 [%]	53.5

The parameters used to estimate the HL-LHC integrated performance are listed in Table 8.

Table 8: parameters assumed for HL-LHC performance estimate.

Scheduled Physics Time for p-p luminosity production/year (T_{phys}) [days]	160
Minimum Turn-Around Time [h]	3
Average Fill length [h]	6 or optimum
Performance Efficiency – goal [%]	50
Pile-up limit [events/crossing]	140
Pile-up Density limit – baseline (stretched) [events/mm/crossing]	1.3 (0.7)

The parameters defining the yearly HL-LHC performance for the 40/20 and 50/25 optics and for the beam parameters and corresponding peak performance listed in Table 1, 3 and 5 are listed in Table 9. It has been assumed that the ATLAS and CMS detectors will be upgraded and will be capable of handling a pile-up as

‡ The 2012 operation had an extended proton physics period (one additional month) as the ion operation was scheduled only for the beginning of 2013.

high as 140 events/crossing. A "visible" cross-section of 85 mb has been considered for determining the pile-up event rate [18].

The optimum fill lengths are determined to maximize the ATLAS and CMS luminosities. In all cases considered the physics efficiency will be larger than 25%. In this case an integrated luminosity of more than 5.5 fb^{-1}/year could be delivered to LHCb provided the detector is upgraded to accept pile-up levels of at least 4.5 events/crossing.

Table 9: Integrated performance estimate for the 40/20 and 50/25 optics for the BCMS and Standard beams

	Lev. Time [h]	Opt. Fill length [h]	η_{6h}/η_{opt} [%]	ϕ_{6h}/ϕ_{opt} [%]	Int. Lumi for η=50% for 6h /opt. fill length [fb^{-1}/y]	Max. Mean Pile-up density/Pile-up [ev./mm]/[ev./xing]
BCMS – 40/20	-	6.5	37/37	25/26	93/94	0.97/84
Standard - 40/20	-	7.3	40/40	27/28	87/88	0.79/69
BCMS – 50/25	-	6.8	39/39	26/27	89/89	0.77/78
Standard - 50/25	-	7.6	43/42	28/30	82/83	0.63/64

From Table 9 we can conclude that:

- All the proposed configurations allow to achieve the target integrated luminosity per year with performance and physics efficiencies compatible with 2012 values.
- Fill lengths are comparable (although slightly longer) to 2012 average, this underlines the importance of a consolidation to increase reliability.
- 50/25 optics provides a reduced pile-up density for a small reduction of the integrated luminosity and it relaxes constraints on aperture/optics.
- The standard PS production scheme provides slightly lower performance but it is more tolerant to additive sources of blow-up.

The maximum acceptable pile-up limit of 140 is not reached for any of the proposed configurations. A limitation of the acceptable pile-up to 45 which is comparable to the values acceptable today by the experiments would on the other hand limit the performance in terms of integrated luminosity per year (see Table 10) that would then become marginal unless a significant improvement in the performance efficiency and (in particular) fill length are reached as compared to 2012 targets. In this case the BCMS and standard filling schemes provide the same performance with a slight advantage for the standard scheme due to the larger number of bunches and therefore larger levelling luminosity for the same pile-up limit. Furthermore the IBS growth times are longer due to the larger transverse emittance of the beam produced with the standard scheme which also makes it less sensitive to additive sources of blow-up.

Table 10: Integrated performance estimate for the 40/20 and 50/25 optics for the BCMS and Standard beams for a pile-up limit of 45.

	Lev. Time [h]	Opt. Fill length [h]	η_{6h}/η_{opt} [%]	ϕ_{6h}/ϕ_{opt} [%]	Int. Lumi for η=50% for 6h /opt. fill length [fb^{-1}/y]	Max. Mean Pile-up density/Pile-up [ev./mm]/[ev./xing]
BCMS – 40/20	6.8	10.2	49/45	33/34	71/79	0.53/45
Standard - 40/20	5.3	9.6	47/44	31/33	75/80	0.53/45
BCMS – 50/25	6.2	9.8	49/45	33/35	71/77	0.45/45
Standard - 50/25	4.5	9.2	47/45	32/34	74/78	0.46/45

The assumed distribution in the fill length (all fills have the same length T_{fill}) is likely optimistic (i.e. over-estimating the performance by 10-20%) [20], but an improvement in reliability could be expected as a result of the consolidation and in particular from:

- The installation of superconducting links in point 1, 5 and 7 allowing to move power converters to the surface away from radiation fields that could induce Single Event Upsets (SEU) or other form of Radiation to Electronics (R2E).
- Upgrade of the cryogenics in point 4 and additional cryogenic plants for IR1 and 5 providing more margin for operation.

KEY QUESTIONS AND STUDIES REQUIRED DURING RUN 2

The attainment of the peak performance indicated in Table 5 relies on the capability of operating the machine with 25 ns beams with negligible emittance blow-up due to electron cloud. For that it will be necessary to demonstrate the feasibility of reducing the Secondary Electron Yield in the beam screen of the LHC dipoles down to 1.3-1.4 by scrubbing with dedicated beams in 2015.

The LHC machine performance in 2012 has been limited by instabilities occurring at high energy during the squeeze and the collision process. The origin of these instabilities is not completely understood and will require additional simulations and experimental studies to quantify more precisely the stability limits for single and two-beams and possible mitigation measures.

Both optics configurations considered feature a smaller β^* in the separation plane (by a factor 2) as compared to that in the crossing plane. The study of the beam-beam effects with flat beams and large tune spread is required to validate this approach. As a possible back-up scenario an optics with β^*=30 cm in the both planes and a normalized beam-beam separation of 12 σ could be considered at the expense of a smaller integrated luminosity (~ -12 %).

Significant emittance blow-up has been during the LHC cycle has been observed in 2012. The tight emittance budget implies the understanding and the minimization of any source of blow-up in addition to IBS and in particular the minimization of the sources of additive emittance blow-up that could strongly affect the performance with small emittance beams like those produced with the BCMS scheme in the PS.

Preliminary tests have been done in 2012 to demonstrate the feasibility of β* levelling, these will have to be further pursued during Run II to validate this levelling scheme as a possible solution for luminosity levelling also for small emittance beams and low β* values implying an excellent control of the orbit at the Interaction Point.

The extrapolations to higher energy of the collimation efficiency, quench limits and beam lifetime must be validated in order to assess the need for the installation of Dispersion Suppressor collimators with 11T dipoles in IR7 [21].

SUMMARY AND CONCLUSIONS

The luminosity target of 70 fb^{-1}/year can be attained comfortably with 40/20 optics with the beams delivered by the injectors as a result of their Performance Improvement Consolidation. This is true provided that the maximum event pile-up acceptable by the general purpose detectors ATLAS and CMS is increased well above the present values.

The beams obtained by the BCMS production scheme in the PS allow reaching a slightly higher performance as compared to those obtained with the standard scheme although the latter are less sensitive to additive sources of emittance blow-up because of their larger transverse emittance.

The 50/25 optics provides more margin in aperture and offers a reduction of the pile-up density below 0.7 events/mm for a small reduction of the integrated luminosity but still within the target.

The key questions and studies required to validate the assumptions made for the performance evaluation have been sketched.

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REFERENCES

[1] K. Hanke, "INJECTORS: PICs: what are we talking about?", these Proceedings.

[2] P. Fessia, "LHC: PICs: what are we talking about?", these Proceedings.

[3] Input provided during the LIU Technical Meetings: http://indico.cern.ch/categoryDisplay.py?categId=4985.

[4] G. Arduini, M. Lamont, T. Pieloni, G. Rumolo, "Implications for Operations", contribution to the "High Luminosity LHC book" to appear in International Journal of Modern Physics A.

[5] G. Rumolo, "Update on Electron Cloud", presentation at the 169th LHC Machine Committee, https://espace.cern.ch/lhc-machine-committee/Presentations/1/lmc_169/lmc_169e.pdf

[6] E. Métral et al., "2-day internal review of LHC performance limitations (linked to transverse collective effects) during run I", https://indico.cern.ch/conferenceDisplay.py?confId=267783.

[7] R. Bruce et al, Aperture calculations and tolerances. Presentation in the 3rd Joint HiLumi LHC-LARP Annual Meeting 13/11/2013. https://indico.cern.ch/contributionDisplay.py?contribId=50&confId=257368.

[8] E. Métral, N. Mounet, "Update on stability limits and collimator impedance upgrade needs", 20th Hi-Lumi Work Package 2 Task Leaders' Meeting, 25/10/2013, https://indico.cern.ch/getFile.py/access?contribId=4&resId=0&materialId=slides&confId=278765.

[9] M. Kuhn, "Emittance Preservation at the LHC", CERN-THESIS-2013-031.

[10] S. Fartoukh, "Towards the LHC Upgrade using the LHC well-characterized technology", sLHC Project report 49.

[11] S. Fartoukh, "Breaching the Phase I optics limitations for the HL-LHC", Proceedings of the Chamonix 2011 Workshop on LHC Performance - Chamonix 2011, Chamonix, France, 24 - 28 Jan 2011, C. Carli, ed., CERN-ATS-2011-005, p. 297-311.

[12] M. Fitterer, R. De Maria, "Optics aspect of PIC and US1 scenarios for HL-LHC", http://ab-dep-abp.web.cern.ch/ab-dep-abp/LCU/LCU_meetings/2013/20130917/LCUMeeting16092013.pdf

[13] S. Fartoukh, private communication.

[14] D. Banfi, J. Barranco, T. Pieloni, A. Valishev, "Required Beam-Beam separation for flat and round beams for 25 ns and considerations on the filling schemes", 19th HiLumi WP2 Task Leader Meeting,

https://indico.cern.ch/getFile.py/access?contribId=0&resId=0&materialId=slides&confId=278323.

[15] D. Banfi, J. Barranco, T. Pieloni, A. Valishev, "Update on crossing angle scaling with bunch intensity", 20th HiLumi WP2 Task Leader Meeting, https://indico.cern.ch/getFile.py/access?contribId=6&resId=1&materialId=slides&confId=278765.

[16] G. Antchev et al., "Luminosity-independent measurements of total, elastic and inelastic cross sections at $\sqrt{s}$=7 TeV", CERN-PH-EP-2012-353.

[17] G. Antchev et al., "Luminosity-independent measurements of the proton-proton total cross section at $\sqrt{s}$=8 TeV", CERN-PH-EP-2012-354.

[18] B. Gorini, private communication.

[19] M. Lamont, "Integrated luminosity scenarios", 6th HL-LHC Coordination Group meeting, 25/7/2013, https://indico.cern.ch/getFile.py/access?contribId=8&resId=0&materialId=slides&confId=264629

[20] J. Wenninger, "Integrated performance of the LHC at 25 ns without and with LINAC4", these proceedings.

[21] "LHC Collimation Review", 30th March 2013, CERN, Geneva, Switzerland, http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=251588

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US1: WHAT DO WE GAIN IN BEAM PERFORMANCE*

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Abstract

The Upgrade Scenario 1 (US1) of the Review of the LIU and LHC Upgrade (RLIU) plans aims at a yearly integrated luminosity of ca. 170 fb^{-1} assuming a total of 160 scheduled operation days for luminosity production and a total of 2000 fb^{-1} over a period of 10 years of operation starting with an integrated luminosity of 300 fb^{-1} after RunII of the LHC. This paper evaluates the required beam parameters for reaching the US1 goals and the required hardware modifications in the LHC and the injector complex. The presented study assumes already all hardware upgrades analysed within the Performance Improving Consolidation (PIC) [1][2][3].

ASSUMPTIONS FOR THE PERFORMANCE EVALUATION

In the following we assume approximately one year long shutdowns every 3 to 4 years with a total of 160 days of scheduled proton-proton physics production every operating year. In order to evaluate the feasibility of a given beam parameter set for reaching the US1 performance goal of 170 fb^{-1} per year we use the concept of a Performance Efficiency which we define as the time fraction needed in a perfect operation cycle (operation with minimum Turnaround time between fills and optimum fill length) for reaching the US1 performance goal. The LHC operational experience showed a Performance Efficiency of 50% during the last year of the RunI operation. In the following we assume a value of 50% as feasible for the HL-LHC operation.

For the Injector Complex we assume the operation of LINAC4, full mitigation of any electron cloud limitations (e.g. vacuum beam pipe coating in the SPS or reduced Secondary Emission Yield (SEY) via beam scrubbing or a wide band feedback system), 2 options for the upgrade of the SPS RF system (low level upgrade and power upgrade) and the operation with either the standard 25ns bunch preparation scheme with 72 bunches per PS cycle, yielding a total of 2760 bunches in each ring of the LHC using 8 SPS injections with 4 PS batches, 3 SPS injections with 2 PS batches and one SPS injection with 1/6 PS batch and resulting in 2736 colliding bunches in IR1 and IR5 for operation with 25ns, or the Batch Compression Beam Merging Scheme (BCMS) for operation with 25ns bunch spacing [4] yielding a total of 2604 high brightness bunches with 48 bunches per PS extraction and up to 6 PS transfers per SPS fill into the LHC and 2592 colliding bunches in the IP1 and IP5.

Figure 1 shows the ideal LHC Turnaround time, amounting to a total of 180 minutes or approximately 3 hours and Table 1 lists the break-down of the minimum LHC Turnaround time.

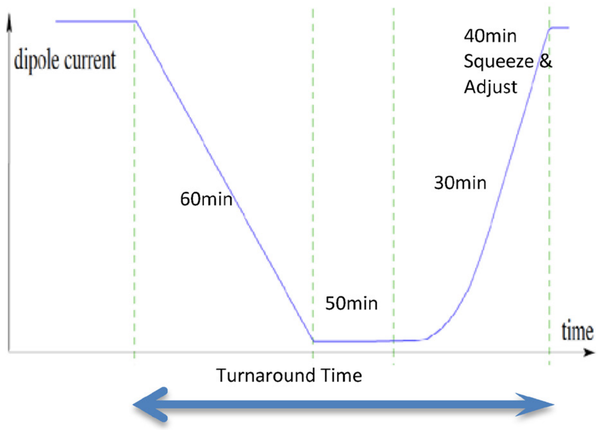

Figure 1: The ideal LHC Turnaround time, amounting to a total of 180 minutes or approximately 3 hours.

Table 1: Break-down of the Turnaround time in the HL-LHC era (Courtesy of M. Lamont) [5].

Phase	Duration [min]
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	20
Ramp preparation	5
Ramp	25
Squeeze/Adjust	40
Total	180

Table 2: Number of bunches and colliding bunch pairs for the standard and the BCMS 25ns filling schemes that are used for this study.

Scheme	Total bunches	IR1/5 Collisions	IR8 Collisions	IR2 Collisions
Standard 25ns	2748	2736	2452	2524
BCMS 25ns	2604	2592	2288	2396

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Table 3: Beam parameters at SPS extraction and at the LHC in collision for 6 cases (PIC, SPS LLRF upgrade, LLRF and SPS power upgrade for the standard and the BCMS 25ns schemes) assuming 20% emittance blow-up and 5% intensity losses between SPS extraction and beam collisions at top energy in the LHC.

	SPS Extraction		LHC collision			
	Bunch population [10^{11}]	**ε_n (H/V) [μm]**	**Bunch population [10^{11}]**	**$\varepsilon_{n\ coll.}$ (H/V) [μm]**	**Blow-up [%] / Intensity loss wrt SPS [%]**	**IBS growth times trans / long [h]**
BCMS* PIC	1.58	1.25/1.25	1.5	1.5/1.5	20 / 5	8/16
Standard† PIC	1.58	1.25/1.25	1.5	1.5/1.5	20 / 5	8/16
BCMS & LLRF	1.45	0.91/0.91	1.38	1.09/1.09	20 / 5	4/12
Standard & LLRF	1.45	1.37/1.37	1.38	1.64/1.64	20 / 5	11/19
BCMS & LLRF & Power	2.0	1.37/1.37	1.9	1.64/1.64	20 / 5	8/14
Standard & LLRF & Power	2.0	1.88/1.88	1.9	2.26/2.26	20 / 5	15/20

* BCMS=Batch Compression Merging and Splitting scheme providing 48 bunches with 25 ns spacing per PS extraction.
† Standard production scheme providing 72 bunches with 25 ns spacing per PS extraction.

Table 4: Beam parameters at SPS extraction and at the LHC in collision for 6 cases (PIC, SPS LLRF upgrade, LLRF and SPS power upgrade for the standard and the BCMS 25ns schemes) assuming emittance blow-up such that the IBS growth rates are longer than the optimum LHC run length.

	SPS Extraction		LHC collision			
	Bunch population [10^{11}]	**ε_n (H/V) [μm]**	**Bunch population [10^{11}]**	**$\varepsilon_{n\ coll.}$ (H/V) [μm]**	**Blow-up [%] / Intensity loss wrt SPS [%]**	**IBS growth times trans / long [h]**
BCMS† PIC	1.58	1.25/1.25	1.5	1.5/1.5	20 / 5	8/16
Standard† PIC	1.58	1.25/1.25	1.5	1.5/1.5	20 / 5	8/16
BCMS & LLRF	1.45	0.91/0.91	1.38	1.8/1.8	98 / 5	13/22
Standard & LLRF	1.45	1.37/1.37	1.38	1.8/1.8	31 / 5	13/22
BCMS & LLRF & Power	2.0	1.37/1.37	1.9	2.65/2.65	93 / 5	22/25
Standard & LLRF & Power	2.0	1.88/1.88	1.9	2.65/2.65	41 / 5	22/25

Table 2 summarizes the number of bunches and colliding bunch pairs for the standard and the BCMS 25ns filling schemes that are used for this study [3].

Assuming a theoretical peak luminosity of 7 10^{34} $cm^{-2} s^{-1}$ and a levelled maximum luminosity for operation of 5 10^{34} $cm^{-2}s^{-1}$ for US1, the luminosity lifetime becomes approximately 10 hours due to luminosity burn-off, the luminosity levelling time approximately 2 hours and the ideal run length for a maximum integrated luminosity becomes approximately 8 hours (2 hours levelling and 6 hours operation with luminosity decay) for the ideal Turnaround time (3 hours) and a perfect operation cycle. The maximum theoretically obtainable integrated yearly luminosity becomes in this case 340fb^{-1} for 160 physics operation days and the US1 performance goal requires Performance Efficiency of 50%. In other words, reaching the US1 performance goals with 50% Performance Efficiency requires a theoretical peak luminosity of approximately 7 10^{34} cm^{-2} s^{-1}.

BEAM PARAMETERS IN THE INJECTORS AND THE LHC

Table 3 summarizes the expected beam parameters at extraction from the SPS and at the LHC in collision as a result of the LIU upgrade in the Injectors with the connection of LINAC4 to the PSB and H- injection and the electron cloud consolidation in the SPS. Table 3 summarizes the parameters for six options: baseline PIC of the injector complex, PIC in Injector complex plus SPS with Low Level RF (LLRF) upgrade and PIC in injector complex plus SPS with LLRF and RF power upgrade and for both for the standard 25ns and the BCMS schemes bunch preparation schemes in the PS. The SPS LLRF system upgrade allows a modulation of the RF power along the revolution period and thus an increase in the bunch population of the 25ns LHC beam in the SPS. The SPS RF power upgrade allows a further increase of the bunch population [1][2]. The energy upgrade of the PSB extraction might also be required for providing larger margins for space charge effects in the PS at injection (implying a full upgrade of the LHC injector complex for the case with SPS LLRF and RF power upgrade). We therefore assume in the following a full LIU upgrade implementation for the US1 study.

The possible filling schemes in the LHC are presented in Table 2 where the total number of bunches and the corresponding number of colliding pairs in IR1 and IR5 are listed for the BCMS and the Standard production schemes assuming up to 6 (respectively 4) PS injections per SPS cycle. 12 non-colliding bunches have been included on request of the experiments for providing beam-gas interaction data necessary for background evaluation.

Experience with the LHC RunI has shown that beam intensity losses of a few percents must be expected during the LHC cycle from SPS to LHC transfer to collisions at top energy in the LHC. Losses are mostly occurring:

- At injection (e.g. satellite bunches preceding or following the main SPS bunch train bunches);
- During the injection plateau in the LHC and at the start of the ramp (e.g. uncaptured particles or particles leaving the bucket because of large angle intra-beam scattering)
- During the ramp in the LHC when the collimators are moved closer to the beam to their final settings;
- When the two beams are brought in collision at top energy in the LHC.

In the following analysis we assume an intensity loss of 5% during the full cycle from SPS extraction to collisions in the LHC.

In addition, an average transverse emittance blow-up of 20% has been considered from SPS extraction to beam collisions at top energy in the LHC. The 20% emittance blow-up is consistent with the LHC operational experience from RunI. All estimates in the following assume that any additional emittance growth due to Intra Beam Scattering (IBS) is small compared to the already accounted for 20% emittance blow-up and imply that the IBS emittance growth rates must be long compared to the average fill length (➔ larger than 10 hours).

The resulting beam parameters for collisions in the LHC are listed in Table 3 together with the assumed total emittance blow-up and intensity loss from SPS extraction to collisions in the LHC at top energy and the resulting IBS emittance growth rates in the LHC at collision energy. One clearly observes that the expected IBS emittance growth rates are too small for all cases, except for the reference PIC cases. Table 4 lists therefore modified beam parameters where we assume a controlled emittance blow-up between the SPS extraction and the LHC injection such that the IBS emittance growth rates are clearly larger than 10 hours during the full LHC cycle. A comparison between Table 3 and Table 4 illustrates that the LHC cannot really benefit from the higher brightness beams that can be generated in the injector complex with full LIU upgrade and with the BCMS scheme. Rather, the LHC performance for US1 will be maximised for the standard 25ns scheme, which offers a slightly larger number of bunches for collisions in IR1 and IR5.

POTENITAL ISSUES FOR HL-LHC WITH US1

Electron cloud

Electron cloud is one of the main potential limitations expected for the operation with 25ns beams. Electron cloud effects include emittance blow-up and heat-load on the beam screen. The experiments conducted in the LHC in 2012 [6] have demonstrated that:

- Emittance blow-up occurs mainly when multipacting occurs in the main dipoles;
- A reduction of the Secondary Electron Yield (SEY) down to ~1.45, which is sufficient to reduce significantly the electron cloud build-up in the dipoles at injection, can be achieved after a few days of scrubbing;
- The above value of the SEY is not sufficiently low to avoid multipacting in the main quadrupoles at injection and in the dipoles during the ramp for beam intensities above nominal LHC beam parameters;
- A SEY as low as 1.3 can be attained in the beam screen of the triplets indicating that low values of the secondary electron yield are within reach in cryogenic surfaces and in the presence of magnetic fields close to 2 T (magnetic field at the beam screen surface in correspondence of the triplet quadrupoles’ poles at 4 TeV);

- No appreciable decrease of the SEY below 1.45 has been observed after scrubbing for several hours in the LHC arc dipoles at 4 TeV in the presence of electron clouds;
- The maximum acceptable heat load in the Stand Alone Modules (SAM) was limiting the rate at which the beam could be injected while the maximum acceptable heat load in the Arc34 beam screen was limiting the maximum number of bunches that could be accelerated taking into account the margin for the transients in the beam screen circuits temperature at the start of the ramp. Both these limitations will be relaxed for the RunII start-up in 2015.

The possibility to inject and accelerate beams with the characteristics indicated in Tables 2 and 4 relies on the effectiveness of the scrubbing in reducing the SEY in the dipoles down to 1.3 or lower to avoid multipacting. According to the present experience it will not be possible to reach sufficiently low SEY to suppress multipacting in the main quadrupoles. For that reason an upgrade of the cryogenics is necessary as part of the LHC PIC [7].

The new HL-LHC triplets and the D1 separation dipoles in the Interaction Regions 1 and 5 will have beam screens coated with low SEY materials and, if necessary, they will be equipped with clearing electrodes to suppress multipacting. Similar countermeasures might have to be applied for the triplets and D1 in IR 2 and 8.

Impedance

Collimators are the largest source of impedance in the LHC at high frequencies, this might limit their minimum opening and correspondingly the minimum β^* reach of the LHC. In the following we assume that eventual impedance limitations can and will be addressed in the LHC by an upgrade of the collimation system to low impedance collimator jaws.

The single beam stability limits are shown in Fig. 2 for different upgrade scenarios for the present collimation system (blue line) and for Mo secondary collimators (purple line) [8].

The effects of chromaticity (assumed to be 15 units), Landau Octupoles (positive polarity of 550 A) and an ideal bunch-by-bunch transverse damper (50 turns damping time) are included in the estimates in Fig. 2 [10].

The beam parameters for the upgrade scenarios in Table 4 are close to the stability limit based on extrapolations from 2012 observations for the present collimation system while “metallic” secondary collimators using a metallic Molybdenum coating offer a comfortable margin and should be implemented already as part of the Performance Improvement Consolidation [7].

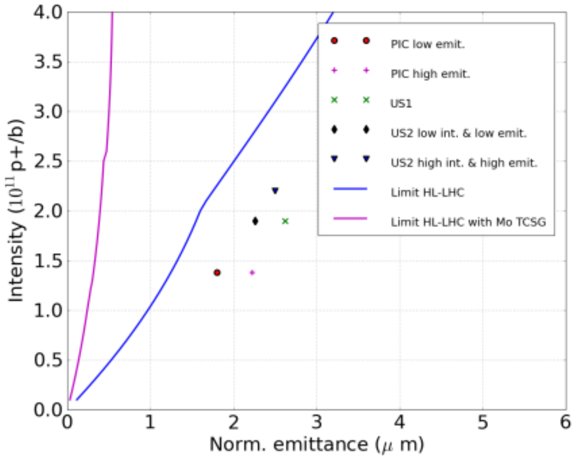

Figure 2: Single-beam stability limits for the present collimation system (blue line) and for the upgraded collimation system with Mo collimators (purple line). PIC low-emit=BCMS beam parameters, PIC high emit.=Standard beam parameters The collimator settings used for the calculation are the assumed HL-LHC baseline with a 2 sigma retraction in IR7 [9].

Unknown sources of emittance blow-up

The required large emittance blow-up between SPS extraction and LHC collision beams for IBS considerations provides comfortable margins for the emittance budget. We therefore do not assume that unknown sources of emittance blow-up are potential issues for the US1.

Aperture limitations

The US1 assumes full implementation of Performance Improving Consolidation in the LHC and therefore assume the replacement of the existing LHC triplet and normal conducting D1 magnets with new, large aperture superconducting magnets in IR1 and IR5.

Pile-up Density

A luminosity of 5 10^{34}cm^{-2}s^{-1} corresponds to approximately 140 events per bunch crossing. Assuming the longitudinal bunch parameters from Table 5 and head on beam-beam collisions this corresponds to a pile-up density of approximately 1 event per mm of luminous region. For the operation with crossing angle and constant luminosity of 5 10^{34}cm^{-2}s^{-1} the pileup density can increase approximately to up to 1.5 events per mm luminous region depending on the detailed beam parameters and the resulting geometric luminosity reduction factor. In case the longitudinal pile-up density limits the detector performance (e.g. 1 event per mm luminous region) the maximum achievable performance of the US1 configurations needs to be readjusted accordingly (e.g. up to 50% reduction of the maximum acceptable luminosity and operation with luminosity levelling).

Long Range Beam-Beam interactions

The full HL-LHC upgrade assumes a 12 σ separation for the parasitic long-range beam-beam interactions of the two counter rotating beams in the common vacuum beam pipes of Interaction Regions of the LHC. The associated loss in performance via the geometric luminosity reduction factor will be compensated for in the HL-LHC via the use of Crab Cavities. The increase in the beam separation with respect to the Run1 configurations has been introduced for reducing the larger accumulated long-range beam-beam interactions with 25ns bunch spacing and the increase in the number of long-range beam-beam interactions with the longer Nb_3Sn triplet magnets. For the US1 scenario we assume operation without Crab Cavities and the performance loss due to the geometric luminosity reduction factor can not be compensated. In order to minimize the performance loss for US1, we assume for US1 a reduced long-range beam-beam separation of 10 σ. The reduction in the long-range beam-beam separation with respect to the nominal HL-LHC upgrade is hoped to be feasible with the use of long-range beam-beam compensation measures (e.g. the use of electric wires or an electron beam with opposite field as generated by the passing proton beams). However, the use of wire compensators poses difficulties for the integration of the wires into the global LHC collimation hierarchy and the use of electron beams is still far from technically feasible. Long-range beam-beam interactions might therefore impose in the end a larger than 10 σ beam separation and might thus limit the performance reach for the US1 operation. Increasing the parasitic long-range beam-beam separation from 10σ to 12σ implies a performance loss between 7% and 15% from the geometric luminosity reduction factor alone, depending on the optics configuration (ca. 7% performance loss for operation with flat and ca. 15% performance loss for operation with round beams). Further performance reduction will come from the aperture loss and the required larger β* values, resulting in a potential net performance reduction between 10% and 25%.

Both aspects, the operationally acceptable minimum beam separation with operation of 25ns bunch spacing at 7 TeV beam energy and for flat optics and the technical feasibility of compensation devices, need to be addressed with high priority during the RunII operation of the LHC.

LHC OPTICS

Given the large aperture of the HL-LHC triplet and D1 magnets, the minimum β* achievable in IP1 and IP5 is limited by the aperture of the remaining matching section devices. In particular, the TAN, Q5, D2 and Q4 elements will become the aperture bottlenecks after the installation of the new HL-LHC triplet and D1 magnets (see Table 4).

Without the use of Crab Cavities the performance reach can be further improved by the use of flat beams at the Interaction Points and a larger beam size in the plane of the beam-crossing angle. The US1 performance reach has therefore been evaluated for two optics configurations: round beam and flat beam options. The minimum β^* reach depends for each option on the actual beam emittance values and the minimum acceptable collimation settings. In the following we assume that β^{**} values of 0.2m are within reach for US1 with round beam operation and β^{**} values of 0.4m/0.2m for US1 with flat beam operation. Table 4 shows the required aperture in terms of n_1 [15] for various optics configurations [11]. The best performance for flat beam operation is expected for a β^{**} aspect ratio of 0.4m/0.1m [12]. However, this aspect ratio seems to be just outside the aperture reach of the LHC with new triplet and D1 magnets but otherwise unchanged Matching Section elements and might imply increased quadrupole strength for Q5 in IR6 and additional sextupole strength.

Table 4: Minimum aperture values calculated using the methods in Ref. [15] in the LHC Matching Sections with new Triplet and D1 magnets but otherwise unchanged Matching Sections [11].

SQUEEZE OPTICS (6.5 TeV)		Minimum over IR1/5 ‡						
β* /[m]	x-angle [μrad]	TAS	MQX	D1	TAN	D2	Q4	Q5
0.1/0.4	±165	16	13.0	13.8	**9.2**	12.5	12.4	12.2
0.2/0.4	±165	22.6	18.5	19.6	13	17.8	17.5	17.4
0.3/0.3	±190	24.6	18.8	19.9	15.2	19.3	18.3	19.6

PERFORMANCE AT 6.5 TEV

The performance reach of US1 has been evaluated for 8 different configurations:

- Round beam configuration with standard 25ns filling scheme and upgrade of the SPS LLRF system.
- Flat beam configuration with standard 25ns filling scheme and upgrade of the SPS LLRF system.
- Round beam configuration with BCMS 25ns filling scheme and upgrade of the SPS LLRF system.
- Flat beam configuration with BCMS 25ns filling scheme and upgrade of the SPS LLRF system.
- Round beam configuration with standard 25ns filling scheme and upgrade of the SPS LLRF system and the SPS RF power.
- Flat beam configuration with standard 25ns filling scheme and upgrade of the SPS LLRF system and the SPS RF power.

‡ The aperture is calculated using the “proposal 1” aperture margins in [11]

- Round beam configuration with BCMS 25ns filling scheme and upgrade of the SPS LLRF system and the SPS RF power.
- Flat beam configuration with BCMS 25ns filling scheme and upgrade of the SPS LLRF system and the SPS RF power.

A beam-beam separation of 10 σ has been assumed for all cases at the parasitic beam-beam encounters. This choice is more optimistic as indicated by the preliminary results of weak-strong simulations [13][14] and might require at least a partial compensation of the long-range beam-beam interactions at the parasitic beam-beam encounters. Table 5 summarizes the assumed longitudinal beam parameters in collision and Table 6 performance targets for US1.

Table 5: Longitudinal parameters in collision

Total RF Voltage [MV]	16
ε_L[eV.s] at start of fill	2.5
Bunch length (4 σ)[ns]/ (r.m.s.) [cm]	1.0/7.5

Table 7 summarizes the resulting performance reach for the different configurations and a peak (levelled) luminosity of 5 10^{34}cm^{-2}s^{-1}.

Table 7: Parameters and estimated peak performance for two options (flat and round beams) options with a long-range beam-beam separation of 10 σ and a levelled luminosity of 5 10^{34}cm^{-2}s^{-1}for two bunch production schemes (Batch Compression Merging Scheme and Standard) and different SPS upgrade scenarios (LLRF only and LLRF plus RF power upgrade).

Case	β^* [m/m]	$\varepsilon^*_{n\ coll}$ [μm]	# Coll. Bunches IP1,5	Xing angle [μrad]	Bunch Intensity [10^{11}]	Theoretical L_{peak} [cm^{-2}s^{-1}]	Integrated Yearly Luminosity [fb^{-1}] / required Performance Efficiency [%]	Optimum Run Length [levelling + decay + Turnaround]
Round Beam BCMS SPS LLRF	20/20	1.80	2592	360	1.38	4.0 10^{34}	219 / 78	0 + 5 + 3
Round Beam Standard SPS LLRF	20/20	1.80	2736	360	1.38	4.4 10^{34}	237 / 72	0 + 5 + 3
Flat Beam BCMS SPS LLRF	40/20	1.80	2592	255	1.38	4.4 10^{34}	237 / 72	0 + 5 + 3
Flat Beam Standard SPS LLRF	40/20	1.80	2736	255	1.38	4.65 10^{34}	258 / 66	0 + 5 + 3
Round Beam BCMS LLRF & Power	20/20	2.65	2592	364	1.9	5.2 10^{34}	317 / 54	0.2 + 5 + 3
Round Beam Standard LLRF & Power	20/20	2.65	2736	400	1.9	5.5 10^{34}	339 / 50	0.6 + 5 + 3
Flat Beam BCMS LLRF & Power	40/20	2.65	2592	326	1.9	5.7 10^{34}	343 / 50	0.8 + 5 + 3
Flat Beam Standard LLRF & Power	40/20	2.65	2736	360	1.9	6.0 10^{34}	363 / 47	1.2 + 5 + 3

Table 8: Parameters and estimated peak performance for different options (flat and round beams) with a long-range beam-beam separation of 10 σ and a levelled luminosity of 2.5 $10^{34}cm^{-2}s^{-1}$ for various bunch production schemes (Batch Compression Merging Scheme and Standard) and full SPS upgrade scenario (LLRF plus RF power upgrade).

Case	β^* [m/m]	$\varepsilon^*_{n\ coll}$ [μm]	# Coll. Bunches IP1,5	Xing angle [μrad]	Bunch Intensity [10^{11}]	Theoretical L_{peak} [$cm^{-2}s^{-1}$]	Integrated Yearly Luminosity [fb^{-1}] / required Performance Efficiency [%]	Optimum Run Length [levelling + decay + Turnaround]
Round Beam BCMS LLRF & Power	20/20	1.85	2592	364	14	5.17 10^{34}	266 / 64	8.3 + 3 + 3
Round Beam Standard LLRF & Power	20/20	2.25	2736	400	14	5.46 10^{34}	271 / 63	9.3 + 3 + 3
Flat Beam BCMS LLRF & Power	40/20	1.85	2592	326	14	5.67 10^{34}	270 / 63	9.2 + 3 + 3
Flat Beam Standard LLRF & Power	40/20	2.25	2736	360	14	6.0 10^{34}	275 / 62	10.2 + 3 + 3

Table 6: Integrated luminosity targets for the PIC scenario.

Int. luminosity end 2021/end 2035 [ab^{-1}]	0.31/2
Number of years of operation after 2021	10
Target luminosity/year [fb^{-1}]	170

A peak luminosity of 5 $10^{34}cm^{-2}s^{-1}$ implies a pile-up density of up to 1.5 events per mm of luminous region. In case the pile-up density is limited by the detector performance one needs to introduce a lower levelled peak luminosity for the US1 evaluation. Table 7 re-evaluates the US1 performance for a levelled peak luminosity of 2.5 $10^{34}cm^{-2}s^{-1}$ (e.g. a maximum pile-up density of ca. 1 event per mm luminous region). Tables 7 and 8 illustrate that the US1 performance goal of 170fb^{-1} per year with a Performance Efficiency of 50% is within reach for scenarios with a full LIU upgrade (LINAC4, e-cloud mitigation in the injector complex and SPS LLRF and RF power upgrade) if the pile-up density in the experiments is not limited (e.g. up-to 1.5 events per mm luminous region are acceptable). In case the pile-up density in the experiments is limited to less than 1 event per mm luminous region, one needs to limit the levelled luminosity to 2.5 $10^{34}cm^{-2}s^{-1}$ and the required Performance Efficiency for achieving an annual integrated luminosity of 170 fb^{-1} increases to 62%, which might still be within reach but will certainly be challenging from the operation point of view.

SUMMARY AND CONCLUSIONS

The luminosity target of 170 fb^{-1}/year can be attained with a Performance Efficiency of 50%, the standard 25 ns filling scheme and a flat beam optics with a β^* ratio of 40 cm/20 cm at the IP and with a full upgrade of the LHC injector complex (an increase of the PS injection energy might be required for obtaining sufficient margins for the space charge effects in the PS) if the HL-LHC experiments are not limited by the pile-up density (number of events per length of luminous region) but only by the total number of events per bunch crossing (we assumed here 140 events per crossing which corresponds to a peak luminosity of 5 $10^{34}cm^{-2}s^{-1}$).

In case the pile-up density is limited to a maximum of 1 event per mm luminous region, one needs to reduce the peak acceptable luminosity to 2.5 $10^{34}cm^{-2}s^{-1}$ in each experiment. In this scenario one requires a Performance Efficiency of a little more than 60% for the production of 170fb^{-1} per year using the standard 25ns filling scheme and a flat beam optics with a β^* ratio of 40cm/20cm at the IP and with a full upgrade of the LHC injector complex. Or, expressed differently, assuming a 50% Performance Efficiency for a levelled luminosity of 2.5 $10^{34}cm^{-2}s^{-1}$ in each experiment, one expects an annual integrated luminosity of 140fb^{-1}, which falls slightly short of the US1 goal considered for the RLIUP workshop but still represents a remarkable performance level for the HL-LHC with PIC only (new triplet and D1 magnets and potentially low impedance collimators) and full LIU upgrade.

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REFERENCES

[1] Input provided during the LIU Technical Meetings: http://indico.cern.ch/categoryDisplay.py?categId=4985.

[2] K. Hanke, "INJECTORS: PICs: what are we talking about?", these Proceedings.

[3] G. Arduini, et al., "PICS: what do we gain in beam performance", contribution to the proceedings of the "Review of the LIU and LHC Upgrades" workshop, CERN, Geneva, 29th-31st October, 2013.

[4] Reference for BCBMS.

[5] G. Arduini, M. Lamont, T. Pieloni, G. Rumolo, "Implications for Operations", contribution to the "High Luminosity LHC book" to appear in International Journal of Modern Physics A.

[6] G. Rumolo, "Update on Electron Cloud", presentation at the 169th LHC Machine Committee, https://espace.cern.ch/lhc-machine-committee/Presentations/1/lmc_169/lmc_169e.pdf

[7] P. Fessia, "LHC: PICs: what are we talking about?", these Proceedings.

[8] E. Métral et al., "2-day internal review of LHC performance limitations (linked to transverse collective effects) during run I", https://indico.cern.ch/conferenceDisplay.py?confId=267783.

[9] R. Bruce et al, Aperture calculations and tolerances. Presentation in the 3rd Joint HiLumi LHC-LARP Annual Meeting 13/11/2013. https://indico.cern.ch/contributionDisplay.py?contribId=50&confId=257368

[10] E. Métral, N. Mounet, "Update on stability limits and collimator impedance upgrade needs", 20th Hi-Lumi Work Package 2 Task Leaders' Meeting, 25/10/2013, https://indico.cern.ch/getFile.py/access?contribId=4&resId=0&materialId=slides&confId=278765.

[11] M. Fitterer, "Update on TAN aperture model and aperture margins for the HL-LHC upgrade", LCU meeting, 15.10.2013, http://ab-dep-abp.web.cern.ch/ab-dep-abp/LCU/LCU_meetings/2013/20131015/LCUMeeting15102013.pdf

[12] S. Fartoukh, private communication.

[13] D. Banfi, J. Barranco, T. Pieloni, A. Valishev, "Required Beam-Beam separation for flat and round beams for 25 ns and considerations on the filling schemes", 19th HiLumi WP2 Task Leader Meeting, https://indico.cern.ch/getFile.py/access?contribId=0&resId=0&materialId=slides&confId=278323.

[14] D. Banfi, J. Barranco, T. Pieloni, A. Valishev, "Update on crossing angle scaling with bunch intensity", 20th HiLumi WP2 Task Leader Meeting, https://indico.cern.ch/getFile.py/access?contribId=6&resId=1&materialId=slides&confId=278765.

[15] R. Bruce, Apertures and protection for HL-LHC layouts (implication of tolerances and review of tolerances based on Run I experience) for different optics configurations (Round/Flat), 3rd Joint HiLumi LHC-LARP Annual Meeting, https://indico.cern.ch/contributionDisplay.py?contribId=50&confId=257368

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UPGRADE SCENARIO ONE: WORK EFFORT

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Abstract

We give an overview of the scenario aiming to gathering 2000 fb^{-1} at the end of the LHC lifetime. The compatibility of the hardware foreseen in the so-called performance improvement consolidation (aiming at 1000 fb^{-1}) is verified, and the requirements on the new hardware are outlined.

SCENARIO

The target of the Upgrade Scenario 1 (US1) is to achieve an integrated luminosity of 2000 fb^{-1} in the year 2035, assuming 10 years of operation and starting from an integrated luminosity of 300 fb^{-1}. This corresponds to double the final target of the Performance Improvement Consolidation (PIC, see [1,2]), with 2.5 times integrated luminosity per year (170 fb^{-1}/year w.r.t. 70 fb^{-1}/year).

For the US1, we assume the same magnetic lattice as in PIC, allowing reach 20/40 cm β^* with flat optics. W.r.t the full upgrade, we do not change the matching section, which becomes a bottleneck for the aperture. The additional performance comes from 40% more protons in the beam (See Table I), namely increasing bunch population from 1.4×10^{11} to 1.9×10^{11}.

In order to be able to achieve this target, US1 relies on two main hardware components: (i) 11 T dipole allowing additional collimators in IR7, IR1 and IR5, and (ii) the beam-beam compensation wire or an equivalent strategy to compensate long range beam-beam interaction caused by the increased bunch population.

For US1, we assume a peak luminosity of 5×10^{34} cm^{-2} s^{-1}, as in the full upgrade. There will be no possibility of luminosity levelling, since the peak luminosity is the maximum reachable for this scenario. For more details on the three scenarios outlined in Table I, see [1], [3] and [4].

Table 1: main parameters of the three upgrade scenario

Scenario	β* (cm)	Bunch pop. (adim)	Emittance (mm mrad)	Peak lumi cm^{-2} s^{-1}	Int. lumi fb^{-1}
PIC	20/40	1.4E+11	2.2E+00	3.0E+34	1000
US1	20/40	1.9E+11	2.6E+00	5.0E+34	2000
US2	15/15 or 7.5/30	2.2E+11	2.5E+00	5.0E+34	3000

RADIATION DAMAGE

We first consider the issue of the radiation damage in the magnets around the IP induced by the collision debris. This damage is proportional to the integrated luminosity. The triplet is designed to have all components able to resist to 25 MGy at 3000 fb^{-1}, so it will be safe for a 2/3 accumulated dose. This is achieved thanks to a thick shielding with tungsten alloy inserts [2,5]. For the rest of the matching section, which will be the same as in the LHC today, we make a first guess by scaling the LHC baseline results [6]. As shown in Fig. 1, one has a maximum of 2 MGy (average) and 4 MGy (local) for 500 fb^{-1} integrated luminosity (see Fig. 1). This provides 16 MGy local for 2000 fb^{-1}, which is within the 20-30 MGy threshold assumed for degradation in the triplet [7]; one should verify that the MQY and MQM has a similar level of degradation.

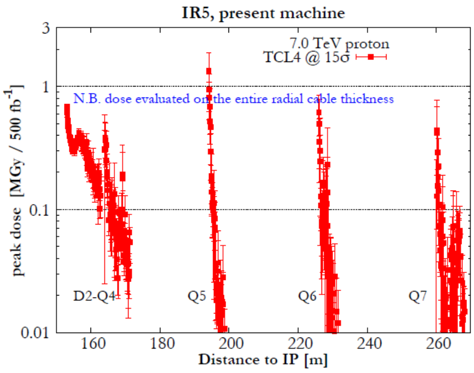

Figure 1: Radiation dose in the LHC matching section for 500 fb^{-1} integrated luminosity [6].

HEAT LOADS

Heat loads are proportional to peak luminosity. The first aspect to be considered is the total cryogenic power. For the triplet+D1 (and correctors), the situation requires an upgrade of the cooling system to be able to evacuate a total heat load in this area of 700 W on the triplet and 600 W on the beam screen. This estimate assumes that the electron cloud does not contribute to the heat load, thanks to a coating of the beam screen. The upgrade of the cryogenic system done in PIC [2] allows to deal with these heat loads.

The second aspect is the local increase of the temperature in the superconducting coils due to the heat load. The triplet+D1 is designed to withstand the peak luminosity of US2 (see Table 1), where there is a wide margin: one expects a heat load of 2 mW/cm^3 (see Fig. 2), which is half of the baseline of the LHC. Quench limits are set at 4 mW/cm^3, that includes a factor three of safety [8]. In the matching section, the rescaling of the baseline gives 1.5 mW/cm^3, (see Fig. 3), which is also well within quench limits.

COLLIMATORS

The plan for collimation in the HL-LHC era will strongly depend on the results of the LHC operation at 7 TeV. With this caveat, today one can define the following baseline [9]: US1 requires the installation of additional collimators in IR7 (2 units), IR1 (4 units) and IR5 (4 units). Here one unit is a 15-m-long module, replacing a LHC dipole, made of two 5.5-m-long 11 T dipole [10] and a 4-m-long collimator module (see Figs. 4 and 5). This is the same hardware to be used in IP2 for PIC scenario.

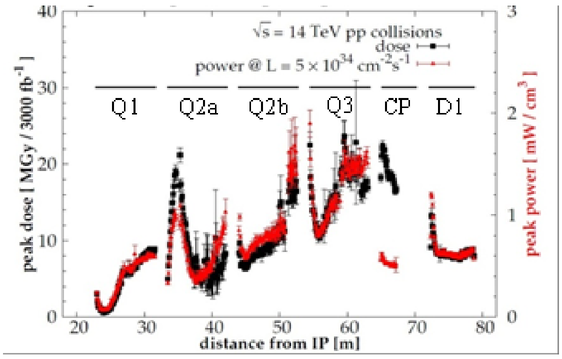

Figure 2: Heat load in the HL-LHC triplet+D1for an integrated luminosity of 3000 fb^{-1} [6].

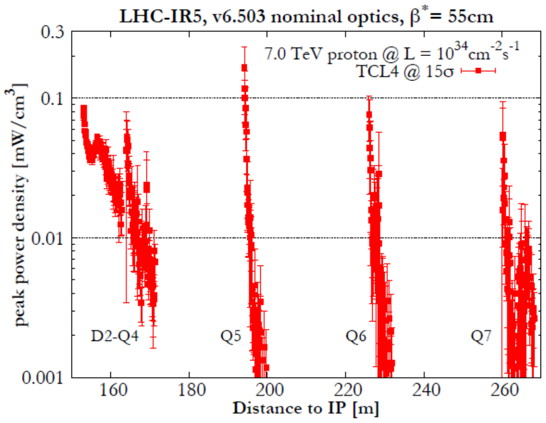

Figure 3: Heat load in the LHC matching section for 500 fb^{-1} integrated luminosity [6].

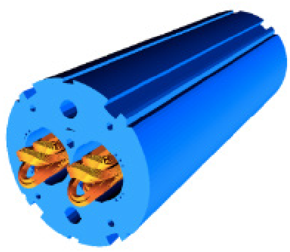

Figure 4: sketch of the 5.5-m-long 11 T dipole [10]

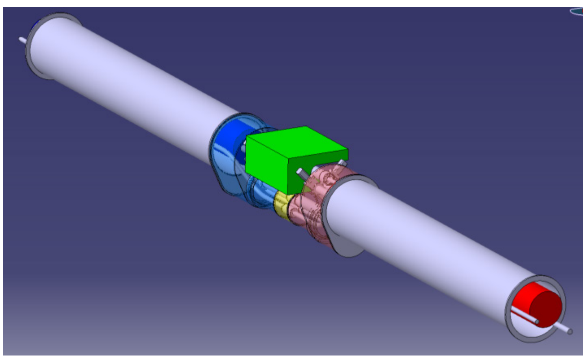

Figure 5: sketch of the 4-m-long collimator module [11]

SUPERCONDUCTING LINK

The aim is to move the power converters of the IR1 and IR5 matching sections from the tunnel to surface. The need of civil engineering is to be verified. This link would rely on the same technology used for the superconducting link for the triplets, based on MgB_2 [12]. A cross section of the triplet superconducting link is shown in Fig. 6. A test of the prototype (both distribution feedbox and superconducting link) is foreseen in 2015, and installation during LS2 or LS3.

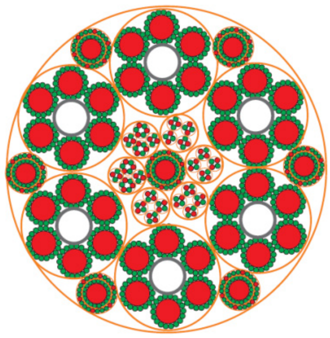

Figure 6: Tentative cross-section of the superconducting link for the triplet+D1.

BEAM BEAM LONG RANGE WIRE COMPENSATOR

The idea of the compensator wire is to use a DC current to cancel the long range beam-beam effect (Fig. 7). In this way one can increase the beam current without the need of opening the crossing angle, i.e. all the additional “fuel” is directly converted in peak luminosity.

The first ideas about a beam-beam wire compensator go back to more than one decade ago [13]. In RHIC it has been showed that a wire can make the beam unstable [14]. In the SPS it has been shown that a wire can compensate the effect of another wire [15]. Even though the physics is solid rock, as it is based on electrostatics, a proof of principle on the LHC is needed to test the device, find the minimal interference with nearby equipment. The timing of this proof is between LS1 and LS2; a couple of years of operation are needed to look at all aspects. The wire should be between separation and recombination dipoles D1 and D2 (see Fig. 8). A first tentative proposal is to place it in the collimators, but it poses considerable problems of integration to avoid to break the collimation hierarchy.

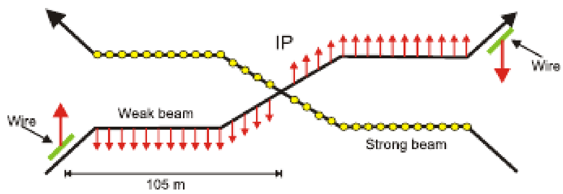

Figure 7: Schematic of long range beam beam compensation wire.

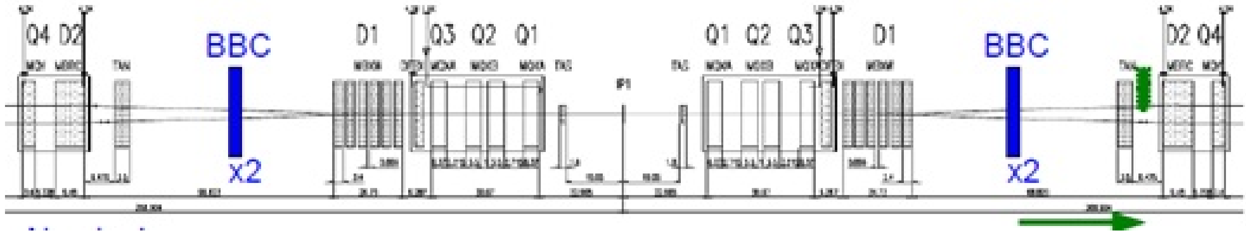

Figure 8: Possible position of long range beam beam compensation wire

Four units would be needed, i.e. two around each high luminosity insertion. There are many delicate points that require further R&R, namely (i) radiation resistance (this is a hot place full of neutrons, and the wire has to stay on the inner side of the beam, i.e. along the neutron beam axis), (ii) compatibility with the flat beams has to be proved, and (iii) integration. As in most hardware related to accelerator physics, evil is in details.

CONCLUSIONS

We outlined the strategy worked out to deliver an integrated luminosity of 2000 fb^{-1} at the end of the LHC lifetime. It relies on a beam intensity increase, which can be tolerated without opening the crossing angle thanks to the beam-beam long range wire compensator. Even though there are no reasons for doubting on the principle of this device, the feasibility, effectiveness, and integrability of this new hardware in the LHC have still to be proved, and a vigorous R&D effort is needed. Plans foresee to have a prototype in the LHC at the end of this decade.

We showed that the hardware will be able to tolerate the radiation damage and the heat load given by a peak luminosity of 5×10^{34} cm^{-2} s^{-1}, and that cryogenics upgrade foreseen for PIC will be enough to deal with the total power to be removed from the accelerator.

Two additional pieces of hardware, namely a superconducting link and an 11 T dipole making room for additional collimators, are needed. They are based on the same technologies which are required for PIC scenario.

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- Collimation: A. Bertarelli, S. Redaelli;
- Cryogenics: L.Tavian;
- PIC scenario: P. Fessia, G. Arduini, R. De Maria.

REFERENCES

[1] G. Arduini, “PICs: what do we gain in beam performances?,” these proceedings
[2] P. Fessia, “PICs: what are we talking about?,” these proceedings
[3] O. Bruning, “How to achieve US1 goals in the LHC ?,” these proceedings
[4] R. De Maria, “How to maximize the HL-LHC performance?,” these proceedings
[5] E. Todesco, et al., “Design Studies for the Low-Beta Quadrupoles for the LHC Luminosity Upgrade,” IEEE Trans. Appl. Supercond., vol. 23 no. 3, pp. 4002405, June 2013
[6] L. S. Esposito, F. Cerutti, E. Todesco, “FLUKA Energy Deposition Studies for the HL-LHC”, TUPFI021, IPAC13 Proc., Shanghai, China.
[7] L. Bottura “What could stop us, and for how long?,” these proceedings.
[8] N. Mokhov, et al., “Protecting LHC IP1/IP5 component against radiation resulting from colliding beam
[9] S. Redaelli, “Do we really need a collimator upgrade?”, Chamonix 2012 workshop on LHC performance CERN-2012-006 352-355.
[10] A. Zlobin, et al., “Quench performance of a 1 m long single aperture 11 T Nb3Sn dipole model for the LHC upgrades” IEEE Trans. Appl. Supercond. 24 (2014) 4000305.
[11] A. Bertarelli
[12] A. Ballarino,”Development of superconducting links for the LHC machine”, EEE/CSC & ESAS Superconductivity news forum (global edition) 2013, and “Design report of task 7.5, High Tc link”, EuCard-REP-2012-003.
[13] J. P. Koutchouk, “Correction of the long-range beam-beam effect in the LHC using electromagnetic lenses” Particle Accelerator Conference (2001) 1681-1683.
[14]W. Fisher, et al., “Experiments with a DC wire in RHIC” Particle Accelerator Conference (2007) 1859-1861.
[15] U. Dorda, et al., “Wire excitation experiments in the CERN SPS”, European Particle Accelerator Conference (2008) 3176-3178.

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LIU: WHICH BEAMS IN THE INJECTORS FULFILL HL-LHC UPGRADE SCENARIO 1 GOALS?

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Abstract

This paper summarizes the current understanding of the issues to be addressed in the injectors in order to fulfill the requirements of the HL-LHC in the framework of the upgrade scenario 1. The required beam parameters in the different accelerators are outlined, and the relevant performance limitations described. Possible beam production schemes are presented, and their relative merits are compared. The upgrades required in the preferred scenario are described and the beam characteristics potentially accessible at LHC injection estimated.

INTRODUCTION

The Upgrade Scenario 1, or US1, is considered as an intermediate possible scenario between realizing a minimum upgrade of the injectors, where only the consolidation would take place plus some performance increase thanks to the modification of the minimum requirements of the renovated hardware (Performance Improving Consolidation - PICS [1]), and the case in which a full upgrade (US2) is accomplished as proposed in [2].

DEFINITION OF UPGRADE SCENARIO 1

HL-LHC defined US1 according to Table 1, with the goal of reaching at least a total integrated luminosity of 2000 fb^{-1}, starting from an already cumulated luminosity of 300 fb^{-1}, and running for 160 days per year. The emittances quoted in Table 1 are given at the start of collisions in LHC. As reported later, a 20% emittance blow up and 5% losses should be used to extrapolate back to the beam parameters at injection, i.e., at SPS extraction.
The interventions or the areas of intervention required by the injectors to approach these parameters are listed in Table 2 and described in detail in the following sections. A special point has to be mentioned for the SPS 200 MHz RF system situation. Originally the full power upgrade of the system, as described in [3], was not included in US1, where only the low-level RF upgrade was considered. Eventually, it became clear that the preferred parameters for HL-LHC are not exclusively the ones mentioned in Table 1, in particular concerning the beam intensity. It is more interesting to exceed the intensity per bunch of 1.5e11 at the expenses of the transverse emittances [6]. For this reason the 200 MHz RF system upgrade has to be included in US1, rendering US1 basically equal to US2 for the part concerning the injectors.

BEAM PARAMETER ESTIMATION

The expected beam performances reachable by implementing only the US1 options were determined under the following assumptions: all upgrades proposed for the injectors should be implemented (see Table 2) and commissioned, as Linac4 should deliver the nominal beam according to the brightness curve presented in [4].
The SPS, as already mentioned, is considered as a special case. The power upgrade of the 200 MHz was not originally included in US1, however it become immediately clear in the US1 performance analysis that this choice would create an intensity limit not compatible with the HL-LHC needs. For this reason, the distinction between US1 and US2 for the injectors, as presented in [2], becomes minimal. It is also assumed that electron cloud will not limit anymore the SPS performances, possibly thanks to the aC coating of vacuum chambers or new scrubbing techniques, or a combination of both [2].
For the preservation of beam quality in the injector complex, i.e., to respect the allocated budgets in terms of losses and emittance blow-up and to reproduce the same performances in terms of beam transmission realized with the 50 and 25 ns beams during Run 1 [4], the following assumption are used:

- the maximum Laslett tune shift due to direct space-charge in the PS should be limited to $|\mathbf{0.31}|$;
- the maximum Laslett tune shift due to direct space-charge in the SPS should be limited to $|\mathbf{0.21}|$;
- the maximum intensity per bunch deliverable by the SPS at extraction *with exclusively the 200 MHz LLRF upgrade* is **1.45e11 p/b** [3];
- the maximum intensity per bunch deliverable by the SPS at extraction *with the 200 MHz LLRF and power upgrade* is **2e11 p/b** [3].

The losses and emittance blow-up budgets are assumed per each machine according to Table 3. Losses and blow-up in the transfer lines should be considered as already included in the limits mentioned. For the LHC, the values refer to the difference between the beam at injection and in collision. Only the 25 ns bunch spacing is considered in this analysis.
Following all these considerations, Table 4 summarizes the beam parameters as requested by the LHC and offered by LIU for the different upgrade scenarios and beam production schemes described in the next section. The scenario

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Table 1: Upgrade Scenario 1 as originally defined. Intensity per bunch and emittances are considered in collision

LHC performance	**Overall Phys. Op. [years]**	$\mathbf{I_b}$ **[10^{11}]**	β^* **[m]**	$\epsilon*$ **[1σ μm]**	$\int\mathcal{L}$**/y [fb^{-1}]**	$\int\mathcal{L}$ **over 10 y [fb^{-1}]**	**Total** $\int\mathcal{L}$ **[fb^{-1}]**
Baseline US1	10	1.5	0.15	1.5	170	1700	2000
Alternative US1	10	1.2	0.15	1	170	1700	2000

Table 2: Upgrade Scenario 1 as defined in the injectors. The activities specific to US1 are indicated in *italic*, whereas the others activities are already at least partially included in PICS [1]

PSB	**PS**	**SPS**
Main and auxiliary Magnets	Beam Instrumentation	Machine interlocks
LL RF	Auxiliary Magnets	800 MHz upgrade
HL RF	Transverse damper	Improved vacuum sectorisation LSS1
Power converters L4 injection	Longitudinal damper	Scraper improvement
Power converters ring, extraction and TL	Radiation shielding	Beam Instrumentation
Beam instrumentation	Power converters	Transverse damper
Beam intercepting devices	Beam dumps	Improved vacuum sectorisation arcs
Linac4 injection	*2 GeV injection*	New TIDVG core
2 GeV extraction and transfer	RF	Other kicker impedance reduction
Vacuum		200 MHz low level improvement
Electrical Systems		*200 MHz power upgrade*
Cooling and Ventilation		SPS and TI2/TI8 protection devices
Installation, Transport and Handling		
Civil Engineering		
Interlock Systems		
Control		

mentioned as *Extended* implies that the LHC would be ready to accept any beam from the injectors in which the intensity per bunch will be larger than 1.45e11 and produced in emittances larger than 1.8 μm (1σ norm.). A more detailed evaluation of the impact of the proposed LIU beam parameters for US1 can be found in [6], but it is already apparent that the LIU US1 scenario well fulfills the needs of the HL-LHC US1 requirements.

Table 3: Allocated budgets for transverse emittance increase and beam losses

Accelerator	$\Delta\epsilon/\epsilon$ **%**	**Losses %**
LHC	20	5
SPS	10	10
PS	5	5
PSB	5	5

25 ns beam production schemes

The production of the 25 ns bunch spacing beam, which remains the baseline for the upgrade, is realized as follows. Linac2, or Linac4 in the future, fills each of the 4 PSB rings at 50 MeV (kinetic energy, 160 MeV for Linac4) on h = 1 (more precisely, each bunch is produced by filling a h=1+2 bucket). Each PSB bunch, in total 4, is transferred to the PS on h = 7 and after 1.2 s, the PS receives two other PSB bunches. On the 1.4 GeV (kinetic E, 2 GeV in the future) PS injection flat bottom, the 6 bunches are captured. Then, after a first acceleration to 2.5 GeV, they are triple split. The resulting 18 bunches are accelerated up to 26 GeV/*c* where two consecutive double splittings produce the final bunch spacing of 25 ns creating a batch of 72 bunches. Prior to the transfer to the SPS, the bunches are rotated in the longitudinal plane to reduce the bunch length to about 4 ns. Up to four consecutive batches of 72 bunches are then injected in the SPS at 26 GeV/*c*, and accelerated to 450 GeV/c prior to extraction to the LHC. The longitudinal emittance is increased in the PS and SPS to reduce longitudinal instabilities, whereas transverse scraping is done in the SPS before reaching the extraction energy to eliminate tails. Beside the classical production scheme, alternative ones were proposed to overcome the brightness limitation of the PSB. The most promising one named BCMS (Batch Compression Merging and Splittings), comprises the injection of 2×4 bunches on the 9th harmonic in the PS, batch compression from h=9 to h=14, bunch merging followed by a triple splitting all done at low energy instead of the triple splitting only. These evolved RF gymnastics are performed at an intermediate kinetic energy (E_k= 2.5 GeV) to avoid transverse emittance blow up due to space charge and to relax the requirements on the longitudinal emittance at injection. The resulting 12 bunches are accelerated to the extraction

Table 4: LHC requirements vs. injector performances after US1. The transverse emittances are the average of the two transverse planes.

Scenario	I_b [10^{11}]	$\epsilon*$ [1σ μm]	Evaluation point
US1 requirements (LHC collision/injection Baseline)	1.5/1.58	1.5/1.25	in LHC
US1 requirements (LHC collision/injection Alternate)	1.2/1.26	1/0.83	in LHC
US1 *Extended requirements (LHC collision/injection)*	> 1.45	> 1.8	in LHC
Linac4 + 2 GeV + SPS LLRF upgrade US1 (PS Standard scheme − 72 bchs)	1.45	1.37	at SPS extr.
Linac4 + 2 GeV + full SPS upgrade (PS Standard scheme − 72 bchs)	2.0	1.88	at SPS extr.
Linac4 + 2 GeV + SPS LLRF upgrade (PS BCMS scheme − 48 bchs)	1.45	0.91	at SPS extr.
Linac4 + 2 GeV + full SPS upgrade (PS BCMS scheme − 48 bchs)	2.0	1.37	at SPS extr.

flat top where two bunch splittings occur to obtain the final 25 ns bunch spacing (only one splitting is done for the 50 ns bunch spacing) as for the nominal scheme. The advantage with respect to the traditional scheme results from the smaller splitting factor of the PSB bunches (6 instead of 12). Before extraction to the SPS, 25 ns spaced bunches have the same transverse emittance but twice the intensity. Beams will be produced according to this scheme for the LHC Run 2.

Challenges of traditional schemes and proposed solutions

The double injection in the PS needed to maximize the number of bunches after the longitudinal splitting requires also very high intensity injected in the PSB. Every PSB bunch is split up to 12 times to get finally 72 bunches at 25 ns spacing at PS extraction, but fewer times for BCMS. This requires Linac2 to inject a high intensity beam with a limited brillance, due to the multi-turn injection process and large space-charge (see [4]). This issue will be solved with the connection of Linac4, which will bring the injection energy from 50 MeV to 160 MeV, a clear advantage for space charge limitations, but also will use H^- instead of protons, making the transverse painting more effective. It is expected that the brilliance of the PSB could be doubled thanks to the new linac [4].

Once the first batch is injected from the PSB to the PS, there is a 1.2 s long waiting time on the PS flat bottom before the second injection can be delivered. During this period, the beam has a very large tune spread induced by the direct space charge, while the synchrotron period is of the order of 1 ms and very large chromaticity in absolute value. The beam, due to the synchrotron motion, crosses many times the integer and the $4q_v$=1 resonance, creating transverse emittance increase and beam losses. The most robust solution to avoid this limitation is, for the fourth time in the PS history, to increase the injection energy, this time from 1.4 GeV to 2 GeV [5]. The reduction of direct space charge effect thanks to the energy increase leaves just enough space in the tune diagram to accommodate the tune shift expected for the future HL-LHC type beams.

Once the triple split beam is accelerated, right after transition crossing, coupled bunch longitudinal instabilities are observed. The consequences are beam losses and a significant variation of longitundinal emittance and intensity along the extracted batch. This lack of reproducibility is a major source of losses, in particular capture losses, in the SPS. The preferred solution for this limitation is the use of a longitudinal damper, a function provided by a newly installed Finemet® cavity. Electron cloud is regularly observed on the extraction flat top, even if there is no evident sign that the beam quality is affected. There is instead a clear horizontal instability appearing, together with electron cloud, if the bunches are shorter than nominal or if the beam is kept artificially in the machine 50 ms longer than necessary. In case this becomes a limitation for the future beams, it was shown that the transverse damper can effectively delay the instability by about 10 ms.

The limitations in the SPS come again from the long waiting time at flat bottom due to the multiple injections (up to 5 from the PS), and by the lack of RF power during acceleration and at flat top. An upgrade of the 200 MHz RF system is then proposed, and it turned out to be necessarily part of US1 for the injectors to be able to fulfill the intensity needs of the LHC. Another major limitation of the SPS could be caused by electron cloud effects resulting in pressure rise, beam instabilities, emittance growth and losses. As presented in more detail in [2], it is commonly accepted that either scrubbing, or coating with aC all or a part of the vacuum chambers, or a combination of both will solve the electron cloud issue after LS2.

Summary of US1-PSB

The two main upgrades of the PSB concern the injection and extraction processes. At injection, Linac2 will be replaced by Linac4, with a more modern H^- injection at 160 MeV instead of the old-fashioned proton injection at 50 MeV. This will permit the doubling of the beam brightness.

The new Linac4 requires the complete exchange of the injection elements: a new painting scheme (in 4 or 6 dimensions) with charge-exchange will replace the proton injection with transverse painting. The injection region design shows already that the integration of the different devices is clearly challenging.

Table 5: Upgrade Scenario 1

	2 GeV-w/o 200 MHz	2 GeV-with 200 MHz	Implication if not done
Linac4 connection	Commissioning of Linac and PSB injection		Space charge limit in PSB
PSB to PS at 2 GeV	Commissioning of extraction-injection devices		Space charge limit in PS
Longer bunches for PSB to PS	To be tested to assess full gain		Space charge limit in PS
PS T-damper for Headtail	Low risk, Headtail as today with ξ_x control		Losses
PS Transition crossing	Stable beam expected	More studies needed	Large losses
e-cloud PS	T-Damper can be used. BCMS should be better		Emittance blow-up
SPS Space charge	The PS limit is reached before the SPS		
SPS 200 MHz upgrade	Max. intensity 1.45e11 p/b	Max. intensity 2e11 p/b	
e-cloud in SPS	Assumed as solved. BCMS should be better		Losses/emittance blow-up

The new extraction energy will bring the main magnets very close to their maximum capabilities, whereas many of the auxiliary systems will need to be replaced. A new POPS-like main power supply will replace the existing one. Concerning the extraction elements in the ring, a series of tests will confirm which ones are not suitable for the new operation, whereas the recombination kickers will be replaced. The PSB-PS transfer line will become PPM and all the principal magnets will be replaced, with the possibility of operating different optics for LHC and fixed-target beams. The PSB external dump will be replaced to cope with the future high-power beams.

Summary of US1-PS

The increase of the injection energy to 2 GeV is needed to reduce space-charge-induced transverse emittance blow-up experienced by the first batch injected on the flat bottom. The new 2 GeV injection requires new injection elements and power converters, (septum, kicker, injection bumpers). In addition to that, new magnets and power converters for orbit correctors and lattice quadrupoles used at low energy will also be produced to cope with the higher injection energy. Unlike the PSB, there is no need for a new MPS.

Headtail instabilities on the injection flat bottom, which are currently cured by introducing linear coupling, will also be controlled thanks to the power upgrade of the transverse damper together with the chromaticity control needed to avoid high order modes.

A fast vertical instability, which was extensively studied on single bunch beams, was observed also on a special high-intensity single-bunch LHC-type beam. Even if the future HL-LHC beams should be stable at transition, future studies with small longitudinal emittance beams will be done to confirm the extrapolation from past measurements.

As mentioned, the longitudinal coupled bunch instability, if not cured, would limit the maximum intensity per bunch well below the 2.5e11 p/b of the future HL-LHC type beam. A new dedicated longitudinal damper, based on a Finemet© cavity and a new LL-RF system is being installed during LS1.

As mentioned e-cloud is observed during the 25 ns beam production but with no influence on beam quality, so this is not expected to be an issue in the future. In any case, studies carried out during the 2012-2013 run [7], proved that the transverse damper can effectively delay the appearance of the instability. In an alternative scheme, a faster final phase rotation may also be used. If e-cloud would turn out, even after all the countermeasures deployed, to be a limitation, beam production schemes with reduced number of bunches, 48 for example, might be used instead. This of course would cause a minor reduction of the number of bunches in the LHC [8], but would still make it possible to approach the HL-LHC requirements.

Summary of US1-SPS

Amongst the different systems requiring an upgrade [2] to cope with the intensity increase for the HL-LHC, the RF system is the most affected by major changes. The beam intensity in the SPS is presently limited by longitudinal instabilities on the ramp and at flat bottom in combination with beam loading in the travelling wave cavities. During acceleration, done with the 200 MHz system alone, the beam becomes longitudinally unstable for an intensity of about 2-3 10^{10} ppb for the 25 ns bunch spacing. Presently this is mitigated by the 800 MHz RF system operating in bunch-shortening mode and a significant controlled longitudinal emittance blow up from 0.35 eVs to 0.5 eVs done with the 200 MHz system [9]. The solution proposed to overcome this limitation is the upgrade of the 200 MHz system, with an increase of the available RF power by at least factor of 2 obtained by increasing the number of cavity modules and by rearranging sections to reduce the impedance by about 20% [9]. As an intermediate step, in principle, it should be possible to operate the RF in pulsed mode (after consolidation) to increase the available power seen by the beam. This operation was never tested with high intensity beams and needs a completely new low-level RF, and it arises some concerns for the reliability of the system. By doing so, the total available power at extraction would be 1.05 MW, and it will probably be possible to reach 1.45e11 ppb with no performance degradation of the extracted beam. In case the full upgrade of the 200 MHz system would take place, as preferred for the US1 case, the maximum available power for 2 longest (4 sections) cavities would be instead about 1.6 MW, bringing the maximum intensity per bunch up to 2.0e11 for 25 ns without any performance degradation in the hypothesis that no new beam stabilities with high intensity (combination of single- and coupled-bunch effects) would appear in the new working regime. Concerning the other SPS activities, a more detailed discussion can be found in [2] for US2.

Risk analysis

A very simplified risk analysis was done considering the implementation of the new elements in the different machines and the results are summarized in Table 5. The two different columns refer to the case with or without the 200 MHz upgrade implementation in the SPS. The activity mentioned concerns only the main group of interventions/limits.

CONCLUSIONS

The HL-LHC US1 requirements can be fulfilled if the three main injector upgrades foreseen by LIU are implemented, i.e., the connection of Linac4, the PSB extraction energy upgrade to 2 GeV and SPS 200 MHz RF power upgrade. In particular the 200 MHz power upgrade is necessary to match the requirements of the preferred HL-LHC-US1 scenario with unchanged parameters at LHC injection (longitudinal in particular).

REFERENCES

[1] K. Hanke *et al.*, these proceedings

[2] H. Bartosik *et al.*, these proceedings

[3] E. Shaposhnikova, LIU technical meeting http://indico.cern.ch/event/262482/

[4] G. Rumolo *et al.*, these proceedings

[5] M. Giovannozzi *et al.*, Chamonix 2010

[6] O. Brunning *et al.*, these proceedings

[7] G. Sterbini, CERN-ACC-2013-0215

[8] H. Damerau *et al.*, these proceedings

[9] E. Shaposhnikova et al., WE01A04, HB2012.

Published by CERN in the Proceedings of RLIUP: Review of LHC and Injector Upgrade Plans, Centre de Convention, Archamps, France, 29–31 October 2013, edited by B. Goddard and F. Zimmermann, CERN–2014–006 (CERN, Geneva, 2014)

WORK EFFORT IN THE LHC INJECTOR COMPLEX FOR THE UPGRADE SCENARIOS

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Abstract

This document describes the work in the PSB, PS and SPS that is required for upgrade scenario 1. It will be shown that the requirements on the hardware work needed for upgrade scenario 1 are identical to the ones of the upgrade scenario 2 [1]. The various activities are detailed as well as their dependencies and an estimate given for the duration of the necessary shutdowns and recommissioning periods with beam. It is mentioned whether some decisions are still to be taken and are related to information to be obtained after LS1. Another important aspect is the evaluation of the risks related to the upgrade interventions and operational complexity, which concern schedule, beam characteristics as well as reliability and overall performance. It has been studied if part of the activities could be spread out over several machine stops, and as conclusion the preferred scenario will be presented.

LINAC4 STATUS

Linac4, presently under construction, will replace the present 50 MeV Linac2 as injector of the CERN proton complex. The commissioning of the linac, which started with the 3 MeV test stand early 2013, will be divided into 5 different stages corresponding to the different accelerating sections and will be completed by the end of 2015. A one year reliability run is foreseen in 2016, after which the linac will be ready to be connected to the injector complex. From that date, any postponement of the connection will entail some major drawbacks:

- The risk of a Linac2 breakdown remains for more years, mitigated only by an emergency connection with 50 MeV protons at reduced performance.
- Linac4 will need to be maintained operational in parallel with Linac2, with a related cost and use of resources.
- Key experts (retirements, staff on limited duration contracts and fellows) will leave the project before 2018.
- Possible uncontrolled shift of the commissioning schedule due to demotivation of the team and redefinition of priorities in case of a delayed connection during LS2.

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CONNECTING LINAC4

The required connection work on the linac side will take place in two different areas: at the Linac2-Linac4 interface and at the present location of the LBE/LBS measurement lines. These areas are surrounded with dashed lines in Fig. 1.

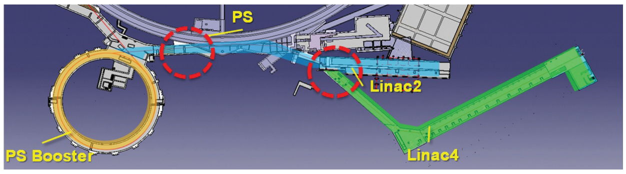

Figure 1: Linac4 connection working areas.

Linac2-Linac4 Interface

Linac4 will be connected to the existing Linac2 transfer line to the PSB at the location of the LT.BHZ20 bending magnet. On top of the line installation, some civil engineering work is required: drill a new DC cable path, build a shielding wall to protect the Linac2 surface building, add some shielding around the beam pipe at the transition, drill a new emergency exit in the Linac2 wall and assemble a chicane of concrete blocks in the Linac2 tunnel. Given the relatively small area where all these tasks need to be done, the work has to be sequenced. Before starting any work in this area, it is required to wait for a 4 weeks cool-down time after the Linac2 beam stop; 8 more weeks will then be needed to complete the connection. This results in a total duration of 12 weeks starting from the Linac2 beam stop until the completion of the work at the Linac2/Linac4 interface.

LBE and LBS Measurement Lines

Two measurement lines are presently used to characterise the beam from Linac2 before PSB injection: The LBE line for transverse emittance and the LBS line for energy and energy spread measurements. These two lines having been designed for an energy of 50 MeV and need to be upgraded for use at 160 MeV with Linac4.
A recent analysis indicated that because of the limited space available and of the difficult access an upgrade of the LBS line would have induced heavy civil engineering work in the direct vicinity of the PS tunnel with many complications and interference in terms of planning for the PSB and the PS upgrade tasks. The working time in the LBS area

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was estimated to 5 months. It was therefore decided to develop a new measurement technique based on longitudinal emittance reconstruction with some additional diagnostics installed in the Linac4 transfer-line [2]. This new measurement technique provides a better resolution for a drastically lower cost than the LBS upgrade, and on top of that does not interfere with the PSB and PS planning. The present LBS line can be kept as is for ion beams from Linac3.
The LBE line instead will be completely upgraded installing 2 quadrupoles, 3 profile monitors and a beam dump. After 6 weeks of cool-down in the PS tunnel (no beam or ion run) before accessing the LBE area, it will take 2 weeks for removing the existing line and 4 weeks to assemble to new one (cabling done in parallel). This results in 12 weeks in total (including cool-down).

Linac4 Operational

Following the 12 weeks needed both for the Linac2-Linac4 interface and for the LBE measurement line, 3 additional weeks have to be added for hardware and beam commissioning. The overall planning is shown in Fig. 2.
15 weeks after the last proton in Linac2, Linac4 could be ready to send a fully characterised beam to the PSB.

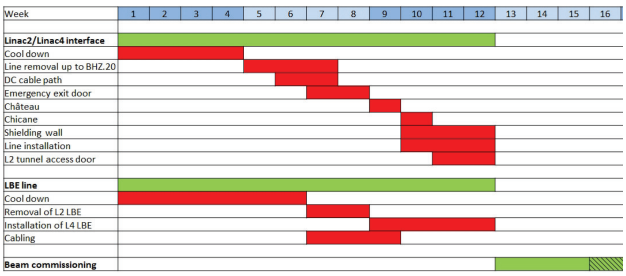

Figure 2: Linac4 connection planning.

Ion Run in Parallel to Linac4 Connection

The only constraint for having an ion run in parallel to the Linac4 connection is given by the time needed on the LBE line upgrade (6 weeks). In fact, the LBE being located in the direct vicinity of the PS tunnel, no work can be done in the area while an ion beam is circulating in the PS. An ion run could take place before the LBE upgrade (and being therefore considered as cool-down time) or after the LBE upgrade. The PSB injection upgrade work can safely take place in parallel to an ion run, the booster being shielded from the PS by a 6 meter thick wall.

WORK EFFORT IN THE PSB

The LIU upgrade activities for the PSB comprise two main parts: Modifications due to the Linac4 connection and the upgrade to 2 GeV extraction energy. The baseline plan foresees that both parts will take place in parallel during LS2, but due to the significant amount of changes affecting major systems of the PSB, this would imply risks for the restart after LS2 and could lead to delays for the whole accelerator chain. Therefore it was also studied if these two distinct parts could be separated by connecting Linac4 to the PSB in an intermediate shorter shutdown.

Connection of Linac4 to the PSB in an Intermediate Shutdown

The connection of Linac4 to the PSB implies an increase in injection energy from 50 to 160 MeV injecting an H^- instead of a proton beam. This requires the following changes:

- Replace certain magnets and power supplies in the PSB injection line due to the increased beam rigidity
- Install new beam instruments adapted to the Linac4 beam and/or specific for the H^- injection process
- Change the vertical beam distribution system to inject the Linac4 beam into the 4 superposed PSB rings (new distributor, vertical septum)
- Exchange the complete PSB injection section: New injection chicane with 4 magnets per ring, charge-exchange stripping foil unit, H^0/H^- dump, horizontal phase-space painting bump using 4 kicker magnets, novel beam instrumentation
- Modify vacuum sectorisation and vacuum chambers in 2 main bending magnets
- Install new beam interlock system.

Fig. 3 shows a simplified 3D-model of the future PSB injection section.

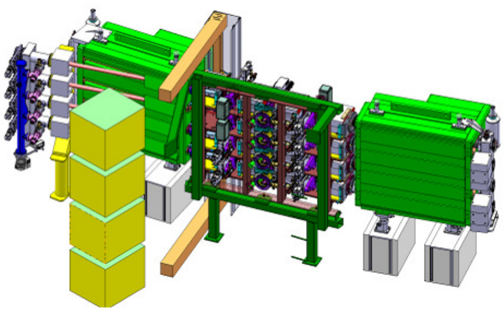

Figure 3: 3D view of the future PSB injection section without services (PSB tunnel wall also not shown). The 4 injection lines are visible at the left behind a transformer stack.

The required cool-down time of 1-1.5 months was assumed to take place in parallel with the end-of-year LHC ion run and the 2 weeks of Christmas break. During this time preparatory work like installation of new racks can take place. Due to the saturation of many cable trays and ducts the necessary cabling and uncabling campaign has been estimated to 5 months by EN-EL, assuming 3 shifts per day. Dismantling and installation of the new equipment will take 4.5 months; for the new injection section a detailed work plan has been elaborated to have confidence in this estimate. This period will be followed by 1 month of high-voltage conditioning of the injection kickers and parallel cold check-out of the machine. The PSB will then be able to send the low-intensity LHCPROBE beam to the PS after 8 weeks of beam commissioning followed by the LHC production beam 2 weeks later. An overview of the work effort for the Linac4 connection to the PSB is given in Table 1.

Table 1: Work breakdown for the connection work.

Activity	duration
Radiation cool-down and preparatory work	1.5 months
Dismantling, installation and cabling campaign	4.5 months
HV testing and cold check-out	1 month
Running in PSB to provide LHC production beam	2 months
Total	**9 months**

In order to virtually shorten this period of 9 months for the LHC, it has been proposed to extend the LHC proton run in 2016 until beginning of December for additional integrated luminosity. Ion commissioning of the LHC ion injector chain would be performed in the last quarter of 2016 in parallel to the proton run and until the Christmas break. Beginning of January an extended LHC ion run of 3.5 months could take place, from which other ion users in the North Area could also profit. This long ion run period would then be followed by 4.5 months of CMS pixel detector installation, which would fill up the 9-month period.

PSB Upgrade - Baseline Work Effort

In the baseline scenario, Linac4 will be connected to the PSB during LS2, and in parallel the 2 GeV PSB upgrade will take place. In addition to the activities mentioned in the previous paragraph, the following work needs to be carried out:

- Replace main power supply; new PSB MPS will be installed in a new building
- Modify main magnet cooling circuits + shimming
- Renovate PSB cooling and ventilation systems (consolidation)
- Upgrade the PSB RF systems
- Exchange certain magnets and/or power supplies in the extraction lines
- New extraction and recombination kickers, new recombination septa
- Add or modify beam instrumentation
- Install new beam interlock system
- Renovate electrical services (consolidation).

During the first 1.5 months of radiation cool-down, the new MPS will be tested, connecting one main magnet circuit. In parallel, the renovation of the PSB cooling system (7 months total duration) and of the ventilation system (12 months) can start. An impressive cabling campaign of 9 months in total (3 shifts per day) needs to be undertaken. The dismantling and installation efforts for the new equipment amount to 5.5 months, which results in the uncomfortable situation that during 3 months equipment testing has to wait for the cabling to be finished.
The PSB can therefore be closed only 10 months after the stop of the run preceding LS2. From this point on, hardware tests can continue in parallel: tests of the MPS with the final load (2 months), running in of the new RF system (5 months), HV DC conditioning of the new extraction kickers and equipment tests (5 months).
Beam commissioning in this case will be extremely complex with the new injection hardware, new instrumentation, new MPS, new RF system plus new extraction equipment with 4 rings to be set up. It is estimated that the LHCPROBE beam can be sent to the downstream machine 2.5 months after beam commissioning start, followed by the LHC production beam 2 weeks later. Additional beams should follow at an approximate rate of 2 per week at best. In summary, the LHC production beam is expected to be available to the PS after **18 months**.

WORK EFFORT IN THE PS

Despite a multitude of LIU-related work has already been carried out during LS1, many LIU-PS activities remain to be undertaken during LS2, but they are not representing a bottleneck for the LS2 duration. The main ones are the following:

- Replace vertical correctors and normal/skew quadrupoles due to increased injection energy of 2 GeV - 5 months
- Exchange PFW (pole face windings) of the main magnets (consolidation) - 11 months
- Install new injection kicker, bumper and septum - 4 months
- Upgrade of 10 MHz RF system
- Install 2 new internal dumps
- Exchange certain magnets and/or power supplies in the extraction lines - in the shadow of other activities
- New beam instrumentation (wire scanners, BLMs, injection SEM grid etc.) - not time-critical
- Upgrade electrical services, vacuum systems etc.

For the PS, no detailed study is yet available concerning potentially needed cabling campaigns. Nevertheless it has been stated by EN-EL that with the current information the expected work load would be less substantial than for the PSB, which would mean that the campaign would not be a bottleneck in the PS.
Counting 1 month of radiation cool-down, general access can be given after 2 months to perform all the above-mentioned tasks. Four weeks of hardware test and 2 weeks of cold check-out will follow the installation period, which means that the PS would be ready to receive beam from the PSB after **14.5 months**.

For beam commissioning and to provide the LHCPROBE beam to the SPS, 5 weeks should be reserved (2 weeks for OP and 3 weeks for RF) under the assumption that the PS will restart with the old beam control and that there will be a switch-over possibility implemented between old and new beam control. Two additional weeks are required to set up the LHC production beam.

WORK EFFORT IN THE SPS

The upgrade activities in the SPS are dominated by 2 tasks: The 200 MHz RF upgrade and the aC-coating of 6 sectors. It has been assumed for the cabling campaign that it would last less than 10 months, but this needs to be confirmed with a more detailed study. In order to reach the beam performance required for the LHC within Upgrade Scenario 1, electron cloud mitigation means need to be adopted already during LS2. This means that Upgrade Scenarios 1 and 2 involve identical hardware modifications for the SPS. The main SPS upgrade items are:

- Upgrade 200 MHz RF system (power and low-level) - 12.5 months
- Perform aC-coating of 6 sectors - 12 months
- Improve ZS and work to reduce the impedance of other kickers
- Install new external high-energy beam dump and exchange TIDVG dump core
- Upgrade the extraction protection system
- Add a new wide-band transverse damper (intra-bunch damping in the vertical plane)
- Renew/improve beam instrumentation
- Improve vacuum sectorisation of the arcs
- Ions: upgrade the injection damper for ions and add new short rise-time kickers (100 ns).

The 200 MHz upgrade activity has already started, and a new building that will house the amplifiers will be handed over end of 2015. The tunnel work during LS2 involves 6 months of cavity rearrangement in LSS3: 18 existing cavity sections with their services have to be displaced and re-installed, 2 new cavity sections added as well as 6 new couplers. The remaining 6.5 months will be used for system commissioning. This activity cannot be split up; once started it has to be completed. From the logistics point of view it will also prohibit transport activities passing through LSS3.

Electron cloud is one of the major limiting factors for 25ns beam operation. One mitigation consists of coating vacuum chambers with a thin film of amorphous carbon. Over the years a technology was developed for treating the chambers in the magnets without the need of dismantlement. Nevertheless this has to be done in a special workshop on the surface. After LS1, 4 SPS half-cells will be coated and their performance can be evaluated with beam. The aim for LS2 will be to coat 90% of the SPS: $>$700 dipoles, the main quadrupoles, long straight sections, pumping port shields and maybe as well the short straight sections. A first planning of the magnet flow between tunnel and surface workshop has been presented [3]. The max. estimated flow consists of 6 magnets in and 6 magnets out per day, yielding 12 months in total including commissioning for this activity.

A first LS2 planning for the SPS has been elaborated and is summarised in Table 2.

Table 2: LS2 work overview for the SPS.

Activity	**duration**
Radiation cool-down and preparatory work	2 months
Upgrade activities	12.5 months
Patrols, DSO tests	1.5 weeks
Magnet + power supply tests	6 weeks
Cold check-out	4 weeks
Commissioning with beam	1.5 months
Total	**≈18 months**

After this planning, the SPS will be ready to receive beam from the PS after **16.5 months**.
Beam commissioning will be very challenging due to the modified RF hardware combined with a new RF beam control, therefore a minimum of 1.5 months have to be reserved. Depending on the electron cloud situation in the SPS and the required scrubbing (machine has been at atmosphere over many months), it is expected that at least another 1.5 months have to be added to be ready to send the LHC production beam to the LHC.

LS2 FOR THE INJECTORS

The required LS2 duration from the point of view of the LHC injectors follows from the previous chapters with the constraint that the manpower availability for the work in the different machines has not yet been studied in detail (service groups, interventions for both upgrade and consolidation). According to this planning the LHC would receive first beam from the injectors **20.5 months** after the end of run before LS2 (see Figure 4), or the LHC production beam after **22 months**. This is longer than the 18 months generally assumed as LS2 duration because of the complexity of the cabling campaigns, especially in the PSB. If the cabling campaign in the PSB could be reduced by 3 months, the PSB could send beam 3 months earlier to the PS, which would exactly match the time when the PS would be ready to receive beam from the PSB. The LS2 injector schedules would then align quite well, and the LHC would receive the LHCPILOT after **18 months** and the LHC production beam after **19.5 months**.

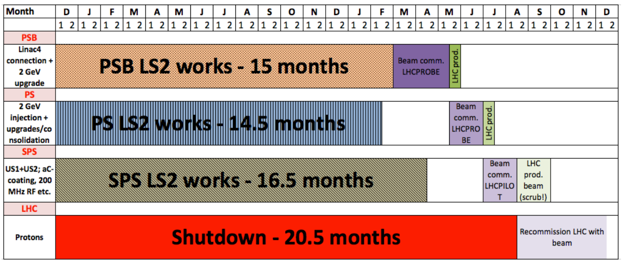

Figure 4: Required duration in the different LHC injectors for modifications during LS2.

RISK MITIGATION

The primary risk resulting from the injector upgrades is related to the schedule, although the technical risks due to the extensive amount of new equipment installed in all of the accelerators is also significant. To minimise these risks, the following points should be considered:

- Identify and advance certain interventions to earlier short shutdowns if possible; in this context a connection of Linac4 to the PSB in an intermediate shutdown should be mentioned
- Perform detailed integration studies that include as well CV and EL equipment (cooling pipes, cable trays etc.) to avoid mechanical conflicts during installation
- Construct mechanical mock-ups for complex installation items
- Produce a more detailed planning of the interventions including manpower resource planning to identify potential co-activity issues; take into account the integrated dose per worker
- Organise test stands or beam tests where possible to reduce technical risks (for example installation of half of the PSB injection chicane in the Linac4 transfer line)
- Prepare new applications/controls well ahead of the deadline and well tested to be ready for the commissioning
- Develop a detailed beam commissioning planning with clear check lists.

CONCLUSIONS

It is necessary to identify solutions to gain 3 months for the PSB cabling campaign in the PSB to align the injector upgrade schedules for LS2. This requires detailed studies of the present cabling situation, identification of obsolete cables to provide space as well as future cabling and rack installation requests. Only under the assumption that such a solution can be found, the LHC can expect to receive an LHCPILOT beam after 18 months of shutdown. The delivery of the LHC production beam is then depending on the required scrubbing after LS2.
From the machine side it would be advantageous to connect Linac4 to the PSB in an intermediate shutdown, which could be an option in case the experiments would be interested in an extended ion run period in addition to the CMS pixel detector exchange.

REFERENCES

[1] "RLIUP Workshop, 29-31 October 2013, Archamps, Timetable and Information, pp. 19-21," `https://espace.cern.ch/ReviewWorkshop/Timetable/RLIUP%20workshop%20Full%20View%20timetable.pdf`

[2] A. Lombardi, J-B. Lallement, "An alternative to the LBS line," Linac4 Beam Coordination Committee meeting 46, 25 July 2013, `http://indico.cern.ch/conferenceDisplay.py?confId=263986`

[3] G. Bauche, P. Costa Pinto, "LIU-SPS Coordination meeting, 2 October 2013," `http://indico.cern.ch/getFile.py/access?contribId=5&resId=4&materialId=slides&confId=274920`

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HOW TO MAXIMIZE THE HL-LHC PERFORMANCE*

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Abstract

This contribution presents an overview of the parameter space for the HL-LHC [1] upgrade options that would maximize the LHC performance after LS3. The analysis is assuming the baseline HL-LHC upgrade options including among others, 25ns spacing, LIU [2] parameters, large aperture triplet and matching-section magnets, as well as crab cavities. The analysis then focuses on illustrations of the transmission efficiency of the LIU beam parameters from the injection process to stable conditions for physics, the minimization of the luminous region volume while preserving at the same time the separation of multiple vertices, the luminosity control mechanisms to extend the duration of the most efficient data taking conditions together with the associated concerns (machine efficiency, beam instabilities, halo population, cryogenic load, and beam dump frequency) and risks (failure scenarios, and radiation damage). In conclusion the expected integrated luminosity per fill and year is presented.

INTRODUCTION

The Review of the LHC and Injector Upgrade Plans (RLIUP [3]) evaluated the upgrade options for the LHC injectors and the LHC ring. The different upgrades are organized in three scenarios with an increasing number of interventions named PIC [4], US1 [5] and US2 [6] aiming at an integrated luminosity of 1000 fb^{-1}, 2000 fb^{-1}, and 3000 fb^{-1} by 2035, respectively.

The following paper reviews what would be needed to fulfil the US2 goals by analysing the parameter space, by examining the challenges and the hardware interventions foreseen, and by quantifying how close specific scenarios approach the prescribed goal.

PARAMETER SPACE

Under the assumption of 10 years of operation including three long shutdowns and starting with an already accumulated luminosity of 310 fb^{-1} in 2021 [7], the newly upgraded LHC will need to accumulate on average 270 fb^{-1} per year. The integrated performance will be compared by calculating the performance efficiency (η), defined as the fraction of physics time to reach the yearly goal over a period of 160 days, with a sequence of successful fills separated by a 3 h long turnaround (see [8] for a more detailed discussion). Two different fill durations are assumed, a fixed duration of 6 h (the average fill length obtained in 2012 [9]) and the one maximizing the physics efficiency for the respective scenario. For comparison, the 2012 run can be associated with η = 53.5% performance efficiency [8]. Equally suitable definitions of efficiency, which have been used in the review, will not be discussed in this paper since they do not affect the conclusion.

The experiments defined a few experimental conditions that should be fulfilled by the scenarios. For ATLAS and CMS, the average pile-up limit is maximum 140 events per crossing with ideally 0.7 events/mm, but no more than 1.3 events/mm in the luminous region [10]. For LHCb, no more than 4.5 events per crossing can be exploited, while for ALICE the maximum levelled luminosity is assumed to be $2\cdot10^{31}$ cm^{-2}s^{-1}[11]. Proton collisions at top energy are assumed to have a total cross section (elastic and inelastic) of 110 mb used for burn-off calculations, while the visible cross section that counts for the observed events is 85 mb for ATLAS and CMS, and 75 mb for LHCb [12-14].

Discussion

While the maximum luminosity tolerated by ATLAS and CMS is widely accepted to be $5\cdot10^{34}$ cm^{-2}s^{-1} and an average of 140 event per crossing (HL-LHC baseline), it is interesting to evaluate how this parameter constrains the physics reach. In fact, it is possible to find an upper bound to the performance reach, regardless of the beam conditions by observing that:

$$L_{\mathrm{int}} \leq \eta t_{\mathrm{phys}} L_{\mathrm{lev}} \frac{t_{\mathrm{fill}}}{t_{\mathrm{fill}} + t_{\mathrm{turnaround}}} \quad (1)$$

where L_{int} is the integrated luminosity, t_{phys}, t_{fill}, $t_{\mathrm{turnaround}}$ stand for the physics time, fill duration, and turnaround time, respectively, while L_{lev} is the assumed peak luminosity always levelled without any decay.

Figure 1 shows that the performance goal is theoretically accessible either by increasing the fill time or more effectively by increasing the maximum levelled luminosity. Including the natural decay of the luminosity due to burn-off, the integrated luminosity can be

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calculated* by only assuming a value of the virtual luminosity and bunch population at the beginning of the fill [15].

If one assumes the virtual luminosities and starting bunch intensities considered for the HL-LHC project, the picture does not change considerably (Fig. 2) if not excluding the integrated luminosities beyond 300 fb^{-1} per year for a levelled luminosity of $8\cdot10^{34}$ $cm^{-2}s^{-1}$ (see Fig. 2) or barely exceeding 250 fb^{-1} per year for 10 h fill length.

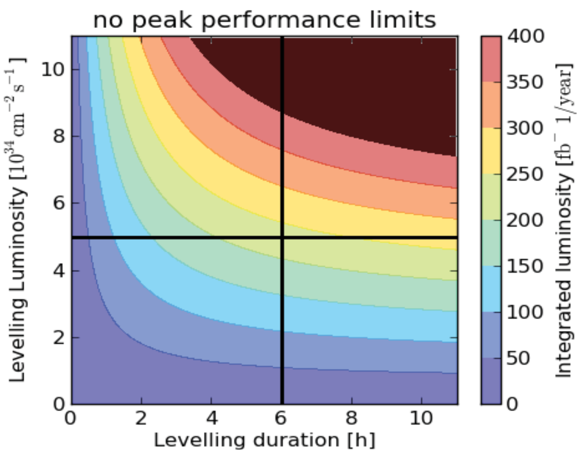

Figure 1: Theoretical LHC performance calculated by assuming 80 days of successful fills (i.e. η = 50 %), 3 h turnaround time and, unrealistically, without any beam related limitations, or equivalently, by assuming that one can always run at the maximum allowed luminosity (see Eq. 1). The black lines highlight the average fill duration of the 2012 LHC run and the baseline maximum instantaneous luminosity tolerated by the ATLAS and CMS experiments. The dark red part represents values above 400 fb^{-1}.

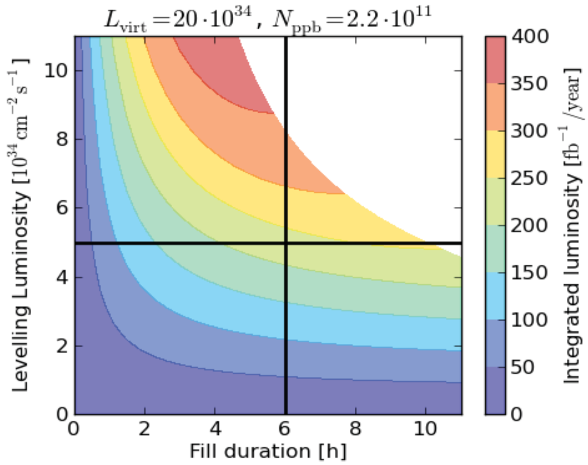

Figure 2: Ideal LHC performance under the conditions of Fig. 1, but including the burn-off decay of the luminosity assuming the peak virtual luminosity and initial bunch population considered for the HL-LHC. The white area is the region for which it would be more efficient to restart a fresh fill and therefore the performance is not evaluated.

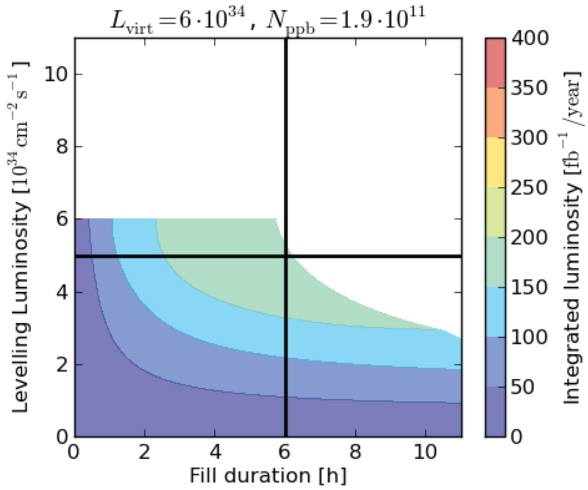

Figure 3: As Fig. 2, but assuming a virtual luminosity much smaller than the ideal scenario (even with large bunch intensity). This scenario does not fully cover the parameter space even under the most conservative assumptions of a levelled luminosity smaller than $5\cdot10^{34}$ $cm^{-2}s^{-1}$ and with fill durations smaller than 6 hours.

* The equations used are [15]: $\frac{dN}{dt} = -\frac{N}{\tau} = -n_{IP}\sigma L_{lev}$; $\tau = \frac{N}{n_{IP}\sigma L_{lev}}$; $L_{virt} = k\,L_{lev}$; $t_{lev} = \tau\left(1-\frac{1}{\sqrt{k}}\right)$; $t_{decay} = \frac{\tau}{2-\frac{1}{\sqrt{k}}}\left(-1+\frac{1}{\sqrt{k}}+\sqrt{\left(1-\frac{1}{\sqrt{k}}\right)^2+\left(2-\frac{1}{\sqrt{k}}\right)\frac{t_{turnaround}}{\tau}}\right)$; $L_{average} = L_{lev}\frac{t_{lev}+\frac{t_{decay}\tau}{t_{decay}+\tau}}{t_{lev}+t_{decay}+t_{turnaround}}$; .

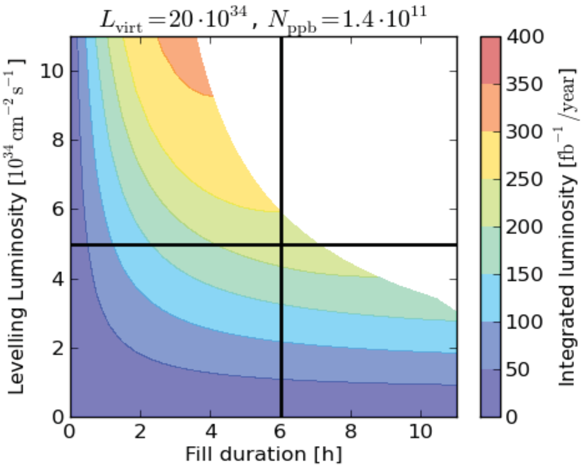

Figure 4: As Fig. 2, but with smaller bunch population than in the baseline scenario. This scenario exploits the conservative region, but it cannot fully profit from long fill durations which are challenging, but not completely excluded. In addition it cannot fully profit from any increase of levelled luminosity.

Optimization Strategy

Figure 2 shows a more realistic case, for which the levelled luminosity is set to $5 \cdot 10^{34}$ cm^{-2}s^{-1}, the virtual luminosity to $20 \cdot 10^{34}$ cm^{-2}s^{-1} and the bunch population to 2.2 10^{11} protons per bunch. This case would fully exploit almost all the parameter space and, if the HL-LHC reaches those values of virtual luminosity and bunch populations (representing the baseline values for the HL-LHC), the upgrade project saturates the capabilities of the experiments and should therefore primarily aim at improving the reliability of the machine.

For a limiting case in which, for instance, a high virtual luminosity is not reached at a reasonably high bunch population, for instance without the crab cavities or other mitigation for the geometric reduction factor, most of the parameter space is excluded and also the conservative quadrant can be fully exploited (Fig. 3).

In another limiting case, if the virtual luminosity target is unrealistically achieved without increasing the bunch population, one could see (Fig. 4) that the conservative part of the parameter space is exploited. However, in case the experiments would be able to cope with larger instantaneous luminosities, or the LHC reliability improves enough to allow longer fill duration, the yearly integrated luminosities will not be maximized. This is due to the fact that, while the levelling time depends only on the virtual luminosity, a short luminosity lifetime during the decay time, which depends on the residual bunch population after levelling, has still a detrimental effect in the integrated luminosity. The bunch population target is therefore essential for the HL-LHC project.

This can be seen also, if an even larger virtual luminosity is achieved (Fig. 5) at the cost of a modest reduction of intensity (for instance by reducing β* or by reducing the emittance to the IBS limit) the integrated performance does not improve and tends to limit the potential and robustness of the upgrade.

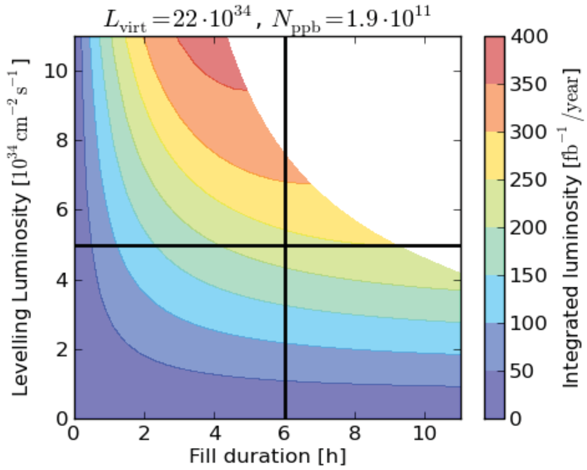

Figure 5: As Fig. 2, but when the virtual luminosity is higher than the ideal scenario at the cost of smaller bunch population (for instance by targeting smaller value β* or by reducing the emittance to the extent allowed by the IBS growth rate). This scenario offers similar features of the baseline one (Fig. 2) but it is inferior for the most aggressive parameters.

From this analysis, one can conclude that the most effective way to optimize the luminosity consists in (besides increasing the efficiency and the days of physics) the maximum levelled luminosity, the fill duration, the bunch intensity and the virtual luminosity. The levelled luminosity is proportional to the number of events per crossing and the present limit is considered extremely challenging to overcome even in the future. Furthermore, the levelled luminosity is proportional to the number of bunches, which are ultimately limited by the bunch spacing (currently limited by both the experiment triggering rate and the e-cloud) and, to a smaller extent, by the rise time of injection, extraction, abort kickers of the LHC and its injectors. The feasibility of an increase of levelled luminosity is not discussed in this paper, but it is under consideration thanks to the possibility that a novel scheme [16] could distribute the events more evenly in the luminous region and therefore ease the event reconstruction.

The remaining part of the paper is devoted to the analysis of the beam parameters and machine scenarios that are needed to achieve the bunch intensity and the virtual luminosity that maximize the HL-LHC performance.

MAXIMIZING THE INTEGRATED LUMINOSITY PER FILL

The way to maximize the luminosity per fill is to maximize the bunch population since the luminosity decay will be dominated by particle burn-off. Efforts should be devoted to keep the sources of emittance growth (instabilities, noise, field imperfections) small. Since the peak luminosity is limited, one should establish a lossless levelling method, which is able to use the reserve performance of a large virtual luminosity. Large virtual luminosities can be achieved by reducing β* thanks to new large aperture triplets and matching section magnets in addition to an improved orbit control at the IP to avoid jitter larger than a fraction of the transverse beam size. Crab cavities are needed to remove the luminosity reduction due to the crossing angle. The option of flat β* and LR beam-beam compensators can reduce the crab cavity voltage requirements and, in addition, support the crab kissing scheme [16]. A reduction of the emittance is certainly helpful, however, due to IBS, the gain saturates at values of ~2 µm. In addition, it should not come at extra costs in terms of reduced number of bunches, or exceeding the threshold of head-on beam-beam tune shift and instabilities.

Since the maximum levelled luminosity depends also on the peak pile-up line density, it is desirable to use long bunches (limited by the RF control, crab cavity RF curvature and hour-glass effect), flat longitudinal density (by a 2^{nd} harmonic RF), and to have enough crabbing kick to support the crab kissing scheme.

The following sections will sketch the challenges associated with the strategy mentioned above.

Beam current limitations

The present understanding (see Fig. 6, 7) indicates that it should be possible to maintain in collisions $2.2 \cdot 10^{11}$ protons per bunch for a total of about 1 A circulating current [17]. This scenario requires that the e-cloud issues are under control (see following subsection), that the coupled bunch instabilities are stabilized by the transverse damper and that the single bunch instabilities have a threshold in agreement with predictions (see Fig. 8) or are stabilized by the head-on beam-beam tune spread [18, 19].

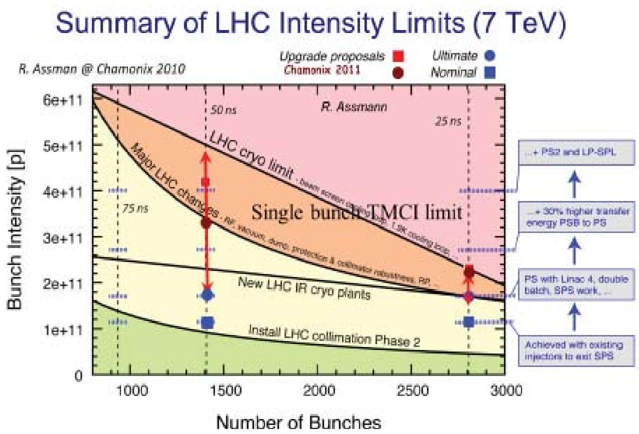

Figure 6: Beam current limitation in the LHC as a function of bunch intensity and number of bunches (courtesy R. Assmann [17]).

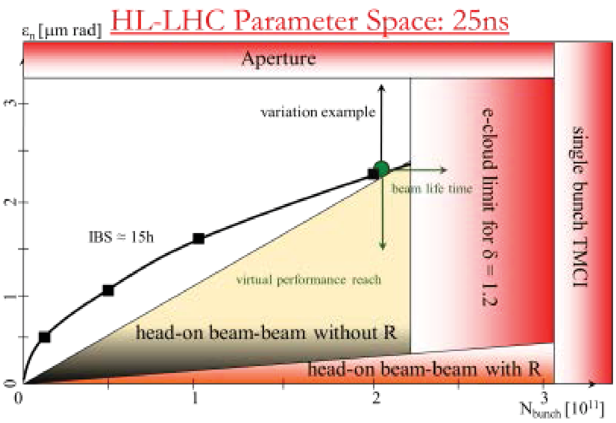

Figure 7: Parameter space of 25 ns beams in terms of emittance and bunch intensity. For large intensity the area is bounded by the e-cloud limit and IBS growth rate if the performance reach is maximized.

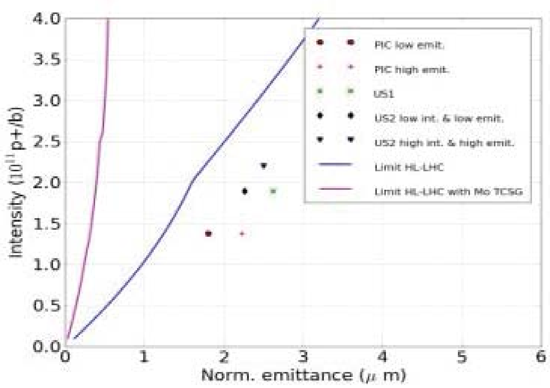

Figure 8: Instability thresholds are still far according to the present impedance model (bottom [19]) if metallic collimators are implemented.

E-cloud

As stated above, the HL-LHC nominal scenario relies on the control of e-cloud issues. The current understanding, based on the observations performed during Run I and on numerical simulations, indicates that by scrubbing the main dipoles until reaching a secondary emission yield (SEY) of 1.3-1.4, one could alleviate the heat-load and emittance growth at injection energy. In addition, it should be possible to increase the cryogenic cooling capacity in the quadrupoles to cope with the heat-load since the required SEY smaller than 1.2, 1.3 (see Fig. 9) would be difficult to achieve with scrubbing [20].

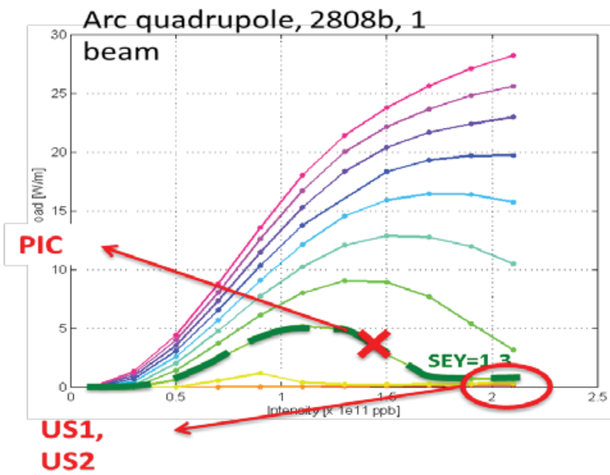

Figure 9: Simulated heat load linear density in the LHC arc quadrupoles as a function of bunch population and SEY. A SEY of 1.3 is needed to reduce the heat load [20].

Filling schemes

The number of bunches is one of most sensitive parameters to gain in performance, because it is proportional to the instantaneous luminosity. The filling schemes in the accelerator chain, the maximization of the colliding bunches for the four experiments, and the need of non-colliding bunches affect the total number of the colliding bunches that would be otherwise limited only by the rise and flat top time of the LHC injection kickers (0.925 μs and 7.86 μs), the rise time of the dump kickers (3 μs), and the 4-fold symmetry to 2808 bunches [21]. Two SPS injection schemes, a standard 72-bunch one and the Batch Compression Merging and Splitting (BCMS) scheme [22] for 48 high brightness bunches, allow to inject in the LHC 2592 and 2736 colliding pairs in both ATLAS and CMS, while keeping a fair number of collisions for ALICE and LHCb (see Fig. 10 and Table 1 [23]). These schemes feature no IP8 private bunches that might be lost (in particular if colliding with large separations) since they will have only the tune spread of one head-on collision to stabilize instabilities due to impedance effects.

The small difference in number of colliding bunches for the two schemes is nevertheless significant in the performance evaluation due to the steeper increase of integrated performance originating from a higher levelled luminosity compared to the gain from higher virtual luminosity that contributes only to the length of the fill.

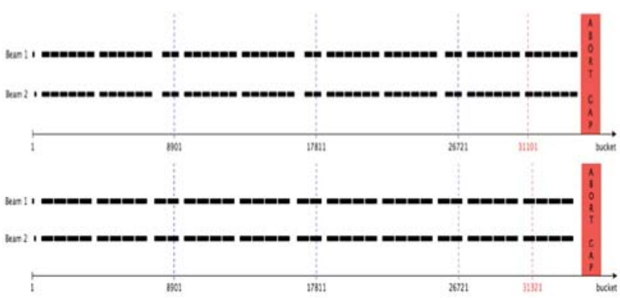

Figure 10 and Table 1: HL-LHC filling schemes for standard 72 bunch injection and BCMS injection featuring 12 non-colliding bunches and no IP8 private bunches [23].

Filling scheme	Total	IP1-5	IP2	IP8
BCMS: 48 b 6 PS injections, 12 SPS injections	2604	2592	2288	2396
Standard: 72 b 4 PS injection, 12 SPS injection	2748	2736	2452	2524

Experimental constraints and levelling

The HL-LHC baseline scenario aims at saturating the capabilities of the high luminosity detectors as long as possible. The limits on data taking for the HL-LHC detectors are not yet fully explored. Some of the conditions to be taken into account are the total pile-up, pile-up density, out of time pile-up or spill-over, centroid movements and size changes of the luminous region, and instantaneous luminosity stability [24].

Regardless of the maximum instantaneous luminosity, the machine needs to establish a method to reduce artificially the luminosity when the bunch population is the largest and to modify slowly those conditions that increase the luminosity with decreasing bunch population. The methods should take into account that the orbit stability should be a small fraction of sigma to avoid beam losses and in particular in the last part of the fill to avoid the reduction of the overlap between bunches of the two beams.

Several methods have been identified: β* levelling, parallel separation, bunch tilt. In case of β* levelling, one has a large range of luminosity reduction and it is the preferred option for ATLAS and CMS. It has the advantage of reducing the impact of the long range beam-beam encounters when the bunch population is large. However, this method relies on the simultaneous modification of the optics and orbit, and it implies a large head on beam-beam tune spread. Both operations rely on a combination of high reproducibility of the magnetic cycles, accurate transfer function models and high precision, accuracy and resolution of the BPMs and power converter controls. In addition, since the HL-LHC optics needs the ATS scheme (discussed later), the preparation of the squeeze sequence is complicated if both CMS and LHCb undergo β* levelling at the same time.

Alternatively, a reduction of luminosity is possible by parallel separation. In this case the head-on tune spread reduces. On one hand, this mitigates the beam–beam related lifetime issues if they are a limiting factor, but, on the other hand this would limit the largest source of Landau damping if it is needed to stabilize instabilities. In addition the parallel separation may enhance beam-beam driven coherent effects. By increasing the crossing angle with the orbit correctors or the bunch tilt with crab cavities, one can have the beneficial effects of the parallel separation without enhancing coherent effects (at the cost of larger synchro-betatron resonances). However, the range is too limited to cover the needs set by the bunch population assumed for the discussed scenarios due to aperture and crab cavity voltage constraints for the crossing angle and bunch tilt respectively.

*Optics for reaching low β**

The nominal transverse beam size at the IP (proportional to $\sqrt{\beta^*}$) is not sufficiently small to reach the peak luminosity needed by the HL-LHC baseline. The further reduction of β* is obtained by the replacement of the inner triplet (that would however have to be replaced after 300 to 600 fb^{-1} of equivalent radiation damage dose) in combination with the implementation of the so-called Achromatic Telescopic Squeezing scheme [25]. The principle of this novel scheme is to extend the optics matching of the high luminosity insertions to the neighbouring arcs and straight sections in order to mitigate the strength limits of the matching quadrupoles (needed for the optics squeeze) and of the arc sextupoles (necessary for the chromatic aberrations generated by the stronger focusing) [26]. The scheme has already been successfully tested for β* as low as 10 cm using pilot bunches ([27] and Fig. 11) and represents a solid base around which the lattice hardware modification are being tailored [28].

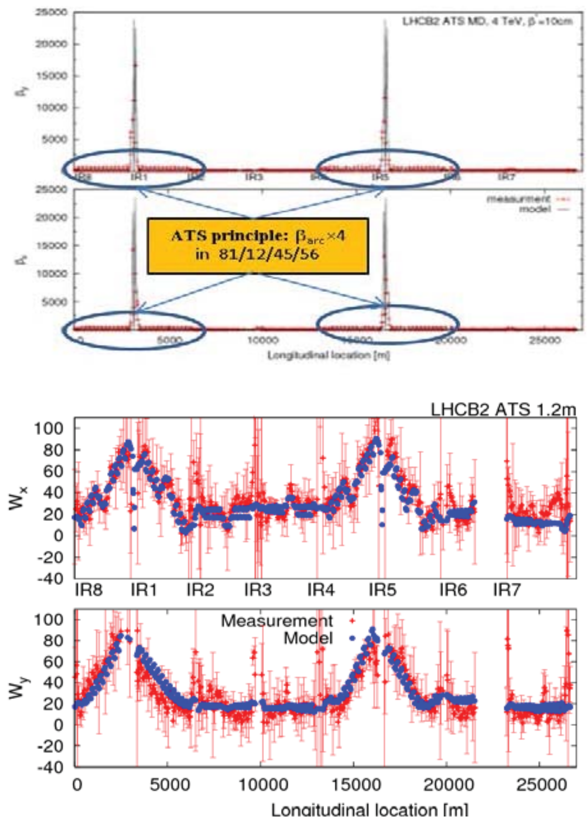

Figure 11: Telescopic optics functions and achromatic matching of the first order chromatic perturbations of the LHC as measured during a machine test demonstrating the feasibility of this optics scheme in view of the HL-LHC [27].

Crab cavities for performance boost

The presence of a crossing angle reduces both the peak luminosity and the size of the luminous region, thus enhancing the pile-up density and at the same time diminishing the constant luminosity. Crab cavities would be able to tilt the bunch at the IP and therefore mitigate those effects ([29] and Fig. 12). Explicitly a gain of 68 % or 41 % in peak luminosity, 13 % and 6 % in integrated performance, and 2.7 and 1.7 reduction of pile-up density for round and flat β* ratio, respectively could be achieved.

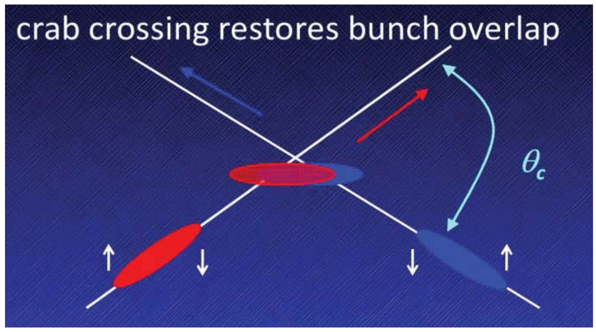

Figure 12: Principle of crab bunch tilting.

The voltage required assuming three or four cavities per beam and side is about 12 MV for round optics. The ideal location for the installation is in between D2 and Q4 on the left and right side of Point 1 and 5 in order to maximise the effect and making the tilt as local as possible [28]. Different cavity designs (Fig. 13) have been studied in parallel and first cold test showed very promising results for obtaining the desired voltage.

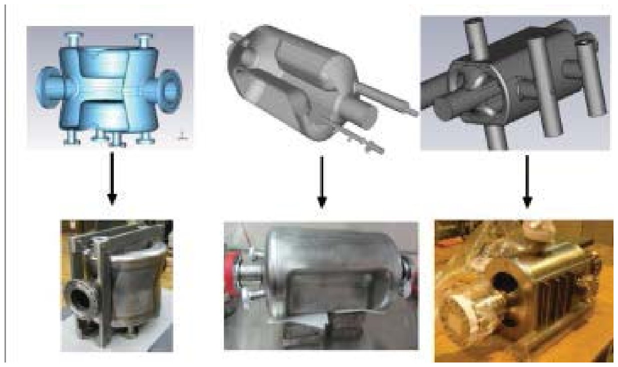

Figure 13: Crab cavity design and prototypes being studied and tested for the LHC [29].

Since these devices have never been used in hadron colliders, considerable effort is put in evaluating the failure scenarios (e.g. loss of a cavity) and the operational aspects (e.g. noise control). A test with beam is foreseen in the SPS that would validate the manufacturing aspects, the peak voltage consistency and the operational issues with beam.

Moreover, the tilting effect can also be used to reduce substantially the peak line density, thanks to the crab kissing scheme [16].

HL-LHC Baseline layout

The replacement of the inner triplets with large aperture Nb_3Sn counterparts is part of a large hardware modification that is needed for optics matching, radiation protection, and collimation improvements. The following interventions are foreseen (see Fig. 14 and 15) [30]:

- new 150 mm, 140 T/m Nb_3Sn triplets for aperture [30] and a superferric non-linear corrector package [31];
- cold 150 mm Nb-Ti D1 [32];
- new TAN-D2-Q4-Q5 with strong orbit correctors for compact crossing, and separation scheme bumps: for aperture, optics flexibility [33], and crab cavity integration [34];
- new TCL and TCT collimators for debris and protection [35];
- three or four crab cavity modules for beam tilt angle control [29];
- 4 additional 2-in-1 MS sextupoles in Q10 around IP1 and IP5 and stronger Q5 in Point 6 in order to exploit the full ATS potential [33];
- superconducting links to connect surface host power converter in order to reduce radiation related faults [36];
- wires for long-range beam-beam compensation [37].

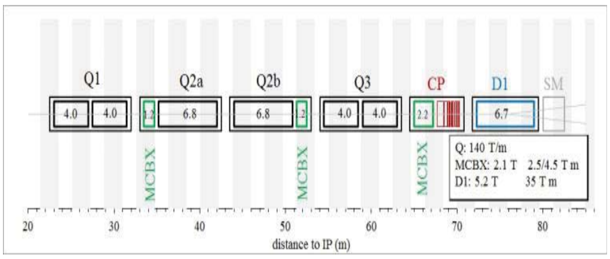

Figure 14: Schematic view of the new inner triplet region foreseen for the HL-LHC in Point 1 and 5.

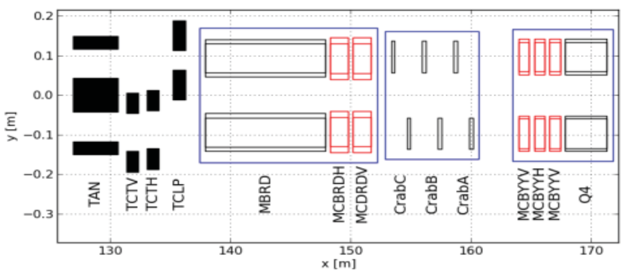

Figure 15: Schematic view of TAN - crab cavities - Q5 region foreseen for the HL-LHC in Point 1 and 5.

With the present layout and thanks to the ATS scheme, the HL-LHC aims at a baseline β* of 15 cm for round optics and 7.5 cm in the non-crossing plane (with 30 cm in the crossing plane) for flat optics.

Radiation protection of high luminosity areas

Several protection devices are being implemented to keep the radiation impact on the elements in the high luminosity regions at acceptable levels, despite the accumulated and instantaneous luminosity targets which are 10 times and 5 times higher than the ones of the nominal LHC, respectively.

Inner triplets have Tungsten inserts along their length to reduce the peak dose in the magnet to a similar level as that of the nominal triplets (about 2-3 mW/cm^3 at $5{\cdot}10^{34}$ $cm^{-2}s^{-1}$ and below 25 to 35 MGy after 3000 fb^{-1} [38], see Fig. 16).

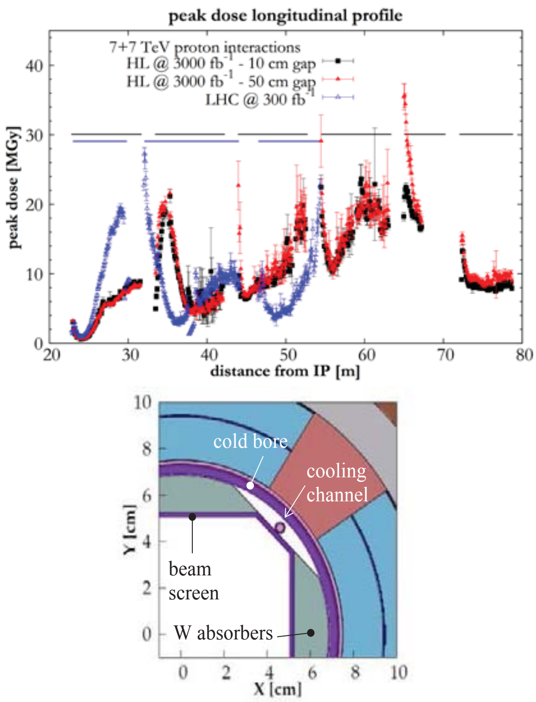

Figure 16: Simulated peak dose in the triplet area for the HL-LHC and LHC (top, [38]) and sketch of the cross section of a part of the inner triplet highlighting the W insert (bottom). The gap in between the triplets (50 cm), which is hosting the BPMs, could be reduced (e.g. 10 cm) by filling with the same high Z material inserts the region in between the couplers, which would result in a reduction of the peak dose from 35 MGy to 25 MGy, equivalent to what is expected for the LHC before the HL-LHC upgrade (LS3).

A new TAN, fixed W masks in front of D2, Q4, Q5 and additional TCLs are considered to protect the matching section (below 1 mW/cm^3 at $5{\cdot}10^{34}$ $cm^{-2}s^{-1}$ and below 25 MGy after 3000 fb^{-1} [39] could be ideally reached if the mask are sufficiently long and close to the sensitive devices, see Fig. 17). Detailed studies are being carried out on a realistic mechanical design for an accurate validation of the protection strategy.

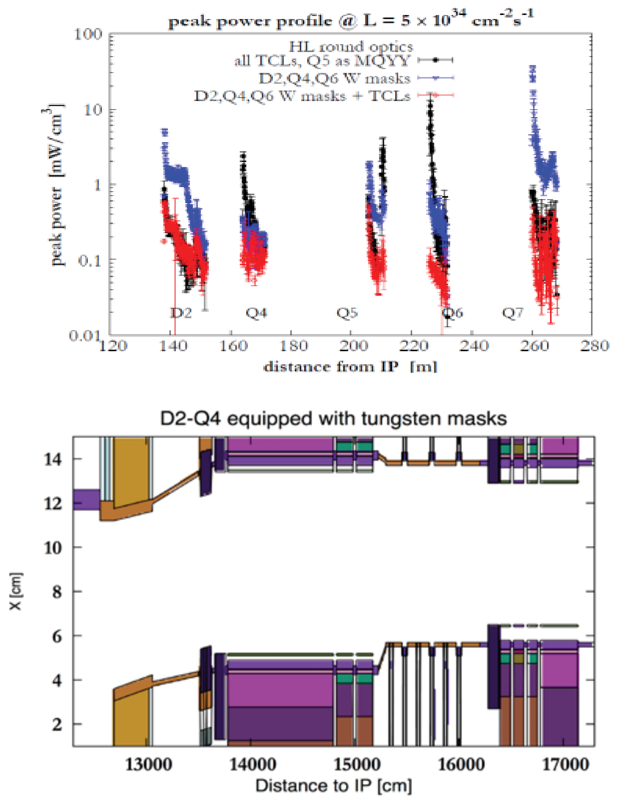

Figure 17: Simulated peak power deposited in the matching section cold magnets foreseen for the HL-LHC and LHC (top [39]) and sketch of a detail of the cross section of the TAN-Q4 area (bottom).

Collimation and aperture protection

The collimation system will face the challenge posed by twice the nominal stored beam energy, while trying to reduce as much as possible the aperture tolerances in order to achieve the lowest β* possible. The collimation system consists of a large number of devices ordered in a strict hierarchy. Closest to the beam are the primary and secondary collimators in Point 7, used for global cleaning. Other important collimators are TCS and TCDQ in Point 6, which should protect the machine in case of asynchronous dumps, and the tertiary collimators in Point 1, 5, 2, 8 that should protect the local aperture bottlenecks and reduce experimental background.

The minimum primary collimator aperture is practically determined by: the impedance budget, the ability to control the orbit to avoid loss spikes and protection during failure scenarios (e.g. asynchronous dumps). Based on these different points the following upgrades are planned [40]: metallic collimators or equivalents for impedance reasons (if compatible with the required robustness), button BPMs at all jaws for accurate and fast alignments and reduced margins, and possibly an e-lens [41] to control the halo population, mitigate loss spikes and possibly for machine protection in case of failure of the crab cavities. Even after the foreseen upgrade, the collimator settings, which define the minimum protected aperture and therefore the β* reach, practically do not scale with the beam emittance, as it would be the case if the collimation settings were determined by lifetime considerations when cutting into the beam only. While detailed cleaning efficiency and loss map simulations will define a solid scenario and collimator settings, a tentative proposal has been developed (see Table 2) to establish the β* reach [42].

Table 2: Aperture of the collimator jaws, expressed in terms of σ calculated with the arbitrary value of 3.5 µm normalized emittance. Values from the LHC design report and HL-LHC first guess are compared.

Aperture at 3.5 µm 7TeV	**LHC Design**	**HL-LHC**
TCP IR7	6.0	5.7
TCS IR7	7.0	7.7
TCS IR6	7.5	8.5
TCDQ IR6	8.0	9.0
TCT IR1/5	8.3	10.5
Min. Aperture IR1/5	8.4	12

At the same time operational margins of orbit control, beta-beating correction, dispersion correction and off-momentum errors are being reviewed in order to qualify the aperture margins. Table 3 shows the last proposal based on experience and non-conformities [43].

Table 3: Operational margin proposed for the HL-LHC aperture evaluations.

Parameter	**LHC Design**	**HL-LHC**
Closed orbit excursion	3 mm	2 mm
Beam size change from β-beat	1.1	1.1
Normalized emittance	3.75 µm	3.5 µm
Momentum offset	$8.6\ 10^{-4}$	$2\ 10^{-4}$
Relative parasitic dispersion	0.27	0.1

Beam-beam effects and crossing angle

In general, beam-beam effects are enhanced by bunch population and for the head-on interaction by small emittances. Concerning head-on effects, the maximum tune spread tolerated by the machine is not known at the moment, although the machine has been running without lifetime degradation at injection energy and without crossing angle (large β*, no long range interaction) with a beam-beam parameter of 0.034. However, three collision points at full intensity with crab crossing are considered very challenging in this respect. The long-range effects limit the minimum crossing angle expressed in beam sigma separations. For the nominal LHC, 10 σ separation was considered as a safe assumption, while for the HL-LHC one would need between 12 σ for round β* and 15 σ for flat β* aspect ratio (Fig. 18) due to the enhanced bunch population, the larger number of long range interactions and the higher beta functions [25]. These values translate to 590 µrad full crossing angle for round β* = 15 cm and 540 µrad for flat β*= 7.5/30 cm.

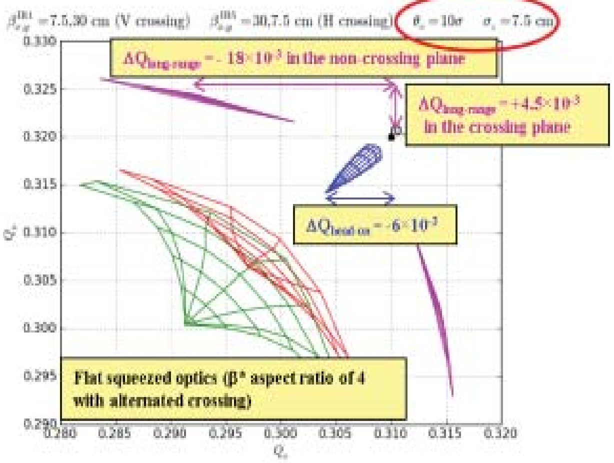

Figure 18: Illustrations of the different contributions of the beam-beam force to the tune footprint for flat beam aspect ratio [25].

In order to reduce the crossing angle with the aim of gaining aperture and reducing the voltage in the crab cavities, a long range beam-beam compensation device (for instance high current wires located close to the interactions) is foreseen to be installed. It is assumed that with this device it would be possible to reduce the required beam separation to 10 σ for both round and flat β* aspect ratios. The minimum beam separation depends also on the luminosity leveling scheme. If β* leveling is used, the minimum separation would not occur at maximum bunch population but at about 1.2 10^{11} proton per bunch (see Fig. 19). Effects like Pac-man bunches and minimum dynamic aperture in the presence of other field imperfection are under study.

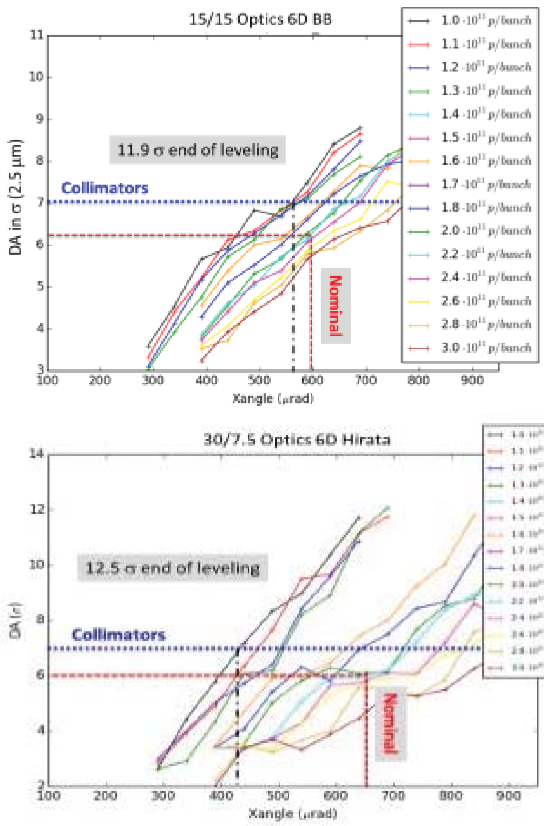

Figure 19: Scan of the dynamic aperture as a function of the crossing angle for round (top) and flat β* (bottom) aspect ratios and bunch population without wire compensation [44, 45].

Injection to collision transmission efficiencies

The beam parameters needed by the HL-LHC exceed the present capabilities of the injector chain. The LHC Injector Upgrade (LIU) project contains all the activities of consolidation and upgrade needed to produce the beam to be injected in the HL-LHC [2]. The beam parameters at LHC injection are related to the ones at collision by a budget of beam losses and emittance growth that are assumed to be 5 % and 20 % respectively. The processes that cause these losses have different sources: injection mismatch, noise, e-cloud, intra beam scattering (IBS) and non-linear diffusion. The IBS effect on the emittance growth has been evaluated by assuming a scenario of ramping time, RF voltage and longitudinal emittance and calculated as a function of bunch population and emittance (see Fig. 20 and [46]).

Three scenarios [47] have been considered with different trade-off between intensity and emittance (see Table 4). The first two correspond to the best performance that the LIU project is confident to deliver for the BCMS filling scheme "LIU-BCMS" and the standard scheme "LIU-STD", respectively. The last corresponds to the ideal parameter set for the HL-LHC. The LIU-BCMS offers very high brightness that however cannot be preserved due to the large emittance growth. This option implies also a smaller number of bunches, which makes it less attractive when the overall performance is considered (see following paragraph). The LIU-STD is still compatible with the emittance growth budget; however it does not reach the desired bunch population. The last option is well within the budget and offers the best integrated performance.

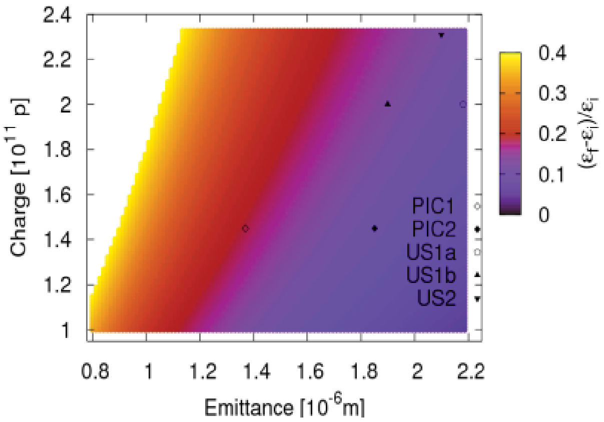

Figure 20: Emittance growth between injection and collision due to IBS. For the intensities needed by the HL-LHC baseline scenario the low value of emittance cannot be transmitted within the foreseen budget.

In order to validate the cycle scenarios it is important to know at which point of the cycle and in which location the beam losses occur (e.g. transfer lines, septa, TDI or the LHC) since the LHC can sustain 5% losses only if evenly spread in time. Concerning the emittance growth - since most of the margin are used by IBS - one has to control the additive sources (e.g. noise, injection errors) of blow-up and the blow-up due to electron cloud, to reduce the impedance with metallic collimators, and support long bunches (10 cm) till stable beams to mitigate the IBS effects.

Table 4: Beam parameters at SPS extraction and at the LHC in collision expected for three cases. The brightest one (LIU-BCMS) exceeds the IBS budget. The underlying model does not assume any horizontal/vertical coupling; therefore the blow-up is only in the horizontal plane. The percentage corresponds to emittance blow-up from injection to collision. In the RLIUP scenarios a budget of only 20% is assumed in both planes and therefore the LIU-BCMS expected emittance exceed this value. This implies that larger emittance (1.85 μm) should be more realistically considered for a fair comparison.

Scenario	**SPS Extraction**		**LHC Collision Minimum value from IBS**	**LHC collision Assumed**	
	Bunch population [10^{11}]	$\epsilon_{n\ inj}$ [μm]	$\epsilon_{n\ coll.\ (H/V)}$ [μm]	Bunch population [10^{11}]	$\epsilon_{n\ coll.}$ [μm]
LIU-BCMS	2.0	1.37	1.78(30%)/1.37	1.9	1.65
LIU-STD	2.0	1.88	2.20(17%)/1.88	1.9	2.26
HL-LHC	2.31	2.08	2.41(15%)/2.08	2.2	2.5

PERFORMACE EVALUATION OF THE HL-LHC SCENARIO

Previous sections highlighted the boundary conditions, the challenges, the upgrade plans and the open questions related to optimization of the HL-LHC performance. This section illustrates quantitative estimates of several operating scenarios and validates the choices of which parameters are to be optimized.

The analysis is carried out by evaluating the differential evolution of an ideal fill including the effect of burn-off, IBS emittance blow-up (plus an additional 200 h in the vertical plane to fit the 2012 experimental data) and radiation damping. The results of the ideal fill are extrapolated in order to obtain the required performance efficiency necessary to achieve the yearly integrated luminosity goal. Table 5shows the parameters that are constant for all scenarios. A bunch length of 10 cm has been used to mitigate the pile-up density; however the nominal 7.55 cm would be more beneficial for the hour-glass effect and the RF curvature.

Table 5: Parameters that are assumed in the evaluation of the integrated luminosity of ideal fills.

"Visible" cross-section IP1-5/8 [mb] for pile-up estimation	**85/75**
Pile-up limit IP1-5/8	140/4.5
Luminosity limit IP2 [10^{34} cm^{-2} s^{-1}]	0.002
Energy [TeV]	6.5 or 7
Total RF Voltage	16
Long. emit.ϵ_L*[eV.s] at start of fill	3.8
Bunch length (4 s)[ns]/ (r.m.s.) [cm]	1.33/10

The typical evolution of the simulated luminosity in ATLAS and CMS during a fill is shown in Fig. 21. The luminosity is levelled until β* reaches the minimum value allowed by the triplet aperture. The bunch population decays almost always linearly as the instantaneous luminosity is constant. The longitudinal emittance decays due to radiation damping and the transverse emittance is in equilibrium thanks to the balance between the growth due to IBS and noise and synchrotron radiation damping.

The β* evolution is also linked to the beam-beam separation (see Fig. 22) around the IP since the crossing angle is physically unchanged during the fill. When the luminosity is constant the length of the luminous region decreases, and therefore the longitudinal pileup density increase, because the geometric reduction factor reduces with β* at constant crossing angle. As soon as the luminosity starts to decay and β* is constant, the pileup density decays as well.

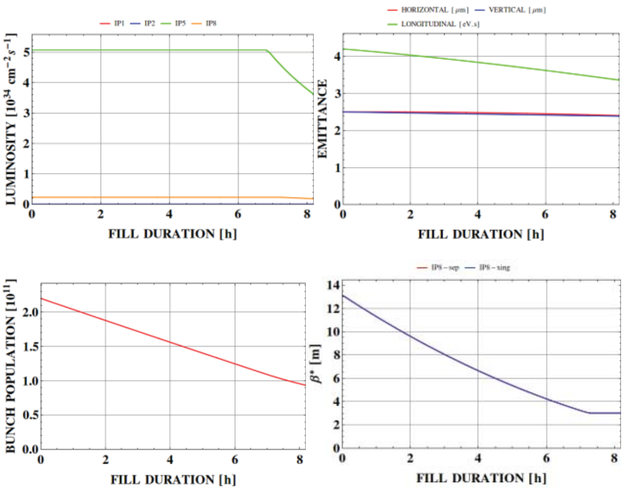

Figure 21: Luminosity (top left), emittance (top right), bunch population (bottom left), β* evolution (bottom right) as a function of time for an ideal fill of the HL-LHC baseline round scenario.

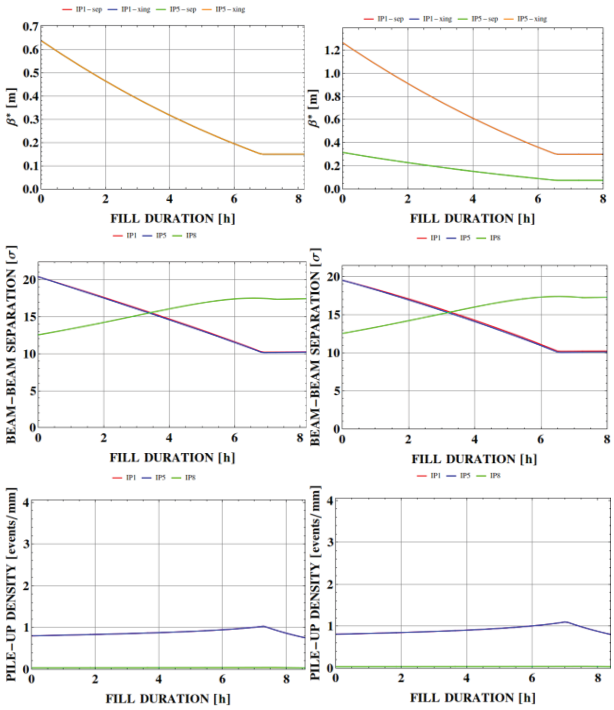

Figure 22: Evolution during an ideal fill of β* (top), beam-beam separation (middle) and pile-up density (bottom) as function of time for an ideal fill of the HL-LHC round (left) and flat (right) scenarios, respectively.

Using the differential evolution, several beam parameter scenarios have been evaluated (see Table 6 and 7) by calculating the integrated luminosity of an ideal fill, the maximum yearly integrated luminosity and the yearly integrated luminosity assuming a fill length of 6 hours. The maximum and 6 hour-fill yearly integrated luminosity is translated in the efficiency required to reach the target of 270 fb^{-1}, respectively η_{6h} and η_{opt}.

The first scenario, labelled RLIUP2, is characterized by a fairly large virtual luminosity obtained by very small transverse emittance and comparably small bunch population. The integrated performance is the worst of the set because the low intensity cannot produce long enough fills and the effect of IBS reduces very quickly the virtual luminosity over time.

Scenario LIU-BCMS is produced by the BCMS scheme and full LIU upgrade and neglecting the part of emittance growth due to the IBS (see Table 3). This scenario offers the largest virtual luminosity, however overall performances are degraded by the lower number of bunches and the IBS effects (slightly underestimated in the table since the starting emittance should be higher to be consistent between the scenarios with a common additive emittance blowup in addition to the IBS effects).

Scenario LIU-STD is produced by the standard production scheme and the full LIU upgrade. This scenario, while having a smaller virtual luminosity, results in larger integrated performance compared to the previous one thanks to the higher number of bunches and the resulting higher levelled luminosity.

Table 6: Parameters and estimated peak performance for several options at 6.5 TeV. [1)] Flat beams are also compatible with the crab kissing scheme. [2)] Long range beam-beam compensators are assumed to allow reducing the crossing angle to 10 σ, otherwise the crossing angle in parenthesis would be needed. [3)] These values of β* are assumed to be possible thanks to the reduction of the crossing angle for the same aperture margins of the nominal round beam case. 4) The value of β* can be reached only with LHC design collimator settings. [5)] Scenarios evaluated with a pile-up limit of 200 events per crossing. [6)] The starting value of the emittance is not compatible with both the IBS blow-up from injection to collision and the otherwise assumed 20% margins. A value of 1.86 μm (30% blow-up) is more likely.

	N_b coll 10^{11}	$\varepsilon_{n,}$ coll μm	β* (ing/ sep) cm	Xing angle μrad	n_{coll} IP1,5	L_{peak} 10^{34} $cm^{-2}s^{-1}$	L_{lev} 10^{34} $cm^{-2}s^{-1}$	t_{lev} h	t_{opt} h	η_{6h} %	η_{opt} %	Avg.Peak pile-up Density ev./mm
RLIUP2	1.5	1.3[6)]	15	366	2592	17.6	4.8	4.4	5.8	64.6	64.6	0.88
LIU-BCMS	1.9	1.65[6)]	13.5[3)]	420	2592	21.7	4.8	6.3	7.5	61	58.4	0.94
LIU-STD	1.9	2.26	14.5[3)]	474	2736	15.8	5.06	5.3	6.9	58.2	57.5	0.97
HL-Flat	2.2	2.5	30/ 7.5[1)]	348[2)] (550)	2736	17.2	5.06	6.5	8.0	57.8	54.5	1.05
HL-Round	2.2	2.5	15	490[2)] (590)	2736	18.7	5.06	6.8	8.2	57.8	54	1.05
LIU-BCMS	1.9	1.65	13.5[3)]	420	2592	21.7	6.87[5)]	4.3	6.2	52.2	52.2	1.34
HL-Round	2.2	2.5	15	490	2736	17.2	7.24[5)]	5.4	7.3	48.8	48.4	1.37
HL-SRound	2.2	2.5	10[4)]	600	2736	18.7	7.24[5)]	4.4	6.7	47.7	46.4	1.55

Table 7: As Table 6, but computed at 7 TeV. Performance increase with respect to 6.5 TeV thanks to the reduction of the geometrical emittance and the increase of radiation damping better mitigating the blow-up due to the IBS.

	N_b coll 10^{11}	$\varepsilon_{n,}$ coll μm	β* (xing/ sep) cm	Xing angle μrad	n_{coll} IP1,5	L_{peak} 10^{34} $cm^{-2}s^{-1}$	L_{lev} 10^{34} $cm^{-2}s^{-1}$	t_{lev} h	t_{opt} h	η_{6h} %	η_{opt} %	Avg.Peak pile-up density ev./mm
RLIUP2	1.5	1.3[6)]	15/15	341	2592	19	4.8	4.7	6	63.4	63.4	0.94
LIU-BCMS	1.9	1.65[6)]	13.5[3)]	405	2592	23.4	4.8	6.7	7.8	61	57.5	0.98
LIU-STD	1.9	2.26	14.5[3)]	457	2736	17	5.06	5.7	7.2	58.2	56.4	1.01
HL-Flat	2.2	2.5	30/ 7.5[1)]	335[2)]/ 550	2736	18.6	5.06	7	8.4	57.8	53.5	1.12
HL-Round	2.2	2.5	15/15	476[2)]/ 590	2736	20.1	5.06	7.3	8.6	57.8	53.1	1.03
LIU-BCMS	1.9	1.65	13.5[3)]	579	2592	23.4	6.87[5)]	4.6	6.4	51.4	51.3	1.34
HL-Round	2.2	2.5	15/15	473	2736	20.1	7.24[5)]	4.8	7	48.2	47.4	1.37
HL-SRound	2.2	2.5	10[4)]	600	2736	26.8	7.24[5)]	5.8	7.6	47.6	45.7	1.55

Scenarios HL-Flat and HL-Round represent the HL-LHC baseline and offer the best performance and are identical besides the difference in the β* values. Flat optics allows for a smaller voltage from the crab cavities, but relies on beam-beam long range compensation to avoid increasing the crossing angle too much. Also beam-beam effects with unequal beam sizes need to be validated. Round optics require a larger crab cavity voltage. Long range beam-beam compensation, while helpful to reduce the crossing angle, is not as critical as for the flat option. The last set of scenarios assumes that the maximum levelled luminosity could be increased such that the maximum number of pile-up events is 200. In this case, the yearly performance of LIU-STR and HL-Round increases, but only HL-Round can reach the performance goal with efficiency below 50%. The reason is that the higher bunch population, as discussed earlier in this paper, gives more margins for aggressive boundary conditions.

SUMMARY AND CONCLUSIONS

The HL-LHC integrated luminosity expectations are bounded by the capabilities of the experiments in using large instantaneous luminosity. Once the maximum level is established, one has to operate the LHC with the beam parameters and the reliability that allows keeping the maximum accepted luminosity as long as possible. Assuming $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$, fills as long as 10 hours are needed to approach the performance goal of 270 fb^{-1} per year or 3000 fb^{-1} by 2035 with performance efficiency close to those achieved in 2012. The maximum number of colliding bunches of 2736, a bunch population of 2.2 10^{11} and a virtual luminosity of $20 \cdot 10^{34}$ $cm^{-2}s^{-1}$ allow to exploit most of the parameter space and give margins either for pushed levelled luminosity or overall robustness against unexpected issues. The full LIU upgrade, the solution of the e-cloud issues and the control of impedance are needed to support a large bunch population. The virtual luminosity is obtained by upgrading the inner triplet and MS magnets to be able to reduce β* thanks to the ATS scheme, and by installing crab cavities and long-range wire compensators to eliminate the geometric reduction factor. Increased radiation levels need to be addressed with a redesign of the TAN-D2-Q4 region. Critical open questions besides the e-cloud are how to establish lossless operations of luminosity levelling and how to drastically reduce the number of unwanted beam dumps.

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REFERENCES

[1] L. Rossi, “LHC Upgrade Options and Plans”, in Proceedings of IPAC2011, San Sebastian, Spain, http://cern.ch/HiLumiLHC.

[2] R. Garoby, “Plans for the upgrade of the LHC injectors”, in Proceedings of IPAC2011, San Sebastian, Spain, http://cern.ch/liu-project.

[3] S. Myers, F. Bordry, “Review of the LHC and Injector Upgrade Plans Workshop”, Archamps, 29th-31st October, 2013, http://indico.cern.ch/conferenceDisplay.py?confId=260492.

[4] M. Meddahi, L. Rossi, “Adding Performance improving consolidation”, RLIUP, Session 3A, Archamps, 29th-31st October, 2013, http://indico.cern.ch/sessionDisplay.py?sessionId=3&confId=260492#20131030.

[5] M. Meddahi, L. Rossi, “Upgrade scenario 1”, RLIUP, Session 3B, Archamps, 29th-31st October, 2013, http://indico.cern.ch/sessionDisplay.py?sessionId=2&confId=260492#20131030.

[6] G. Goddard, R. Garoby, “Upgrade scenario 2”, RLIUP, Session 4, Archamps, 29th-31st October, 2013, http://indico.cern.ch/sessionDisplay.py?sessionId=4&confId=260492#20131030.

[7] M. Lamont, “Integrated luminosity scenarios”, 6th HL-LHC Coordination Group meeting, 25/7/2013, https://indico.cern.ch/getFile.py/access?contribId=8&resId=0&materialId=slides&confId=264629.

[8] G. Arduini, et al., “PICS: what do we gain in beam performance”, these proceedings.

[9] J. Wenninger, “Integrated performance of the LHC at 25 ns without and with LINAC4”, these proceedings.

[10] B. Di Girolamo, “Detector Limits”, these proceedings.

[11] R. Jacobsson, “Plans and physics outlook for non-high luminosity experiments until and after LS3”, these proceedings.

[12] G. Antchev et al., “Luminosity-independent measurements of total, elastic and inelastic cross sections at $\sqrt{s}$=7 TeV”, CERN-PH-EP-2012-353.

[13] G. Antchev et al., “Luminosity-independent measurements of the proton-proton total cross section at $\sqrt{s}$=8 TeV”, CERN-PH-EP-2012-354.

[14] B. Gorini, private communication.

[15] F.Zimmermann, “New ideas”, HL-LHC/LIU Joint Workshop, CERN, 30 March 2012, https://indico.cern.ch/contributionDisplay.py?contribId=4&confId=175259.

[16] S. Fartoukh, “Pile-up at HL-LHC and possible mitigation”, ECFA High Luminosity LHC Experiments Workshop, 1st October 2013, Aix-les-Bains, France, http://indico.cern.ch/materialDisplay.py?contribId=14&sessionId=5&materialId=slides&confId=252045.

[17] R. Assmann, “Implications of higher intensities in the LHC”, Proceedings of Chamonix 2010 workshop on LHC Performance.

[18] O. Bruning, “HL-LHC Parameter Space and Scenarios”, Proceedings of Chamonix 2012 workshop on LHC Performance.

[19] E. Métral, N. Mounet, “Update on stability limits and collimator impedance upgrade needs”, 20th Hi-Lumi Work Package 2 Task Leaders’ Meeting, 25/10/2013, https://indico.cern.ch/getFile.py/access?contribId=4&resId=0&materialId=slides&confId=278765.

[20] G. Rumolo, “Update on Electron Cloud”, presentation at the 169th LHC Machine Committee, https://espace.cern.ch/lhc-machine-committee/Presentations/1/lmc_169/lmc_169e.pdf.

[21] R. Bailey, P. Collier .”Standard Filling Schemes for Various LHC Operation Modes”, LHC-Project-note-323.

[22] H. Damerau, A. Findlay, S. Gilardoni, S. Hancock, “RF manipulations for higher brightness LHC-type beams”, WEPEA044, IPAC 2013.

[23] B. Gorini, private communication.

[24] R. Jacobsson, “Needs and requirements from the LHC physics experiments”, Proceedings of ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders, CERN, March 2013, https://indico.cern.ch/getFile.py/access?contribId=60&sessionId=12&resId=0&materialId=paper&confId=189544.

[25] S. Fartoukh, “Breaching the Phase I optics limitations for the HL-LHC”, Proceedings of Chamonix 2011 workshop on LHC Performance.

[26] S. Fartoukh, “Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade”, Phys. Rev. ST Accel. Beams 16, 111002.

[27] S. Fartoukh et al, “The 10cm beta* MD”, CERN-ATS-Note-2013-004 MD.

[28] R. De Maria, S. Fartoukh, A. Bogomyakov, M. Korostelev, “HLLHCV1.0: HL-LHC Layout and Optics Models for 150 mm Nb3Sn Triplets and Local Crab-cavities”, IPAC 2013.

[29] R. Calaga et al, "Crab Cavity Workshop", Proceedings of Chamonix 2012 workshop on LHC Performance.

[30] E. Todesco, et al., (2013) Design studies of Nb3Sn quadrupole magnet for the high luminosity LHC. Submitted to: IEEE Trans. Appl. Supercond. *ASC Conference proceeding*, 2012 Portland.

[31] E. Todesco, et al. HiLumi PLC meeting, 26 March 2013.

[32] Q. Xu, et al., (2013) Design of a large single-aperture dipole magnet for HL LHC upgrade. Submitted to: IEEE Trans. Appl. Supercond. *ASC Conference proceeding*, 2012 Portland.

[33] S. Fartoukh, "Towards the LHC Upgrade using the LHC well characterized technology", sLHC-Project-report-0049, 2010.

[34] R. De Maria, S. Fartoukh, "Optics and Layout for the HL-LHC Upgrade Project with a Local Crab-Cavity Scheme," sLHC-Project-Report-55, 2011.

[35] S. Redaelli, Collimation Status and plans, 2nd joint HiLumi-Larp Annual meeting, Frascati, 2012, https://indico.cern.ch/contributionDisplay.py?contribId=61&sessionId=4&confId=183635.

[36] A. Ballarino, HiLumi WP6.

[37] J.-P. Koutchouk, "Principle of a correction of the long-range beam-beam effect in LHC using electromagnetic lenses", LHC Project Note 223, 2000, http://cds.cern.ch/record/692058.

[38] L. Esposito, F. Cerutti, "Energy deposition in the 150 mm baseline", WP3 meeting, 28 May 2013, https://lhc-div-mms.web.cern.ch/lhc-div-ms/tests/MAG/docum/hilumi/Presentations/2013-05-28_FLUKA_HL-LHC_EnDep.pptx.

[39] L. Esposito, F. Cerutti, "Update in energy deposition for the HL-LHC IR1-5", HiLumi WP2 Task leader meeting, 25th October, 2013, http://indico.cern.ch/materialDisplay.py?contribId=5&materialId=slides&confId=278765.

[40] S. Redaelli, Collimation Status and plans, 2nd joint HiLumi-Larp Annual meeting, Frascati, 2012, https://indico.cern.ch/contributionDisplay.py?contribId=61&sessionId=4&confId=183635.

[41] G. Stancari, et al. "Beam halo dynamics and control with hollow electron beams", in Proceedings of the 52nd ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB2012), http://arxiv.org/abs/1209.5380.

[42] R. Bruce, S. Redaelli, "Update on aperture margin estimation for HL-LHC", HiLumi WP2 Task Leader Meeting, 13 September 2013, http://indico.cern.ch/materialDisplay.py?contribId=1&materialId=slides&confId=270585.

[43] R. Bruce, "Apertures and protection for HL-LHC layouts (implication of tolerances and review of tolerances based on Run I experience) for different optics configurations (Round/Flat)", 3rd Joint HiLumi LHC-LARP Annual Meeting, https://indico.cern.ch/contributionDisplay.py?contribId=50&confId=257368.

[44] D. Banfi, J. Barranco, T. Pieloni, A. Valishev, "Required Beam-Beam separation for flat and round beams for 25 ns and considerations on the filling schemes", 19th HiLumi WP2 Task Leader Meeting, https://indico.cern.ch/getFile.py/access?contribId=0&resId=0&materialId=slides&confId=278323.

[45] D. Banfi, J. Barranco, T. Pieloni, A. Valishev, "Update on crossing angle scaling with bunch intensity", 20th HiLumi WP2 Task Leader Meeting, https://indico.cern.ch/getFile.py/access?contribId=6&resId=1&materialId=slides&confId=278765.

[46] R. Tomas, "IBS blow-up estimates and alternative scenarios for HL-LHC", 17th HiLumi WP2 Task Leader Meeting, https://indico.cern.ch/materialDisplay.py?contribId=3&materialId=slides&confId=272141.

[47] Input provided during the LIU Technical Meetings: http://indico.cern.ch/categoryDisplay.py?categId=4985.

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CAN WE EVER REACH THE HL-LHC REQUIREMENTS WITH THE INJECTORS?

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Abstract

The present intensity and brightness limitations of the LHC injector synchrotrons for 25 ns beams are space charge, beam loading, instabilities in the transverse and longitudinal planes and electron cloud effects. This paper reviews how these performance limitations are expected to change after implementing the mitigation measures foreseen within the Upgrade Scenario 2. The question is addressed whether the beam performance will match the requirements of the HL-LHC project. In particular, we assume operational scenarios with 25 ns beams produced with the traditional bunch splitting scheme in the PS and with the already tested batch compression scheme. A set of baseline parameters at LHC injection is then established based on extrapolation from the beam characteristics achieved in 2012 and the expected gains from the upgrades.

INTRODUCTION

The Upgrade Scenario 2 (US2) of the HL-LHC project aims at accumulating an integrated luminosity of 3000 fb^{-1} in p-p collisions at a center of mass energy of $\sqrt{s} = 14$ TeV by the end of 2035. Reaching this goal requires an average integrated luminosity of 270 fb^{-1}/year during the HL-LHC era with levelling at an instantaneous luminosity of 5×10^{34} cm^{-2}s^{-1} and the nominal 25 ns bunch spacing. The US2 baseline beam parameters at LHC injection are therefore targeted at an intensity of $N = 2.3 \times 10^{11}$ p/b within a normalized transverse emittance of $\varepsilon_n = 2.1\,\mu$m at LHC injection [1].

Before discussing the performance reach of the injector complex in US2, i.e. after the implementation of all upgrades planned within the LIU project, the operational beam characteristics achieved in 2012 shall be reviewed. Using the standard production scheme with 72 bunches per PS batch, the injectors delivered the 25 ns beam with about $N \approx 1.2{\times}10^{11}$ p/b and transverse emittances of $\varepsilon_n \approx 2.6\,\mu$m for the LHC Scrubbing Run. The successful implementation of the Batch Compression bunch Merging and Splitting (BCMS) scheme [2, 3] in the PS allowed reducing the number of splittings of each PSB bunch by a factor two at the expense of reducing the number of bunches per PS batch from 72 to 48. With this scheme a high brightness 25 ns beam with similar intensity per bunch but a transverse emittance of about $\varepsilon_n \approx 1.4\,\mu$m at SPS extraction was provided to the LHC for the 25 ns pilot physics run. For both beam types, the achievable beam brightness is determined by the multi-turn injection in the PSB and space charge in the PS. The main intensity limitations for the 25 ns beams in the injector complex are due to electron cloud effects and longitudinal instabilities in the SPS. Stable beam conditions with four PS batches and bunch lengths at SPS extraction compatible with injection into the LHC were achieved for a maximum intensity of about $N \approx 1.3 \times 10^{11}$ p/b.

Table 1: Beam loss and emittance growth budgets.

Machine	$-\Delta N/N_0$	$\Delta\varepsilon/\varepsilon_0$
PSB injection to extraction	5 %	5 %
PS injection to extraction	5 %	5 %
SPS injection to extraction	10 %	10 %
Total	19 %	21 %

For the following estimation of the achievable beam parameters out of the LHC injectors in the future, it is assumed that emittance growth and losses are both limited to 5 % in the PSB and in the PS, respectively, and to 10 % in the SPS as summarized in Table 1.

All upgrades for the PSB and PS foreseen in US2 are also part of Upgrade Scenario 1 (US1) and are discussed in more detail in Ref. [4]. The expected performance reach of the PS complex is therefore discussed only briefly in what follows. This paper is focused on the upgrades and measures, which aim at mitigating the performance limitations of the SPS.

PS COMPLEX

Space charge and beam brightness limitations

In the present configuration with LINAC2, the LHC beams are produced in the PSB at a constant beam brightness [5], which is mainly determined by the multi-turn injection process and space charge effects in the low energy part of the cycle. It is expected that the connection of LINAC4 and the H$^-$ charge exchange injection at 160 MeV will allow doubling the beam brightness out of the PSB [6], i.e. achieving twice the intensity for the same transverse emittance as compared to today's operation. This is illustrated in the limitation diagrams for the standard and the BCMS beam production schemes shown in Fig. 1, where the shaded areas correspond to beam parameters not accessible after the LIU upgrade. Note that the normalized transverse emittance is plotted as a function of the intensity per bunch at LHC injection (450 GeV) including already the budgets for emittance growth and losses through the injector chain as defined in Table 1.

In order to mitigate space charge effects on the PS injection plateau with the higher beam brightness available with

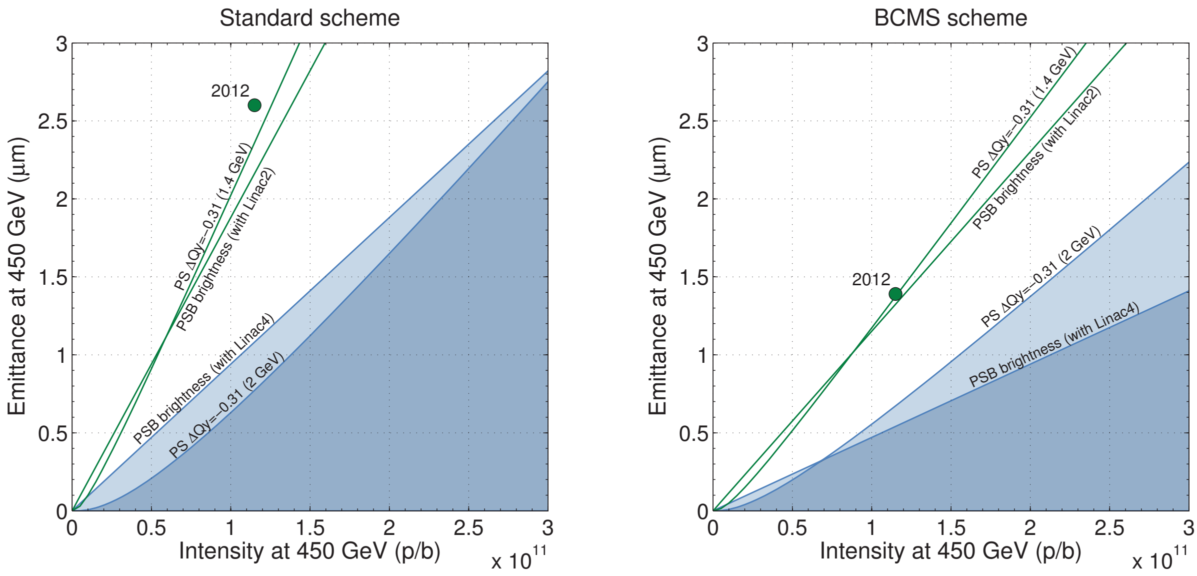

Figure 1: Beam brightness limitations in the PS complex for the standard 25 ns beam production scheme (left) and the 25 ns BCMS scheme (right) after the LIU upgrades (blue curves) and at present (green curves) together with the beam performance achieved in 2012 (green dots).

LINAC4, the PSB-PS transfer energy will be increased from the present 1.4 GeV to 2 GeV as part of the baseline LIU PSB and PS upgrades. Based on measurements with single bunch beams [7] and the operational experience with the high brightness 25 ns BCMS beam at 1.4 GeV, a maximum vertical space charge tune shift of $\Delta Q_y \approx -0.31$ on the PS injection plateau can be considered acceptable with respect to blow-up and losses [6]. The corresponding transverse emittance as a function of intensity per LHC bunch for this tune shift is shown in Fig. 1 together with the beam parameters at LHC injection achieved in 2012. The highest beam brightness in the PS achievable with the 2 GeV upgrade is then estimated assuming the maximum bunch length compatible with the PSB recombination kicker rise time, i.e. $\tau = 205$ ns for the standard production scheme (6 PSB bunches injected on harmonic number $h = 7$ in the PS) and $\tau = 135$ ns for the BCMS beams (8 PSB bunches injected on $h = 9$), and the largest longitudinal emittance compatible with the RF gymnastics. Note that after the implementation of the LIU upgrades, i.e. the connection of LINAC4 and the 2 GeV PSB-PS transfer, the PS complex is expected to deliver practically 25 ns beams with twice higher brightness as compared to the present performance.

Intensity limitations

Considering the operational experience with other high intensity beams, no intensity limitations from coherent beam instabilities are to be expected in the PSB within the parameter range of interest for HL-LHC

In the PS, longitudinal coupled-bunch instabilities during acceleration and at flat top presently limit the intensity of LHC beams to about $N \approx 1.9 \times 10^{11}$ p/b at extraction. Furthermore, transient beam loading induces asymmetries of the various bunch splittings and thus a bunch-to-bunch intensity variation along the bunch train. After the installation of a new coupled-bunch feedback system with a dedicated kicker cavity and new 1-turn delay feedback boards for beam loading compensation, the intensity limit will be pushed to more than $N = 2.5 \times 10^{11}$ p/b, beyond the requirement for the 25 ns HL-LHC beam [4].

Various instabilities in the transverse plane can be observed with LHC beams in the PS. Horizontal head-tail instabilities are encountered at flat bottom [8], which are presently cured by introducing linear coupling between the transverse planes and operating close to the coupling resonance. It was demonstrated in recent Machine Development (MD) studies that these head-tail instabilities at 1.4 GeV can be suppressed also by the PS transverse feedback system commissioned in 2012 [9], which has the advantage of providing additional flexibility for optimizing the machine working point for the space charge dominated LHC beams. The power amplifiers of this feedback are presently being upgraded in the frame of the LIU project in preparation for the future injection at 2 GeV.

The fast vertical instability observed in the PS during transition crossing with high intensity (TOF-like) beams is not expected to be a limitation for the HL-LHC beams [10]. However, a similar instability discovered recently with single bunch beams of small longitudinal emittance needs to be analyzed further in future MD studies, as it could not be cured with the aforementioned PS transverse feedback system due to its limited bandwidth [9].

After the final bunch splittings at the PS top energy resulting in the 25 ns bunch spacing, an electron cloud is developing during the bunch shortening and bunch rotation before extraction to the SPS [11]. Nevertheless, no beam degradation has been observed so far in operational conditions as the time of interaction between the beam and the electron cloud is restricted to a few tens of milliseconds. It was observed in dedicated MD studies that the electron cloud drives a horizontal coupled bunch instability if the 25 ns beam is stored at top energy [12]. The onset time of this instability could be efficiently delayed by the PS transverse feedback system [9]. The electron cloud is therefore not expected to be a limitation for the HL-LHC beams.

SPS

The main challenges for future high intensity 25 ns LHC beams in the SPS are instabilities in the transverse and longitudinal planes, beam loading and RF power, electron cloud and space charge effects on the long injection plateau. Since the end of 2010, extensive machine studies have been performed with a low gamma transition optics. In comparison to the Q26 optics used in the past, which has 26 as the integer part of the betatron tunes and a gamma transition of $\gamma_t = 22.8$, the working point is lowered by 6 integer units in both planes in the Q20 optics [13] such that the transition energy is reduced to $\gamma_t = 18$. Consequently, the phase slip factor $\eta \equiv 1/\gamma_t^2 - 1/\gamma^2$ is increased throughout the acceleration cycle with the largest relative gain of a factor 3 at injection energy, as illustrated in Fig. 2. As the

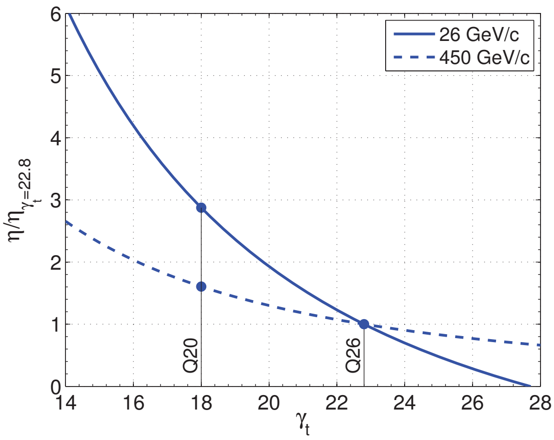

Figure 2: Phase slip factor η relative to the value of the Q26 SPS optics as a function of the gamma transition. The values of $\gamma_t = 22.8$ and $\gamma_t = 18$ correspond to the Q26 and Q20 optics, respectively.

intensity thresholds for all instabilities observed in the SPS scale with the slip factor η, a significant improvement of beam stability is achieved with the Q20 optics as discussed in more detail below. The Q20 optics is being used successfully in routine operation for LHC filling since September 2012 [14] and will be the default machine configuration for LHC beams in the SPS in the future.

Transverse Mode Coupling Instability

The vertical single bunch Transverse Mode Coupling Instability (TMCI) at injection is one of the main intensity limitations in the Q26 optics. For bunches injected with the nominal longitudinal emittance $\varepsilon_l = 0.35$ eVs, the corresponding instability threshold is around $N_{th} \approx 1.6 \times 10^{11}$ p/b (with vertical chromaticity close to zero) [15]. The instability results in emittance blow-up and fast losses as shown in Fig. 3 (top). Slightly higher intensities can be reached when increasing the chromaticity, however at the expense of enhanced incoherent emittance growth and losses on the flat bottom.

Analytical models based on a broadband impedance predict that the instability threshold with zero chromaticity scales like $N_{th} \propto |\eta|\varepsilon_l/\beta_y$ [16], where β_y denotes the vertical beta function at the location of the impedance source. Thus, the instability threshold can be raised by injecting bunches with larger longitudinal emittance. However, the

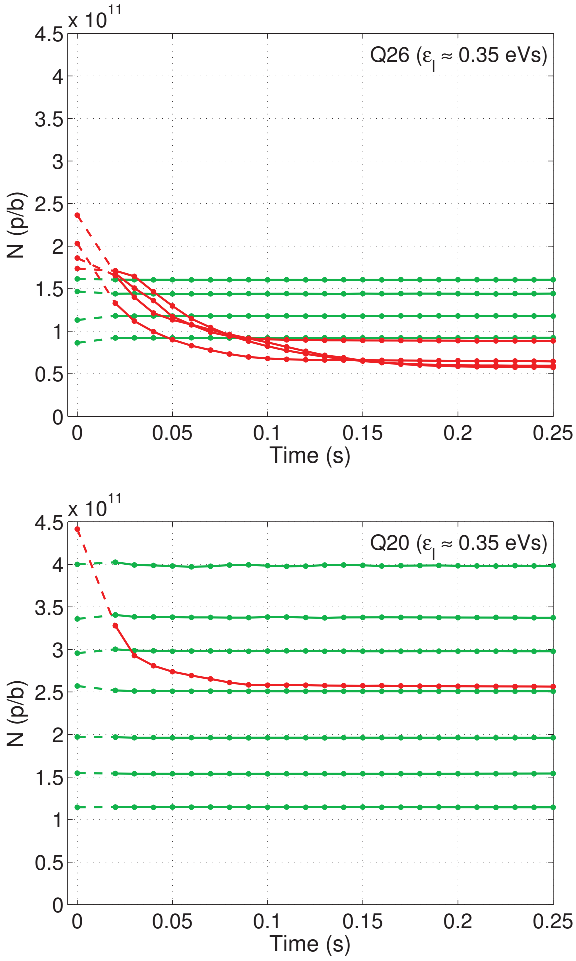

Figure 3: Examples of the intensity evolution as a function of time after injection in the Q26 optics (top) and the Q20 optics (bottom). Green curves correspond to stable beam conditions, red traces indicate cases above the TMCI threshold.

beam transmission between PS and SPS is degrading for larger longitudinal emittances unless additional cavities in the PS are used for optimizing the bunch rotation at extraction [17]. On the other hand, a significant increase of the instability threshold is expected in the Q20 optics even with the nominal longitudinal emittance, since the product of the slip factor and the vertical beta function at important impedance sources ($\eta\,\beta_y$) is about 2.5 times higher compared to the Q26 optics. This has been verified in measurements with high intensity single bunch beams as shown in Fig. 3 (bottom). The instability threshold in the Q20 optics for chromaticity close to zero and nominal longitudinal emittance was found at around $N_{th}\approx 4.5\times 10^{11}$ p/b in good agreement with numerical simulations using the latest SPS impedance model [18].

With the Q20 optics the TMCI is not of concern for the beam parameters envisaged by the HL-LHC, even for the 50 ns "back-up" scenario [19] which requires significantly higher intensities per bunch compared to the 25 ns beams.

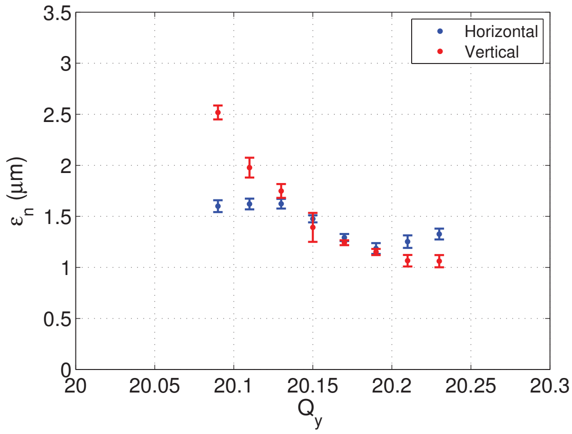

Figure 4: Transverse emittances measured at the end of the flat bottom as a function of the vertical tune. Measurements performed with single batches of the 50 ns BCMS beam.

Space charge

After the successful implementation of the BCMS scheme [3], the PS was able to provide a high brightness 50 ns beam with an intensity of $N \approx 1.95\times 10^{11}$ p/b and transverse emittances of about $\varepsilon_n \approx 1.1\,\mu$m at the end of 2012. A working point scan was performed with the Q20 optics using this beam in order to see how much space in the tune diagram is needed to accommodate the incoherent space charge tune spread and thus to minimize emittance blow-up. For each working point, the transverse emittances were measured with the wire scanners in turn acquisition mode (average profile along the bunch train) at the end of the 10.8 s flat bottom of the LHC cycle. Single batches were used for this experiment in order to study the blow-up along the entire injection plateau.

Figure 4 shows the measured transverse emittances for vertical tunes between $Q_y = 20.08$ and $Q_y = 20.23$ and a horizontal tune of about $Q_x \approx 20.13$, where the error bars indicate the spread over several measurements. Significant emittance blow-up is observed for vertical tunes close to the integer resonance, while the sum of the two transverse emittances is preserved for vertical tunes above $Q_y = 20.19$. This is consistent with the calculated incoherent space charge tune spread of $\Delta Q_x = -0.11$ and $\Delta Q_y = -0.20$ for a bunch length of $\tau \approx 3$ ns and an rms momentum spread of $\delta p/p_0 \approx 1.5\times 10^{-3}$. For all the working points studied here, the losses on the injection plateau were typically of the order of 1% and the total transmission up to flat top was usually about 93% (without scraping). Further details are given in Ref. [20].

Based on the above results and considering the budgets for emittance blow-up and losses defined in Table 1, which permit slightly more blow-up in the SPS than observed in the measurements, the presently maximum acceptable space charge tune shift in the SPS for an optimized working point is set to $\Delta Q_y = -0.21$.

Longitudinal instabilities and RF power

The longitudinal instabilities observed with LHC beams in the SPS are a combination of single bunch and coupled bunch effects [21]. The beam is stabilized in routine operation by increasing the synchrotron frequency spread using the 4th harmonic (800 MHz) RF system in bunch-shortening mode in combination with controlled longitudinal emittance blow-up along the ramp, which is performed with band-limited phase noise in the main 200 MHz RF system.

For a given longitudinal emittance and matched RF voltage the thresholds of the longitudinal coupled bunch instability and the single bunch instability due to loss of Landau damping scale proportional to the slip factor η [22]. Improved longitudinal beam stability was therefore observed in measurements with the Q20 optics at injection and during the ramp [23], where sufficient RF voltage is available to restore the same bucket area as with the Q26 optics. In fact, the Q20 optics provides significant margin for increasing the beam intensity at injection energy, where the attainable longitudinal emittance is limited by capture losses and the transfer efficiency between the PS and SPS.

The situation is different at flat top. The maximum voltage is applied in both optics in order to shorten the bunches for the transfer into the 400 MHz buckets of the LHC. Better beam stability would still be achieved in the Q20 optics for a given longitudinal emittance, however, in this case the bunches would be longer. In order to have the same bunch length in the two optics, the longitudinal emittance thus has to be smaller in the Q20 optics. From the scaling of the instability threshold for loss of Landau damping (LD) [22] it follows that the same beam stability is obtained in both optics for the same bunch length at extraction.

At the end of 2012, a series of MD sessions were devoted to the study of high intensity 25 ns beams in the Q20 optics. Figure 5 shows the measurements of the bunch length along

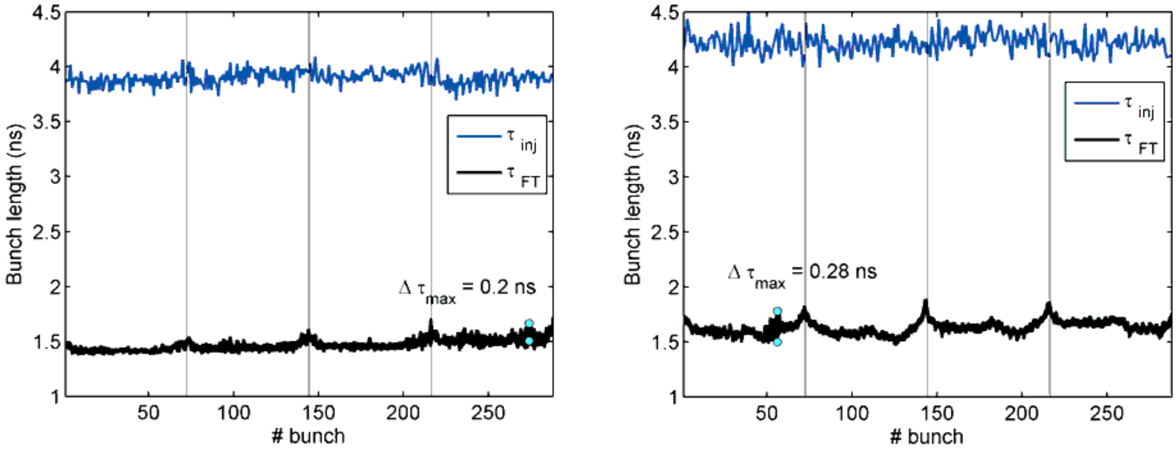

Figure 5: Bunch length measurements along the four batches of the 25 ns beam in the Q20 optics for intensities of about $N \approx 1.2 \times 10^{11}$ p/b (left) and $N \approx 1.35 \times 10^{11}$ p/b (right). The blue trace corresponds to injection and the black traces correspond to 8 measurements within one synchrotron period at flat top. The maximum bunch length variation $\Delta\tau_{\max}$ due to quadrupole oscillations at flat top is indicated.

the train at injection and at flat top for two different intensities. Note that the average bunch length increases by about 10% when pushing the intensity from $N \approx 1.2 \times 10^{11}$ p/b to $N \approx 1.35 \times 10^{11}$ p/b. The reason for that is the larger longitudinal emittance of the beam already at injection (bunches are already longer) and the controlled longitudinal emittance blow-up in the SPS required for beam stabilization. The intensity of $N \approx 1.35 \times 10^{11}$ p/b is considered to be the maximum intensity reachable with the present RF system in the SPS, since the average bunch length of $\tau \approx 1.65$ ns achieved with this intensity is close to the maximum acceptable for transfer to the LHC. For higher beam intensities, larger RF voltage is needed in order to maintain the same bunch length with the increased longitudinal emittance required for beam stability. Using the scaling law for single bunch instability due to loss of Landau damping, the RF voltage needs to be increased proportional to the intensity [24].

The 200 MHz main RF system of the SPS consists of four travelling wave cavities [25], of which two are made of four sections and the other two are made of five sections. The maximum RF power presently available in continuos mode is about 0.75 MW per cavity, which corresponds to a maximum total RF voltage of about 7.5 MV at nominal intensity of the 25 ns beam. However, less RF voltage is available for higher beam intensity due to the effect of beam loading and the limited RF power [26]. This voltage reduction is larger for longer cavities, i.e. it is increasing with the number of cavity sections. The LIU baseline upgrades for the SPS include an upgrade of the low-level RF and a major upgrade of the 200 MHz RF system [27]. The low-level RF upgrade, which is also part of US1 [4], will allow pulsing the RF amplifiers with the revolution frequency (the LHC beam occupies less than half of the SPS circumference) leading to an increase of the RF power up to about 1.05 MW per cavity. The main upgrade consists of the rearrangement of the four existing cavities and two spare sections into two 4-section cavities and four 3-section cavities, and the construction of two additional power plants providing 1.6 MW each. This will entail a reduction of the beam loading per cavity, an increase of the available RF voltage and a reduction of the beam coupling impedance (the peak value at the fundamental frequency).

Figure 6 shows the maximum total RF voltage of the SPS 200 MHz system as a function of the beam current with and without the RF upgrades. The RF voltage required for keeping the bunch length constant with increasing inten-

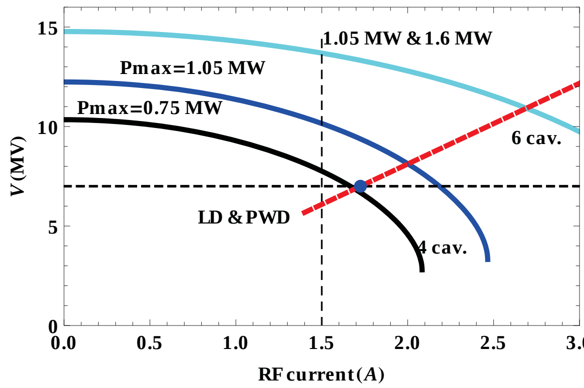

Figure 6: Maximum total RF voltage as a function of the beam current for different cases: present situation (black line), after the low-level RF upgrade to operate in pulsed mode (blue line) and after the cavity rearrangement and the construction of two additional power plants of 1.6 MW each (light blue line). The voltage required for maintaining constant bunch length at extraction taking into account the single bunch longitudinal instability and the voltage reduction due to potential well distortion is also shown (red dashed line) together with the reference point (blue dot).

sity taking into account the compensation of potential well distortion (PWD) and the required longitudinal emittance blow-up for stabilizing the beam against the single bunch instability (loss of Landau damping) is indicated in the same graph. The presently maximum achieved intensity of $N \approx 1.35 \times 10^{11}$ p/b (corresponding to 1.7 A beam current) together with the corresponding maximum RF voltage of 7 MV serves as reference point. It follows that a maximum beam current of 1.9 A will be in reach after the low-level upgrade (4 times 1.05 MW pulsed) and 2.7 A after the full RF upgrade (cavities rearranged into six with 4×1.05 MW and 2×1.6 MW) [24]. These values correspond to maximum intensities at extraction of about $N \approx 1.45 \times 10^{11}$ p/b and $N \approx 2.0 \times 10^{11}$ p/b, respectively, when taking into account 3% intensity reduction due to scraping before extraction for cleaning transverse beam tails. However it should be emphasized that this estimation is based on simplified scaling laws and that slightly longer bunches, if accepted by the LHC, are significantly more stable ($\sim \tau^5$).

Electron cloud

The electron cloud effect has been identified as a possible performance limitation for the SPS since LHC type beams with 25 ns spacing were injected into the machine for the first time in the early years of 2000. At that time a severe pressure rise was observed all around the machine together with transverse beam instabilities, important losses and emittance blow-up on the trailing bunches of the train [28]. Since 2002, Scrubbing Runs with 25 ns beams were carried out almost every year of operation in order to condition the inner surfaces of the vacuum chambers and therefore mitigate the electron cloud. This allowed achieving a good conditioning state of the SPS up to 2012, both in terms of dynamic pressure rise and beam quality. During the Scrubbing Run of the LHC at the end of 2012, the 25 ns beam was regularly extracted from the SPS Q20 optics with four batches of 72 bunches with $N \approx 1.2 \times 10^{11}$ p/b and normalized transverse emittances of about 2.6 μm [14]. Extensive machine studies showed that for this beam intensity the 2012 conditioning state of the SPS is sufficient for suppressing any possible beam degradation due to electron cloud on the cycle timescale [29].

Further experiments performed with the Q20 optics showed that it was possible to inject the full train of the 25 ns beam with up to $N \approx 1.35 \times 10^{11}$ p/b without transverse emittance blow-up and preserve the beam quality up to extraction energy, as shown in Fig. 7 (top). For higher intensities ($N \approx 1.45 \times 10^{11}$ p/b injected) a transverse instability was observed after the injection of the third and the fourth batch, leading to emittance blow up as shown in Fig. 7 (bottom) and particle losses on the trailing bunches of the injected trains. The observed pattern on the bunch by bunch emittance is typical for electron cloud effects. Since the SPS was never scrubbed with such high beam intensities, an additional scrubbing step might be required for suppressing these effects.

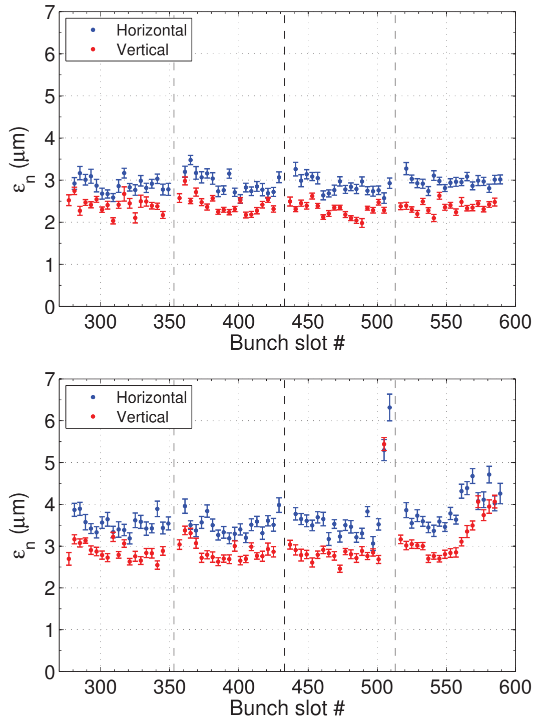

Figure 7: Bunch by bunch emittances measured at the SPS flat top for 4×72 bunches of the 25 ns LHC beam with intensities at injection of $N \approx 1.35 \times 10^{11}$ p/b (top) and $N \approx 1.45 \times 10^{11}$ p/b (bottom).

Several studies have been devoted in 2012 to the optimization of the scrubbing process and in particular to the definition and test of a possible "scrubbing beam", i.e. a beam produced specifically for scrubbing purposes, providing a higher scrubbing efficiency compared to the standard LHC type 25 ns beam. A 25 ns spaced train of "doublets", each of these consisting of two 5 ns spaced bunches, has been proposed [30]. As shown in simulations, this beam has indeed a lower multipacting threshold compared to the standard 25 ns beam due to the shorter empty gap between subsequent doublets, which enhances the accumulation of electrons in the vacuum chamber. For producing this beam with the existing RF systems of the injectors, long bunches from the PS ($\tau \approx 10$ ns full length) have to be injected into the SPS on the unstable phase of the 200 MHz RF system and captured in two neighboring buckets by raising the voltage within the first few milliseconds. Very good capture efficiency (above 90%) could be achieved for intensities up to 1.7×10^{11} p/doublet.

Figure 8 (top) shows the evolution of the longitudinal profile of the beam during the "splitting" right after the injection in the SPS. Figure 8 (bottom) shows the "final" beam profile, measured one second after injection. It was also verified that it is possible to rapidly lower the RF voltage and inject a second train from the PS without any important degradation of the circulating beam. Observations on the dynamic pressure rise in the SPS arcs confirmed

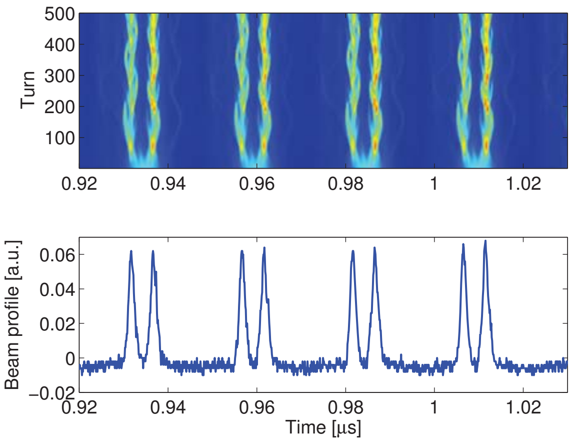

Figure 8: Evolution of the longitudinal beam profile in the SPS during the splitting at injection for the production of the doublet beam (top) and longitudinal bunch profiles of the doublet beam measured 1 s after injection (bottom).

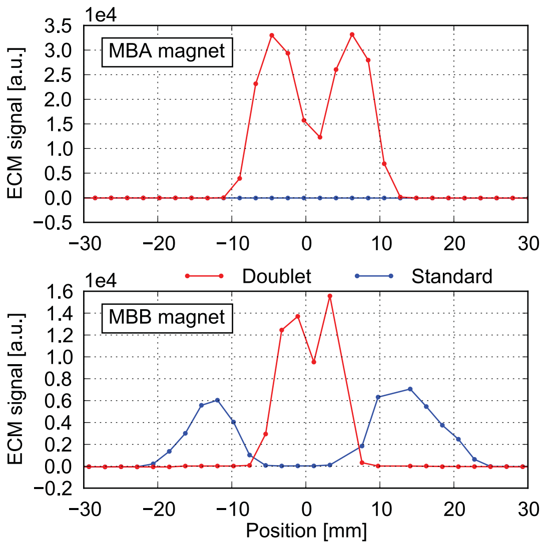

Figure 9: Electron cloud profiles measured in the strip detectors with MBA (top) and MBB (bottom) chambers with the standard 25 ns beam and with the doublet beam (same total intensity, 72 bunches from the PS with $N \approx 1.65 \times 10^{11}$ p/b).

the enhancement of the electron cloud activity as expected from simulations. The enhancement was also observed with the dedicated SPS strip detectors as shown in Fig. 9 for the two SPS vacuum chamber types, MBA and MBB, where the electron cloud profiles measured with the standard 25 ns beam and with the doublet beam are compared for the same total intensity. In this experiment with a single batch from the PS, electron cloud formation in the MBA is only observed with the doublet beam due to its lower multipacting threshold compared to the standard beam. In the MBB, where the nominal beam was still able to produce electron cloud, a clear enhancement of the peak electron density can be observed. It is important to note that the electron cloud produced by the doublets does not cover the full region to be conditioned for the standard beam. Therefore it is necessary to periodically displace the beam (using radial steering and orbit correction dipoles) during the scrubbing in order to achieve a satisfactory conditioning across the chamber surface.

A high bandwidth (intra-bunch) transverse feedback system is being developed for the SPS as part of the LIU project in collaboration with the LHC Accelerator Research Program (LARP), with the goal of fighting electron cloud instabilities and improving the beam quality during the scrubbing for making it more efficient. In 2013, experimental studies with prototype hardware already demonstrated the successful suppression of slow headtail instabilities of mode 0 (dipole mode) with single bunches. Further studies with improved hardware will follow in 2014.

In case scrubbing is not sufficient for suppressing the electron cloud effect with the high beam intensity and small transverse emittance required for HL-LHC, or in case the reconditioning process is very slow after large parts of the machine are vented (like during a long shutdown), the inner surface of the SPS vacuum chambers has to be coated with a low SEY material. The solution developed at CERN is to produce a thin film of amorphous Carbon using DC Hollow Cathode sputtering directly inside the vacuum chamber [31]. The suppression of electron cloud in coated prototype vacuum chambers has been fully validated with beam in the SPS [29]. Additional four SPS half cells (including quadrupoles) coated with amorphous Carbon will be ready for the startup in 2014 for further tests with beam.

The coating of the entire machine circumference of the SPS with amorphous Carbon is a major work, which requires careful preparation and planning of resources (as all magnets need to be transported to a workshop). The decision if the SPS needs to be coated or if scrubbing as electron cloud mitigation is sufficient has therefore to be taken not later than mid 2015. After the long shutdown, a Scrubbing Run of about two weeks will be performed during the startup at the end of 2014 with the goal of recovering the operational performance, as it is expected that the good conditioning state of the SPS will be degraded due to the long period without beam operation and the related interventions on the machine. Another Scrubbing Run will be performed in the first half of 2015 in order to scrub the machine for high intensity 25 ns beams. The final decision about the coating will be based on the experience during this period and on the outcome of experimental studies with the high intensity 25 ns beams.

INJECTORS PERFORMANCE REACH

The expected performance reach of the entire LHC injector chain after implementation of the LIU upgrades is shown in Fig. 10 for the standard and the BCMS scheme. The beam parameters are given at LHC injection taking

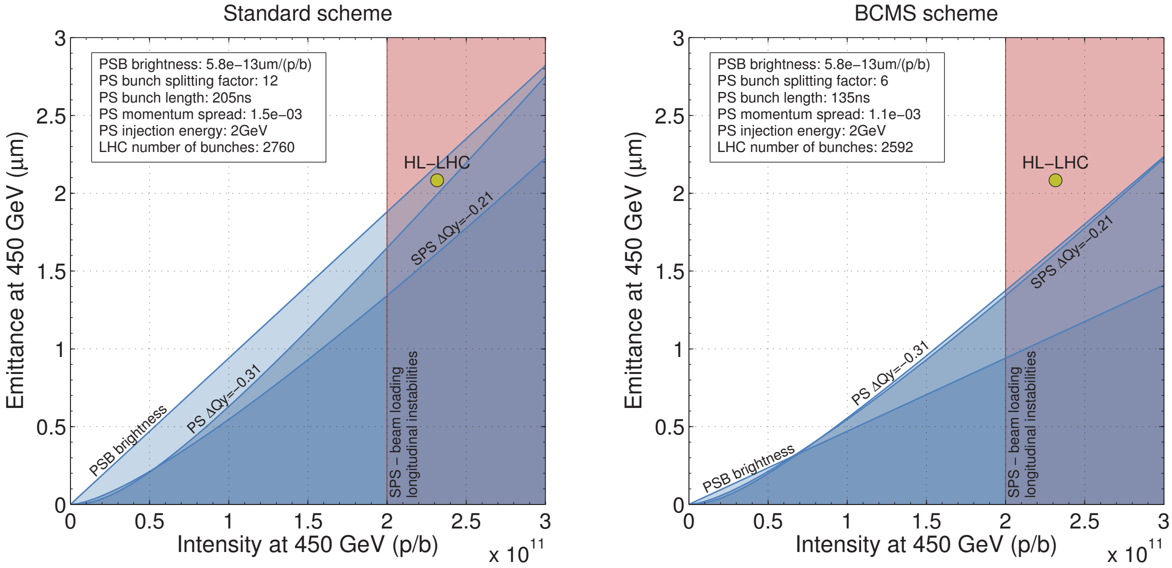

Figure 10: Limitation diagrams for 25 ns beams produced with the standard scheme (left) and the BCMS scheme (right) after implementation of the LIU upgrades.

Table 2: Achievable beam parameters after implementation of LIU upgrades in comparison with HL-LHC request.

PSB		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU-US2	Standard	29.55	1.55	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.55, 0.66)
	BCMS	14.77	1.13	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.35, 0.44)
HL-LHC		34.21	1.72	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.58, 0.69)

PS (double injection)		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU-US2	Standard	28.07	1.63	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.16, 0.28)
	BCMS	14.04	1.19	2.0	1.48	135	$1.1 \cdot 10^{-3}$	(0.19, 0.31)
HL-LHC		32.50	1.80	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.18, 0.30)

SPS (several injections)		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU-US2	Standard	2.22	1.71	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.09, 0.16)
	BCMS	2.22	1.25	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.12, 0.21)
HL-LHC		2.57	1.89	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.10, 0.17)

LHC		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	bunches/train
LIU-US2	Standard	2.00	1.88	450	0.60	1.65	72
	BCMS	2.00	1.37	450	0.60	1.65	48
HL-LHC		2.32	2.08	450	0.65	1.65	72

into account the emittance growth and loss budgets from Table 1. The shaded areas correspond to regions in the parameter space that cannot be accessed. The best beam parameters correspond to an intensity of $N = 2.0 \times 10^{11}$ p/b (limited by longitudinal instabilities and RF power in the SPS) within transverse emittances of $\varepsilon_n = 1.88\,\mu$m for the standard scheme (limited by the PSB brigthness) and $\varepsilon_n = 1.37\,\mu$m for the BCMS scheme (limited by space charge in the PS and SPS), as summarized in Table 2. Although the beam parameters do not match the HL-LHC 'point-like' request (in particular the intensity per bunch), the injectors performance will be enough to saturate the LHC performance for the assumed pile-up limit and availability/fill length [1].

SUMMARY AND CONCLUSIONS

The connection of LINAC4 will double the beam brightness out of the PSB compared to the present operation, thanks to the H^- charge exchange injection and the higher injection energy of 160 MeV. Raising the PS injection energy to 2 GeV will mitigate space charge effects on the injection plateau and match the performance of the PS to the higher brightness available with LINAC4. The upgrades of the transverse and longitudinal feedbacks in the PS together with the RF upgrades will push present intensity limits beyond the requirements for HL-HLC. With the SPS Q20 optics the TMCI at injection is not an issue. The major SPS RF upgrade with two new power plants and rearranged RF cavities will push the achievable intensity from the present $N = 1.3 \times 10^{11}$ p/b to $N = 2.0 \times 10^{11}$ p/b. The decision if the SPS vacuum chambers all around the machine will be coated with amorphous Carbon in order to suppress the electron cloud will be taken in mid 2015 based on the experience and experimental studies from two Scrubbing Runs to be performed in 2014 and 2015. The main question is if scrubbing (for example with the doublet scrubbing beam) as electron cloud mitigation instead of the coating is a viable path for recovering the operational performance after a long shutdown and if the electron cloud can be suppressed for the future high intensity beams.

The overall performance of the LHC injectors after the implementation of all baseline LIU upgrades, i.e. an intensity of $N = 2.0 \times 10^{11}$ p/b and a transverse emittance of $\varepsilon_n = 1.88\,\mu$m for the 25 ns beam with 72 bunches per PS batch (standard scheme), approximately matches the parameters needed by HL-LHC with the presently assumed pile-up limit and machine physics efficiency. For achieving this performance, all upgrades must be effective, i.e. also those not explicitly mentioned in this paper but important for eliminating operational limitations or assuring reliability of the complex. Unless slightly longer bunches can be accepted by the LHC, there is little or no margin to further increase the intensity per bunch extracted from the SPS, as longitudinal instabilities in combination with beam loading will limit the maximum intensity even after the major RF upgrade of the SPS.

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REFERENCES

[1] R. de Maria *et al.*, “How to maximize the HL-LHC performance?”, these proceedings.

[2] R. Garoby, “New RF Exercises Envisaged in the CERN-PS for the Antiprotons Production Beam of the ACOL Machine”, IEEE Transactions on Nuclear Science, Vol. NS-32., No. 5 (1985).

[3] H. Damerau *et al.*, “RF manipulations for higher beam brightness LHC-type beams”, CERN-ACC-2013-0210.

[4] S. Gilardoni *et al.*, “LIU: Which beams in the injectors fulfil HL-LHC Upgrade Scenario 1 goals?”, these proceedings.

[5] B. Mikulec *et al.*, “Performance reach of LHC beams”, in LIU Beam Studies Review, CERN (2012).

[6] G. Rumolo *et al.*, “Expected performance in the injectors at 25 ns without and with LINAC4”, these proceedings.

[7] R. Wasef *et al.*, “Space Charge Effects and Limitations in the CERN Proton Synchrotron”, CERN-ACC-2013-0176.

[8] R. Cappi, “Observation of high-order head-tail instabilities at the CERN-PS”, CERN-PS-95-02-PA.

[9] G. Sterbini *et al.*, “Beam Tests and Plans for the Cern PS Transverse Damper System”, CERN-ACC-2013-0215.

[10] S. Aumon, “High Intensity Beam Issues in the CERN Proton Synchrotron”, CERN-THESIS-2012-261, PhD. thesis (2012).

[11] G. Iadarola *et al.*, “Electron Cloud Studies for the Upgrade of the CERN PS”, CERN-ACC-2013-0095.

[12] R. Cappi *et al.*, “Electron cloud buildup and related instability in the CERN Proton Synchrotron”, PRST-AB 5, 094401 (2002).

[13] H. Bartosik *et al.*, “Optics considerations for lowering transition energy in the SPS”, CERN-ATS-2011-088.

[14] Y. Papaphilippou *et al.*, “Operational performance of the LHC proton beams with the SPS low transition optics”, CERN-ACC-2013-0124.

[15] B. Salvant *et al.*, “Probing intensity limits of LHC-Type bunches in CERN SPS with nominal optics”, CERN-ATS-2011-176.

[16] E. Métral, “Overview of Single-Beam Coherent Instabilities in Circular Accelerators”, Proceedings of the 1st CARE-HHH-APD Workshop on Beam Dynamics in Future Hadron Colliders and Rapidly Cycling High-Intensity Synchrotrons, Geneva, Switzerland (2004).

[17] H. Timko *et al.*, “Experimental and simulation studies of the PS-to-SPS beam transfer efficiency”, CERN-ATS-Note-2012-059 PERF.

[18] H. Bartosik, “Beam dynamics and optics studies for the LHC injectors upgrade”, CERN-THESIS-2013-257, PhD. thesis (2013).

[19] V. Kain *et al.*, “50 ns back-up scenario”, these proceedings.

[20] H. Bartosik *et al.*, “Experimental Studies for Future LHC Beams in the SPS”, CERN-ACC-2013-0151.

[21] E. Shaposhnikova *et al.*, “Longitudinal Instabilities in the SPS and Beam Dynamics Issues with High Harmonic RF Systems”, Proceedings of HB2012, Beijing, China (2012).

[22] E. Shaposhnikova, “Longitudinal stability of the LHC beam in the SPS”, SL-Note-2001-031-HRF.

[23] H. Bartosik *et al.*, “Experimental studies with low transition energy optics in the SPS”, CERN-ATS-2011-086.

[24] E. Shaposhnikova, “SPS intensity limitation with and without 200 MHz RF upgrade”, presentation in the LIU SPS-Beam Dynamics Working Group meeting, CERN (2013).

[25] G. Dôme, “The SPS acceleration system travelling wave drift-tube structure for the CERN SPS”, CERN-SPS-ARF-77-11.

[26] T. Bohl, “The 200 MHz Travelling Wave Cavities in the SPS”, Proceedings of the 10th Chamonix SPS and LEP Performance workshop, Chamonix, France (2000).

[27] E. Shaposhnikova *et al.*, “Upgrade of the 200 MHZ RF System in the CERN SPS”, CERN-ATS-2011-042.

[28] G. Arduini *et al.*, “Beam observations with electron cloud in the CERN PS and SPS complex”, Proceedings of the ECLOUD04 workshop, Napa, CA, USA (2005).

[29] H. Bartosik *et al.*, “Electron Cloud and Scrubbing Studies for the SPS in 2012”, CERN-ATS-Note-2013-019 MD.

[30] G. Iadarola *et al.*, “Recent electron cloud studies in the SPS”, CERN-ACC-2013-0115.

[31] C. Vallgren *et al.*, “Amorphous carbon coatings for the mitigation of electron cloud in the CERN Super Proton Synchrotron”, Phys. Rev. ST Accel. Beams, 14, 071001 (2011).

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HOW TO IMPLEMENT ALL HL-LHC UPGRADES

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Abstract

The luminosity upgrade will require major changes in the LHC machine layout: about 1.2 km of the machine will undergo major renovation or modification. In the paper we will review the list of main equipment foreseen to be replaced or to be added. We will review the upgrade plan that should start already in the Long Shutdown (LS) 2 (with the installation of the first dispersion suppressor 11T dipole – collimator unit, the superconducting link in Point 7 and the cryo-plant in Point 4), through to the major works in LS3, synchronized with an upgrade of the LHC detectors. Best estimates of the required duration of the various shutdowns will be discussed, and also the main risks and their mitigation.

INTRODUCTION

The High Luminosity LHC (HL-LHC) Project has been established in autumn 2010 by the CERN Director of Accelerator & Technology, as a new plan for LHC and injector upgrades following the plan change suggested at the Chamonix LHC Performance workshop held on 25-29 January 2010 [1,2]. By summer 2010 the project mission, a design phase detailed plan, the constitution of a world-wide collaboration (20 Institutes) and a global plan for construction and implementation were set up. This allowed writing at the end of 2010 an application to the European Commission to get support as FP7 Design Study, called HiLumi LHC. The application has been successful and the FP7-HiLumi LHC Design Study began on the 1st of November 2011, successfully marking the official start of the design phase.

Another milestone of the project has been the 30th of May 2013, when the CERN Council in a special session held in Brussels, in presence of EU Commission and CERN Member States officials, adopted the new European Strategy for high energy physics. The HL-LHC was placed as a first priority program in the strategy declaration [3], supporting the LHC upgrade in luminosity by the following statement: ...*Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.* This was exactly the initial scope of HL-LHC project, aiming at increasing the integrated luminosity reach from the initial target of 300 fb^{-1} up to about 3000 fb^{-1}, at a rate of 250 fb^{-1}/y. This main goal has been complemented with two "conditions": the first one is to limit the pile up at about 140 events/crossing, which means limiting the peak luminosity to $5 \cdot 10^{34}$ cm^{-2} s^{-1}. The second condition is subtler: to limit the pile up linear density to about 1 event/mm. Pile up density, mentioned in the second joint HL-LHC and LIU workshop, has emerged as target only recently [4], however a novel solution to fulfil it without reducing integrated luminosity it has been very recently devised [5].

In this paper we will not discuss the technical solutions for the upgrade that are described in other papers of this workshop and in more complete way in previous publications [6, 7]. Rather, we will review the various upgrade and the installation plan and time, with an overview of the upgrade matrix of the various scenarios examined in this workshop: performance improving consolidation (PIC), upgrade scenario 1 (US1) and upgrade scenario 2 (US2). The cost breakdown for the main equipment will also be reported.

GLOBAL VIEW OF FORESEEN UPGRADES

The total hardware renovation and upgrade of LHC are equivalent to manufacturing and installing about 1.2 km of a new accelerator, in various places of the LHC ring. Figure 1 gives the extent of the challenge. The LHC regions where important hardware upgrades will be carried out are evidenced: however the work will concern also surface buildings in P1 and P5 (for SC links and new powering) and along the full ring for an advanced magnet protection system. In term of timing the scheduled considered for the installation is the CERN official one at the time of the workshop (October 2013) that foresees a one year-long LS2 in 2018 and a two year-long LS3 in 2022-23. Comments on the feasibility from the point of view of the planning (both construction and installation) are given in the section at the end of the paper.

INSTALLATION DURING LS2

Cryoplant for superconducting RF in P4

The cryogenic scheme and the main elements to be cooled are depicted in Fig. 2. In point 4 the refrigerator has to maintain cold the superconducting magnets of the arc and of the long straight section and on one side (right side of P4) also the inner triplet region at the left side of IP5. In P4 the same cryo-plant is also the refrigerator of the superconducting RF (SCRF) cavities, the accelerating system of the LHC. This has two inconveniences:

- The available power for the inner triplet and matching section magnets is less than in the other points.
- A magnet problem requiring the warm up of the magnetic system will affect the functionality of the SCRF system and vice-versa. The coupling may become a severe constraint when the machine will run at maximum energy and intensity, pushing all system at their limits.

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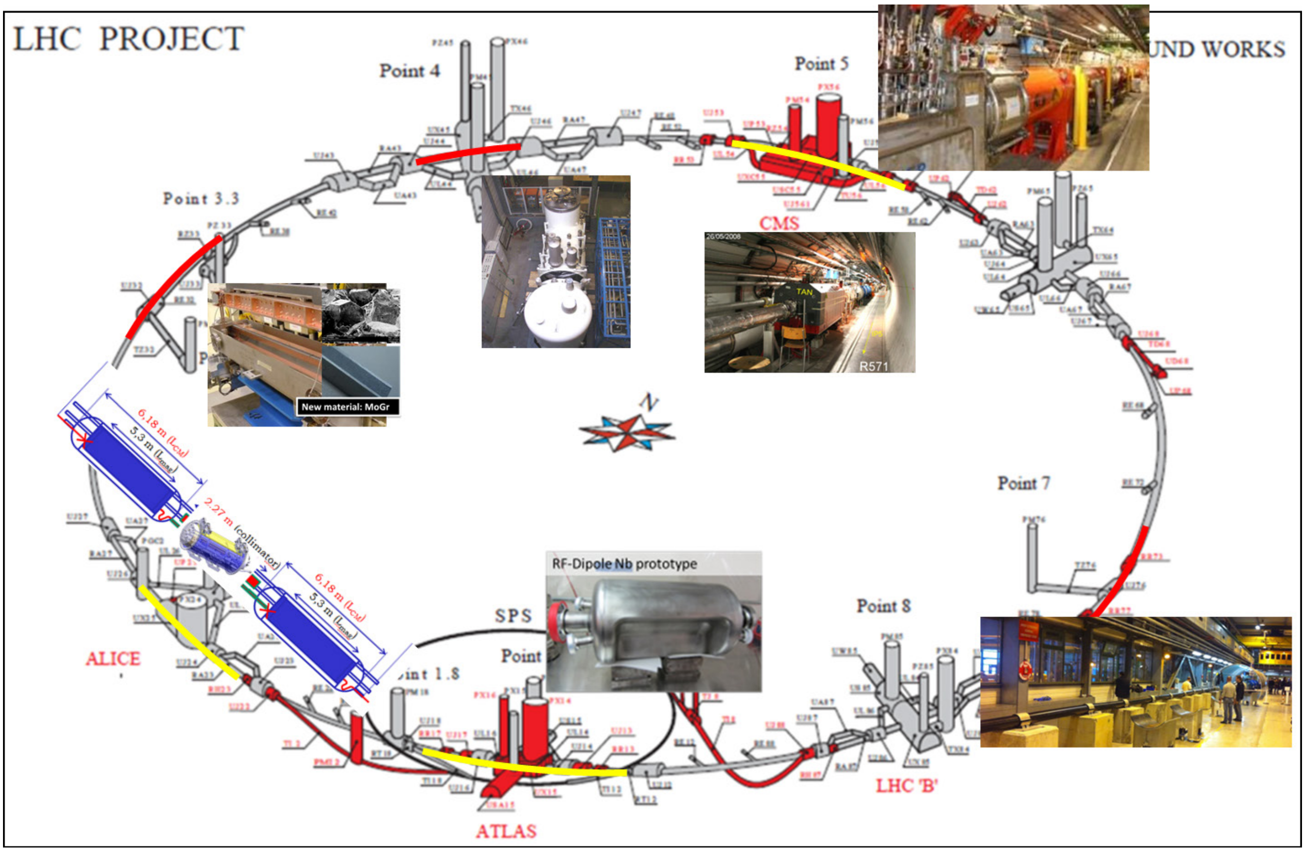

Figure 1: LHC ring areas where major works are required for the upgrade are marked with solid line. In yellow when works concern insertion regions (IRs) with experiments and in red when works concern IRs with only machine functions (length of solid lines not to scale).

The cure is to install a new cryo-plant in P4 for the SCRF system and fully decouple the magnet and the SCRF systems. The cryogenic power to be installed is in the range of 5 kW at 4.4K which is sufficient with considerable margin. However, since recently the idea of installing a second SCRF system (either 800 or 200 MHz [8] has been advanced, the power will be re-evaluated to cope with this possible additional system. Another system that may increase refrigeration needs in P4 is the superconducting solenoid of the electron lens (see dedicated paragraph later in the text). However its cryogenic power is so small to be in the shadow of the necessary margins.

Horizontal superconducting links in P7

In Point 7 some electrical power converters (EPCs) feeding the superconducting magnets of long straight section are placed in alcoves called RR73 and RR77, near the betatron collimation system, intercepting a large fraction of the total beam losses in LHC, and therefore significantly increasing the probability of single event effects (SEE) occurrence. A project, called radiation-to-electronics (R2E), is taking care of consolidating the EPC with new rad-hard systems [9]. However, a displacement of EPCs far from the accelerator is advantageous because:

- Interventions on power converters are, and will remain, one of the main reasons of tunnel access. Removal of power converters from the tunnel will increase operational efficiency.
- In front of collimators the residual radioactivity will increase steadily up to high values. Safety principle ALARA calls for a radical action, if possible, to minimize radiation personnel exposure.
- The access to P7 requires special procedures for the ventilation of the tunnel, with even heavier consequences on operation time.

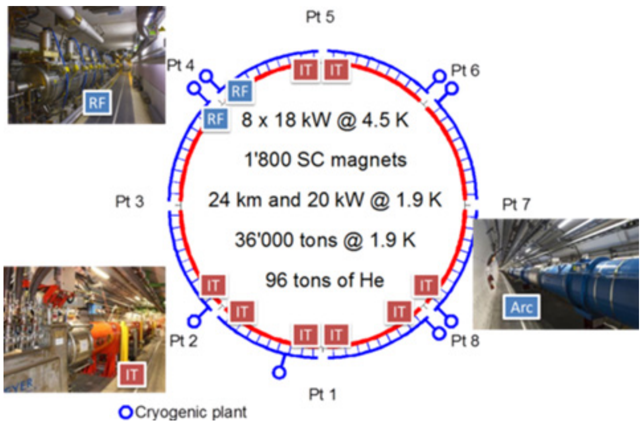

Figure 2: LHC cryogenics with indicated the main loads: Arc magnets (including MS), IT magnets and RF systems.

The solution that has been proposed is to place EPCs and relative distribution feed box (DFB), lodging the 300 K - 4 K current leads, in a side tunnel, about 250 m far from main tunnel. In Fig.1 is shown this radial tunnel (TZ76) starting from P7 and reaching its access pit. This would require some twenty-four, 500 m long, cable pairs to connect the DFB to a service module in line with the beam pipe. To avoid a very high power dissipation and voltage drop, and also to remove the DFB from the tunnel as well, one has to use SC links [10]. To make use of the existing cryogenics, the system will rely on tapping supercritical helium at about 5 K from the LHC line C and using the enthalpy provided by an additional temperature rise, up to about 20-25 K. A flow of about 4-5 g/s is sufficient to provide a refrigeration power of 250 W for adsorbing the static and dynamic losses of the superconducting link and to provide the cooling the current leads. For the superconductor both MgB_2 and YBCO or Bi-2223 can be used. The cable is rated for 30 kA (in 600 A circuits). Test were done on a 2 m – 30 kA model and a 20 m - 25 kA prototype is ready for testing, see Fig. 3.

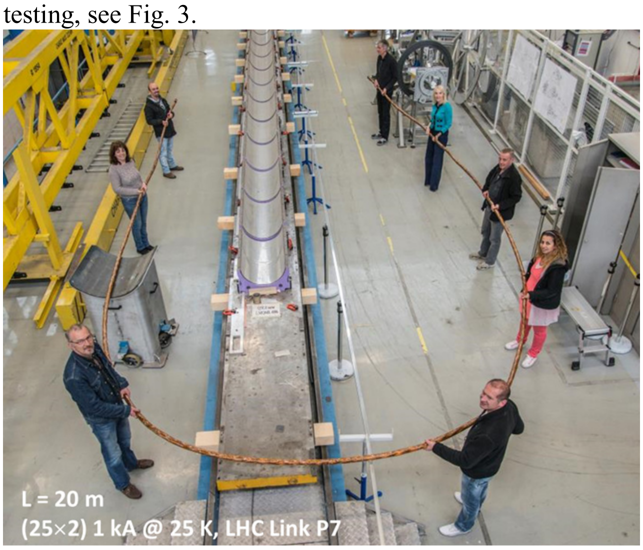

Figure 3: First 20 m long prototype of SC link (25 kA) for P7.

DS collimator for IP2 (ions) and P7 (protons)

The issue of collimators in the LHC cold regions, namely in the Dispersion Suppressor (DS), has been raised at various occasions [11, 12]. The particle losses in the DS regions are driven by three different mechanisms:

1. Protons losing energy due to diffractive scattering against the collimator jaws in both cleaning insertions of IR3 and IR7. This loss is not continuous since it is relevant only when a consistent part of the beam, is intercepted by collimators, i.e. during the short period when beam life-time is low. However their time scale ranges from a few ms to a several seconds: when a loss burst lasts fraction of seconds or longer, from a point of view of the energy depositions in the magnets, it should be regarded as a continuous loss.
2. Protons losing energy due to diffractive interaction at the collision point. This is a continuous process and it is important in P1 and P5, since it is proportional to luminosity.
3. Particles changing magnetic rigidities due to ultra-peripheral electromagnetic interactions of the counter-rotating ion beams at the collision point. This is a continuous mechanism, too, proportional to ion collision luminosity. It is relevant in P2 but also in P1 and P5, if the luminosity is as in P2.

These losses cannot be intercepted by the present momentum cleaning because diffractive losses are lost in the first dipoles of the DSs, acting as spectrometers, before reaching IR3. The only cure is to put collimators in the first high dispersion region, the DS zone where there are the first main dipoles of the arc. Since the filling factor in the arc is maximized for reaching the highest beam energy, the only viable solution is to create space by substituting a main dipole with an 11 T dipole. The 119 T·m (8.3T×14.3m) bending strength of an LHC dipole would be imparted to the beam by a 11T×10.85m new dipole, nicknamed 11 T dipole [13]. For convenience the 11T-11m dipole is split into 2×5.5 m long cold masses with the bypass/collimator unit in the middle, see Fig. 4, to minimize the orbit distorsion. The use of 11 T dipole,

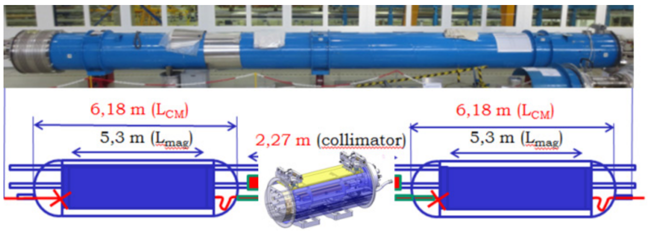

Figure 4: Present LHC dipole (top) to be replaced by two Nb_3Sn dipoles with by pass/collimator unit in the middle.

with the new challenging technology based in Nb_3Sn, would leave about 4 meters for two cold-warm transitions and a bypass cryostat lodging a 80 cm long collimator jaws, sufficient to reduce by factors 10 (IR7) to 50-100 (IR2 for ions) the radiation load compared to that on the present dipoles. The design of the collimator is complex but it not substantially different from the one of the main collimation system. The design of the by-pass poses serious technical and integration challenges, given the complexity of equipment and the very tight space left by the magnet. The design and construction of the 11 T is a new R&D, and the feasibility of this equipment has still to be demonstrated. In the frame of the CERN-Fermilab collaboration for the 11 T dipole, recently the second dipole short model build at Fermilab has reached and overcome the 11 T operational field [14]. However, instability issues call for a third model to give the final demonstration of the feasibility.

The 2013 review of the collimation system has established the following priority for 11T-DS collimators:

1. To install DS collimators in P2 during LS2, for intercepting the losses of the ions run and taking the maximum profit of the ALICE detector upgrade scheduled during LS2. Of course the same protection would be necessary in the DS regions around IP1 and IP5, since both ATLAS and CMS takes data during ions runs. However the decision is to give priority to ALICE, which has ions physics as main goals, and eventually limit the ion collision luminosity in P1-P5 just below quench limit;
2. To be ready to install collimators in the DS regions of P7 during LS2 for the proton beam losses. It seems that the need of DS collimation for the run after LS2 is marginal in P7, but it cannot be excluded. We plan to have the hardware ready (4 units) and then decide if installing it during LS2;
3. To be ready to install collimators in the DS regions around P1 and P5 for the proton continuous losses from the IPs during LS3. At present, the need of such collimation for HL-LHC parameters seems marginal, so experience in the next LHC run is necessary for a final assessment;
4. Eventually, to be ready to install DS collimation for P1 and P5 ions program, if ATLAS and CMS ions physics program and experience with P2 DS collimation call for it.

A problem is that while the system for P2, two 15 m long units, should be ready for installation at end of 2017, manufacturing the additional systems (four 15 m long units) needed for P7 requires one year more.

Low impedance collimators

Low impedance collimators have been considered for a collimation upgrade since quite some times. Based on an extensive test campaign in HiRadMat facility on various materials [15], the most promising candidate for secondary collimator jaw is a molybdenum-graphite composite (MoGr) that, once coated with molybdenum is robust against impact of very high brightness beam and has a high surface electrical conductivity. In this way the impedance of collimators can be reduced by a factor ten, dramatically reducing the problem of beam instabilities driven by impedance.

The plan is to complete the design of such collimators and then install 2-4 of them during LS2 for testing and for getting experience, preparing for a massive campaign of substitution in 2022, during LS3 in view of the HL-LHC operation [16]. Note that the MoGr without coating might be used to increase the robustness of the present W tertiary collimators.

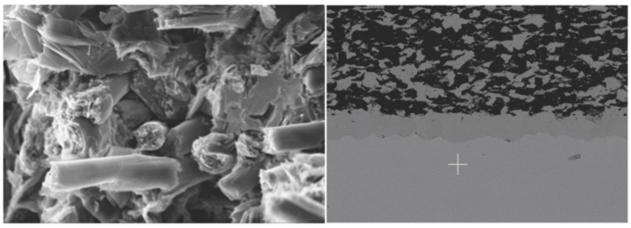

Figure 5: Molybdenum-Graphite (MoGR) composite reinforced with Carbon Fibers (left) and MoGR coated with Mo (right), with an intermediate Carbide layer (darker gray layer).

Somehow the plan can be accelerated or slowed down according to actual needs (to be verified during next run) and to available resources. Indeed, since collimators are in room temperature regions, access is much easier (with respect to the DS region, which is in the continuous cryostat). Also note that empty slots for new secondary collimators are already available for a quick installation (one of these slots will be used for prototyping at the LHC). Would an additional extended technical winter stop be present, as envisaged at the workshop, probably the installation of a prototype could be anticipated during such stop. Then, if the experience is positive, a massive campaign of substitution of secondary collimators may be carried out already in LS2, with the scope of reducing the impedance of the total collimation system by more than a factor two.

This upgrade is to be considered also a renovation of the collimation that can cure the long term wear of the system and, as such, it is also an unavoidable consolidation plan.

INSTALLATION DURING LS3

Interaction Region (Q1-Q3, D1)

The change of the inner triplet (IT) quadrupoles with new magnets of larger aperture is the backbone of the upgrade. These magnets will reach the threshold of radiation damage (typical mechanical weakening and loss of dielectric strength in the insulators), estimated to be about 20-30 MGy [17] at around 300-400 fb^{-1} of accumulated luminosity. The triplet is a typical example of PIC: we profit of the necessary replacement of the IT quadrupoles to install new quadrupoles with larger aperture, in order to increase the luminosity reach. Recently their coil aperture has been fixed to 150 mm [18] to maximize the upgrade performance, with an operational gradient of 140 T/m. These parameters imply a peak field of more than 12 T on the coils, requiring the use of Nb_3Sn technology which has been principally developed in the USA via the DOE Conductor Development Program and LARP [19], and more recently at CERN [13]. The more than doubling of the quadrupole aperture entails a new larger TAS (the first absorber between detector and machine) and an a larger aperture of all magnetic elements of the interaction regions, where the two beams are circulating in the same beam pipe: separation dipole D1 and corrector magnets of various types, with a new beam screen supporting a thick W-shield (up to 16 mm) to reduce radiation on the superconducting magnets. The system has been described in various papers [13, 20-22], so here we limit our discussion to installation time.

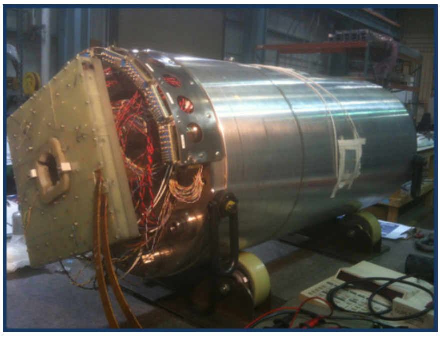

Figure 6: The cold mass of the HQ02 120 mm aperture quadrupole, designed and built by USA-LARP. This magnet, near to the final design of HL-LHC IT quadrupoles, routinely passed 12 T of peak field during power test at Fermilab. Picture taken at LBNL after structure assembly.

The plan is to carefully prepare installation by carrying out a full test in operational conditions of a complete "string": Q1-Q2a-Q2b-Q3-Corrector Package-D1, to be done at least one year prior installation, to check all integration problems. Having the triplet ready for installation in 2022-23 is feasible, although with reduced margin: the plan is today to have Q1-Q3 delivered as in-kind contribution by USA and D1 by KEK.

A critical point is the de-installation of the present triplet, which will be highly radioactive. A prudent plan would require about four months for radiation "cooling", six months for de-installation and one year for installation and commissioning of the new equipment. This leaves just two months of margin over the two year shutdown duration. The main concern is not the time duration, which looks sufficient, but the availability of personnel and CERN services to carry out parallel installation in the various IRs.

Before concluding this part one has to take not of the good suggestion, made at the workshop by the CMS coordination, of studying an anticipated removal of the TAS already in LS2, to reduce dose to personnel (the TAS is the most radioactive equipment of LHC). In such a case a special removable insert should reduce the aperture form the 60 mm of the new TAS to 35 mm, the present baseline. In such a way, during LS3 only the job of taking away the removable TAS insert will be left, making the inner diameter 60 mm wide, the aperture needed for the 10-15 cm β^* target.

Matching section magnets

Increasing the aperture of more than a factor two in the IT, and consequently decreasing β^* by a factor almost four, strongly affects the aperture of the matching section (MS) optics elements, especially D2, Q4 and Q5 with their corrector magnets and the neutral absorber, called TAN. In addition the situation is complicated by the fact that the crab cavities will be installed between Q4 and D2.

Here we summarize the baseline plan for the matching sections:

1. The present TAN needs to be replaced with a new one with larger aperture and possibly with different geometry. Optimization of the TAN geometry (Which has to protect also the CC, is under investigation). It is just worth remembering that the present TAN hosts some physics detectors, too.
2. The new D2 recombination dipole will feature an aperture of 105 mm (vs. a present of 90 mm) and higher bending strength than today, which will require increasing peak field (not an easy goal, because of excessive flux in the yoke, due to the same field direction along the two apertures) or its magnetic length.
3. The aperture of Q4, which is the first two-in-one quadrupole moving from IP, will increase from 70 to 90 mm, and will be longer than the present magnet.
4. The Q5 also will be increased in aperture (at least 70 mm from the present standard 56 mm) and length. A first possibility is re-using the present Q4, but one would need to increase its gradient or its length. The first case is maybe possible because one can gain available peak field by passing from 4.4 K (present operating temperature) to 1.9 K as foreseen in HL-LHC configuration. The issue is under study.
5. As above mentioned, the operating temperature of the matching section will pass from 4.4 K, as it is at present for all stand-alone magnets, to 1.9 K by means of pressurized superfluid helium as for the LHC arc and inner triplet.
6. A change is required in the optics of the MS of IR6, as required by the new optics scheme called ATS [23]. This will require the installation of two additional Q5 (MQY) quadrupoles to increase the integrated strength
7. At least four chromaticity sextupoles will have to be added at Q10 position close to the interaction points for third order resonance compensation in with the ATS optics.

The change of current and of refrigeration scheme of the MS magnets gives the opportunity to radically re-designing the cold powering of these magnets, as discussed in the next section.

The deep modification of the MS [24] requires a lot of design work because there are many superconducting magnets. Even though of standard Nb-Ti technology, integration is tighter than in the present LHC and de-installation will have certainly to respect ALARA procedures. A first evaluation based on LHC installation experience indicates that all hardware can be tested and made ready for installation by 2022. The two year duration of LS3 seems adequate for the installation of the new MS, provided that sufficient resources are available.

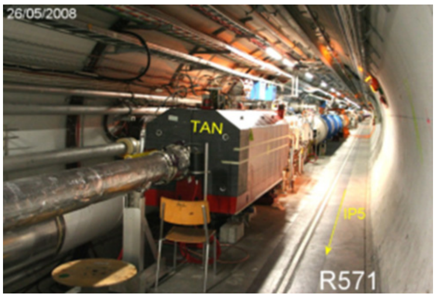

Figure 7: The TAN and MS magnets region in IR5 (right).

Crab cavities

The LHC beams collide with an angle to avoid multiple collisions in the detectors and parasitic collisions outside. The collision angle must also guarantee a beam separation as large as 12 σ (for the intense HL-LHC beam) to reduce long range beam-beam interactions to a level to be negligible. Because of the very small β* the separation angle become large, 590 μrad, while in the nominal LHC is 290 μrad (separation is 9.5 σ and β* is 55 cm), with an important reduction of the luminosity due to worsening of the geometric factor (length of the bunch overlapping region normalized to the bunch length), as shown in Fig. 8.

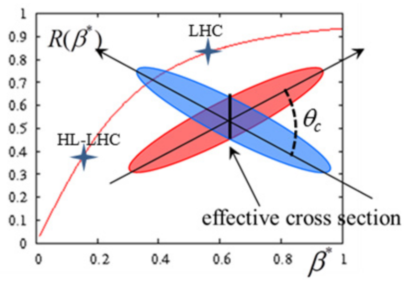

Figure 8: Luminosity reduction effect of the a crossing angle θ_c between colliding bunches vs. β*.

The crab cavities (CC) can provide a rotation to the bunch, seen as rigid body, to recover the geometric factor and restoring the full luminosity gain given by the reduction of β*. Of course an identical counter rotation must be given to each bunch at the opposite side of the IP, to close the bump.

In addition to this function, CC have been recently proposed for controlling the pile up density [5] a concept that is becoming more and more important for the experiments at very high luminosity. Here we will not discuss the crab cavity physics and technology that can be found in other papers [25, 26]: we will mainly discuss integration issues and plan.

To be most effective, i.e. to give the maximum rotation at IP per unit of transverse voltage kick, the CC have to be placed where the β-function is the largest and the counter-rotating beams are still parallel and at normal separation of 194 mm in separate vacuum chamber (before D2 start to recombine the two beams). So a space must be found by enlarging the distance between Q4 and D2, to lodge the CC unit. This poses some challenges for integration of the 10 m long CC cryostat and the place for the RF infrastructure (Klystron, modulator, controls, etc.) in an area far from the interaction point gallery.

As far as feasibility and operation issue of CC one has to underline that this is an absolute *prima* in two respects: use of CC on hadrons and use of compact CC. So far, we have the very encouraging results of 2013 on the first three types of single CC, tested in vertical and all reaching or passing the target voltage of 3.4 MV, see Fig. 9. Second generation cavity prototypes are under construction, to be eventually assembled in cryo-modules. A proof-of-principle test has been proposed and approved in the SPS, for all cryo-modules that will be manufactured for this second generation. The SPS test is critical to assess the ability of controlling unwanted beam effects.

The CC project heavily relies, like the IT quadrupoles, on the effort the US-LARP program. The plan and the issues can be summarized as followed:

1. The CC cryo-module will be placed between Q4 and D2, as near as possible to D2.
2. To allow both correction of geometrid factor and control of the pile up density, four cavities per beam on each IP side are necessary.
3. Each of the eight CC units will be housed in one 2 K saturated He II cryo-module, interleaving the cavities of the two beams (see Fig. 10).
4. CC second generation must be ready by 2015, tested and then assembled in cryo-modules for testing in SPS that must start in 2017 at latest. SPS test results must be conclusive well before the stop for LS2.
5. Construction of CC can start only in 2018 (although prototyping of a possible generation 2.1 or 3.0 and procurement of main tools and material will continue all along 2016-17.

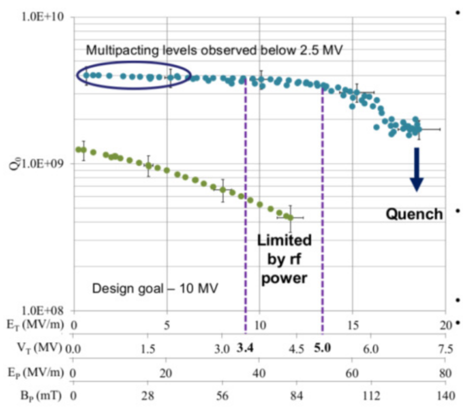

Figure 9: Results of the test of the RF dipole CC (courtesy of J. Delayen, ODU university and J-lab).

Clearly the time for manufacturing and testing the four complete cryo-modules, plus two spares, of CC by beginning of 2022 is tight, although possible.

In addition one should take a decision on the space needed for the RF infrastructure and on location. Today the excavation of a lateral hall seems necessary because the space in the RR alcove it is too small and RR itself is too far from the cavity (problem of phase control). This hall will be expensive, and even more expensive would be a dedicated new access pit that appears mandatory. However, from the point of view of the logistic this can satisfy also other equipment request and the civil engineering works can take place during LS2, without interfering with LHC works.

In conclusion the CC project can fit inside the LHC schedule as for October 2013, but clearly a longer LS2, to allow early excavation of the new lateral halls, and a shift of LS3 by one year will be both welcome.

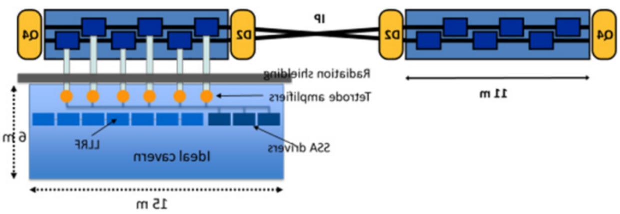

Figure 10: Schematic of the crab cavity concept around IP and room required for lateral hall.

Availability: cold powering and QPS

The reason for displacing the power converters and the feed-boxes outside the LHC tunnel, when they are in the most highly radio-activated zones, has been already presented in a previous section *Horizontal superconducting links in P7.* Since all IR optics elements will be replaced by new ones with different characteristics (all requiring larger operating current than the present ones), it is also a chance to rationalize the cold powering according to modern criteria.

Considering the lack of space for proper integration of the new equipment infrastructure in the IR1 and IR5 and the dose of radiation that will inevitably affect the zone when producing 250 fb^{-1}/year, all new power converters and distribution feed-boxes (both the one for the triplet and the one for the matching section magnets) will be removed on surface by means of powerful (150 kA) superconducting links that will bring the current at cold with the minimal power loss, like depicted in Fig. 11. This will solve the problem of SEE and will considerably increase the availability of the LHC, with benefit for the integrated luminosity.

Last but not least, the removal of EPCs and especially of the DFBs, will dramatically decrease the radiation dose to personnel in charge of intervention and maintenance of such equipment, beside easing the maintenance itself from a technical point of view. This ALARA argument is very important and it is high in the priority list of the HL-LHC project.

Detailing the plan for cold powering of all magnetic elements would requires a too long and tedious list. Here it suffice to mention that we will need eight SC cables, about 300 m long, rated between 150 and 200 kA, with 5 kV voltage (in terms of power capacity this mean about 1 GW per cable!). The amperage is composed of different circuits, of which some, the quadrupole triplet, rated at 20 kA). Despite the big technical challenge represented by these superconducting lines, the project can fit into the given schedule, provided that the needed civil engineering on surface and the small pit for the cable passage surface to underground is done in LS2, which should not pose a problem.

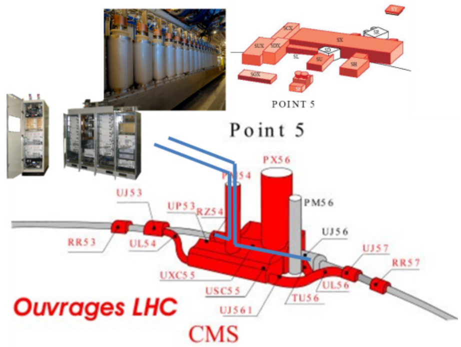

Figure 11: Removal of power converter and DFBs on surface at P5 by means of SC link (blue lines).

Important challenges for the system, beside the superconducting cables, are given by the need of assuring the proper support in the vertical pit and by the full powering system, including connection and distribution boxes , given the huge amperage and the many circuits to connect.

The 20 kA HTS current leads will be based on an extrapolation of the present LHC 13 kA design. The IR1 and IR5 SC links and new DFBs will be cooled by means of new dedicated IT cryo-plants (see next subsection)

The quench protection system (QPS) is one of the critical systems of LHC requiring more intervention, and indeed is among the systems more contributing g to the machine down.-time. Already in LS1 important improvements will be carried out. However, also profiting of necessary revamping of electronics, dated of year 2000s and that will be obsolete in the 2020s, we envisage for HL-LHC a radical solution: to displace on surface as much as possible of the electronics boxes that today are underneath of the dipole magnets, with clear benefit for availability, ease of maintenance and, again last but not least, the dose to personnel.

Germinal ideas have been discussed, the next step, after LS1 completion, is to study a solid technical solution and to make a realistic plan.

New IT cryoplants

Much higher radiation is expected escaping from IP1 and IP5 debris because of the increased luminosity in HL-LHC [27]. A large fraction of the power will be intercept at 4-10 K, by the tungsten shield, thermally connected to the beam screen. In total about 600 W will be intercepted in the IT-D1 beam screen and about the same will be absorbed by the coil and cold mass at 1.9 K. An extra cryogenic load will be given also by the much larger amperages of the IT quads and by the change of D1 from normal conducting to superconducting type. In Fig. 12 the needs of cryogenic power are represented in the various scenarii in terms of available power for e-cloud after all known losses have been subtracted from the refrigeration capability.

Refrigeration needs will considerably increase also in the MS because of increased amperage of the magnets and their cooling at 1.9 K, and because of the presence of CC cryo-module, as well as of the SC links. Indeed, if no additional cooling power is added, the helium circuit in the MS may increase the temperature of 0.1-0.15 K according to the various scenarios, dangerously reducing the margin for the stand-alone quadrupoles.

The baseline is to cope with the increased need of refrigeration by installing two new cryo-plants, each one capable of at least 12 kW power at 4.2 K. The cryogenic infrastructure will be modified to separate the QRL of LSS, serving the MSs, the CC and the IT, from the arc QRL serving the continuous cryostat of the arc (regular lattice and DS). By virtue of this new sectorization, a stop of refrigeration of the LSS will not cause a warm up of the arc and vice versa, greatly increasing the availability and the flexibility. Sectorization can be engineered in such a way that each IT new cryo-plant could serve as redundancy for the adjacent arc cryo-plant, of course with degraded operation mode. To make this redundancy most effective, installation of 18 kW plants will also be considered. Another advantage is to modify the cooling circuit in the IP1-5 such that the new cryo-plants could also serve as redundancy for the experimental magnet cryo-plants, and vice versa, again maximizing the flexibility in order to increase availability. The study of the new cryo-plants for IP1 and IP5 will be launched after LS1, since they are not on the critical path for LS3. However installing two new large cryo-plants necessitates an increase of space, service and infrastructure therefore integration study will be advanced in 2014.

The possibility to inject and accelerate beams with the HL-LHC characteristics relies on the effectiveness of the scrubbing in reducing the SEY in the dipoles down to 1.4 or lower to avoid multipacting. The new HL-LHC triplets and the D1 separation dipoles in the Interaction Regions (IR) 1 and 5 will have beam screens coated with low SEY materials and, if necessary, they will be equipped with clearing electrodes to suppress multipacting. Similar countermeasures might have to be applied for the triplets and D1 in IR 2 and 8.

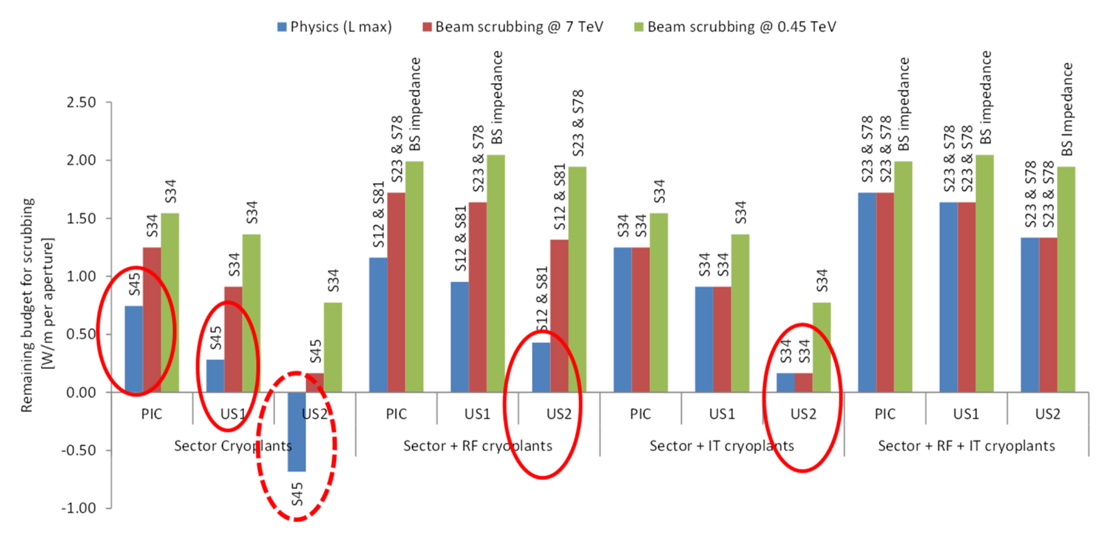

Figure 12: Power available in the arc once all known consumption are deduced, in the various scenarios (PIC, US1 and US2) with various configuration of LHC cryo-plants (RF means new cryo-plant in P4, IT means new cryo-plant in P1 and P5). In red are circled the case of impossible or very dangerous operation. A good margin is 1W/m and is assured only by installing all three new plants.

Long range beam-beam compensating wires

Use of electric wires parallel to the beam to compensate the long-range effect of the inter-beam interaction has been proposed for LHC long time ago [28], see Fig. 13. However for various reasons practical work to design a prototype for the LHC has started only recently. This equipment may allow reducing the crossing angle, reducing the demands on crab cavity or even constituting, in the case of flat beams, a possible mitigation plan in the unfortunate case that CC would not be viable. The plan calls for a test of preliminary prototype, built using the present collimator technology [29], in LHC by 2015-2016 and then the construction of a final prototype with specific technology (although the vicinity to the beam will always require collimator-like design), to be installed during LS2 for having it tested in best configuration on LHC beam during RunIII. This should allow building the final systems, with eventual corrective actions, in time for LS3.

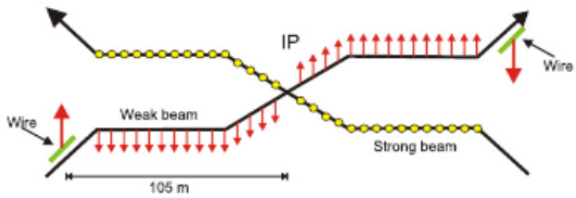

Figure 13: Effect of wires, compensating the effect of the long range beam.-beam interaction (here schematized in the strong-weak representation).

New collimation and halo control: electron-lens and crystals

There are two main functions of the collimation system in the high-luminosity IRs:

1. halo cleaning and protection of the triplet magnets;
2. cleaning of physics debris products.

The collimators on the incoming beam side that provide the first functionalities might also be used for background optimization. For the present LHC, the IR aperture limitation with small β* is found at the triplet magnets and one single pair of horizontal and vertical tertiary collimators (TCTs) is sufficient for the first function. This situation will change for the HL-LHC optics baseline, potentially requiring additional TCT-like collimators further upstream in the MS, at appropriate phase advances to shield the Q4 and Q5 magnets. Details on the numbers and locations of required TCTs are being studied.

For the physics debris, in addition to the DS collimation concept previously discussed, the MS layout changes for HL-LHC will impose obvious updates of the TCL collimators that are used to catch physics debris products (they have to follow the new magnet positions). The TCL layout is being upgraded in LS1 to have 3 collimators in cells 4, 5 and 6 at each IP side. This baseline is being studied also for the HL-LHC and it seems promising, but simulations are to be performed for the final layout. Other issues, like collimator needs for CC protection and effect of CC field on far debris losses, are being addressed.

Since a few years, following the promising results achieved at the Tevatron and under the umbrella of LARP collaboration with the collimation team, CERN is considering the possibility of controlling the beam halo through a slow diffusion of the particle by means of hollow electron beams which overlapping for a few meters with the proton beams (one device per beam). Investigation is going on [30] and the plan today is to study its application directly in the LHC without passing through a test in the SPS, since the functionality of the hardware has been already positively assessed in the Tevatron beam, see Fig. 14. The decision if this system would be necessary for LHC and HL-LHC will be taken after enough operational experience is accumulated after 2015: the RunII will give important information on the halo population and loss/repopulation mechanism and after that other possible alternative halo control system (tune modulation, feedback system and suitable use of LR b-b interaction) will be also studied in detail. A revised estimate of quench limits and beam lifetime will be needed. Effort has started at CERN with the ambitious goal to achieve a design report of such system, based on a conceptual design report provided by the Fermilab team, in order to be ready for possible implementation during LS2, which is a very challenging goal.

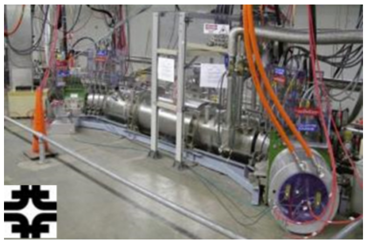

Figure 14: The Tevatron e-lens (e-gun not shown).

Crystal collimators have shown their interest with the success of the UA9 experiment in the SPS [31]. Here it is more difficult to make a plan since the suitability for LHC and the eventual R&D needed will be clarified after the first test in 2015 on LHC beam. Potentially, the crystal collimation is a change of paradigm, virtually all the beam halo is extracted onto, and absorbed by one single collimator, see Fig. 15. Crystal collimation is expected to provide a cleaning improvement due to reduced dispersive losses in the DS and reduced impedance. This scheme could be particularly interesting for the ion collimation in IR7. The time scale is not yet clear, however since the hardware is not bulky, once proved to be viable, a few years might be sufficient to design, manufacture and install this equipment. The integration into a safe LHC operation and the absorption of high-power channelled beams will have to be demonstrated.

It is important to note that the two advanced techniques discussed above are only helping betatron collimation and cannot improve losses in the interaction regions from physics debris. Hence, it is important to continue R&D on the 11 T dipole solution coupled with “standard” LHC collimators.

Both e-lens and crystal are not on the critical path for HL-LHC provided that a decision is taken before LS2. The e-lens has also to be scrutinized for integration issues, since the only region where they can be installed is in IR4 where the special dog-leg enlarges the inter-beam distance from 194 to 420 mm.

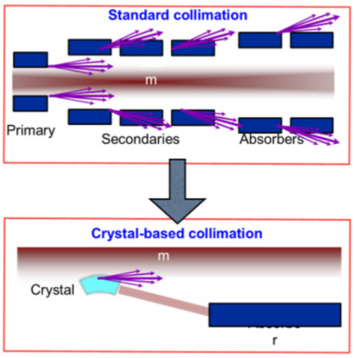

Figure 15: Principle of crystal collimation.

RF harmonic system

The advantage of a harmonic system of the 400 MHz LHC main RF cavities to increase the luminosity has been put through very early in the LHC upgrade studies, envisaging either an 800 or a 1200 MHz SCRF system [32]. A study of the possible benefit, and issues to overcome, of a 800 MHz have already started, also because of the synergy with the energy recirculating linac envisaged for LHeC. In the frame of the collaboration with the university of Stuttgard (Germany) two 800 MHz SCRF cavities are under construction and could be used as prototype for HL-LHC.

Very recently in the frame of the preparation for this workshop the possibility of using 200 MHz cavities has been put through and compared with the use of the 800 MHz system [8]. The idea is to use the 200 MHz as main accelerating system and the present 400 MHz would become the harmonic system, at least in certain phase of the operation cycle. The proposal is too recent to be examined in terms of integration. However is clear that a 200 MHz system may be too large for the tight space of LHC, even in the dog-leg of IR4, if built in elliptical shape: the proposal is indeed to use Quarter-wave type cavity, which would pose less problem of space. In any case careful integration studies should be carried out before validating this idea.

IMPLEMENTATION MATRIX AND COST

For the operation-shutdown schedule, we refer to the official CERN plan of October 2013 (see Fig. 16).

The main difficulty for the implementation works foreseen for LS2 concerns the 11 T dipole – DS collimation. Indeed, six months of delay have been accumulated, virtually reducing to zero all previous margins. Further, the larger than planned engagement of the CERN teams for the LS1, which is of course the priority of all equipment groups, has adverse consequence on the personnel availability. One year of shift in the end of LS2 is certainly welcome for this project.

A short shutdown, called extend year end technical stop (see slim red box in the schedule of Fig. 15) would be extremely useful to install low-impedance collimators prototype and to advancing infrastructure works for the P7 SC link as well as for the new cryo-plant in P4. This also helps to fit the LS2 works in the one year schedule. The extension of LS2 to 18 months is beneficial, especially for the 11 T project.

The extended stop, in conjunction with the shift of at least six months of the LS2 start, is also necessary to install the CC in the SPS and to properly carry out beam tests in 2017-18.

The shift of LS3 by one year, widely discussed at the workshop is probably necessary for the CC project and it is a welcome (but not mandatory) for the inner triplet and the other equipment. The shift of LS3 is not mandatory because we can always devise a plan where the inner triplet and MS magnets, with cryogenics and cold powering, are installed in the LS3 and the CC are installed in the subsequent long shutdown. The HL-LHC project needs two years for installing and commissioning all the hardware. An extension by six months is certainly useful, however an even longer shutdown, especially if coupled with a further shift, may suggest a new scenario (for example a merging of LS2 and LS3). Indeed to increase the integrated luminosity we should not delay too much the installation of the new triplet that has very good chance to be ready by 2022, also thanks to the USA and Japan contribution.

In Fig. 17 is reported the implementation matrix, according to the scheme reported in the document for the workshop preparation (https://espace.cern.ch/ReviewWorkshop/Timetable/RLIUP%20workshop%20Full%20View%20timetable.pdf). Here we remind that PIC (performance Improving consolidation) has the goal of reaching 1000 fb^{-1} limiting the upgrade to those equipment that needs to be replace for wear and damage, like the inner triplet; US1 (upgrade scenario 1) has the goal of reaching 2000 fb^{-1}; US2 has the goal of reaching the full goal of the upgrade, 3000 fb^{-1}.

Figure 17 contains also a budgetary evolution of the material cost, done in the CERN accounting system. A rigorous bottom-up with management validation budget will be carried out in 2014.

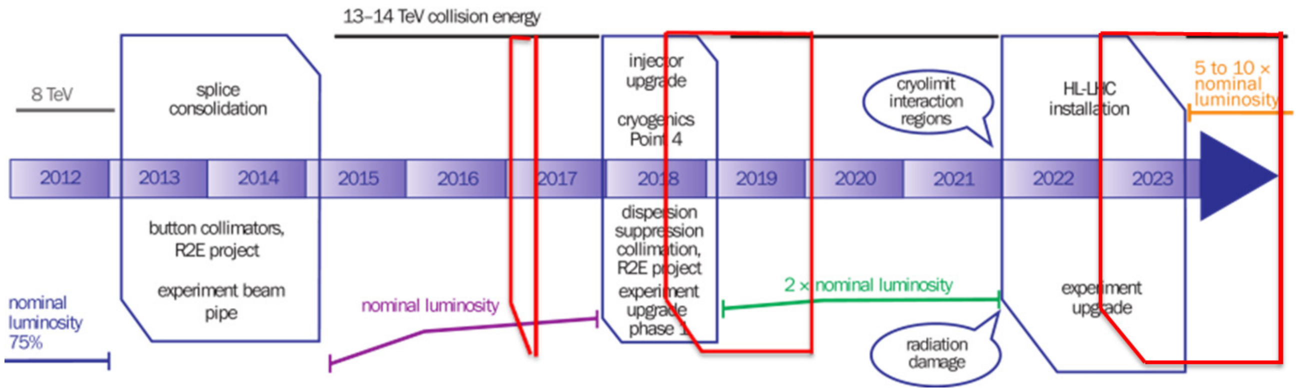

Figure 16: CERN 10-Year plan at the time of the RLIUP workshop. The blue boxes indicate the major shutdowns (winter stops not indicated). The red boxes indicating possible, or desired, modification to shutdown schedule.

The budget figures are substantially the ones of end 2011, at the beginning of the FP7 HiLumi design Study, and do not contain:

- The cost of possible lateral galleries, nor their access pits, for CC infrastructure.
- The cost of the SCRF 2^{nd} harmonic system and its infrastructure.
- The cost of the e-lens, crystal collimators and high band feedback system.

The cost of the LRBB wire is very approximate since the hardware development has just started. Both this equipment and the SCRF harmonic system are not in the official baseline. However they are considered important and even essential (LRBB wire) for reaching the HL-LHC targets.

In the same table of Fig. 17, it is indicated the possible in-kind contributions from non-member States. The in-kind contributions will reduce the CERN cost, of course; however, given the different accounting system, the value of the contributions may not decrease the CERN cost of the same amount. In this respect the figures shown in the table are to be considered as “CORE cost”, very much like in the LHC experiments. The figures do include all cost of technical infrastructure related to the equipment of the upgrade, but not the cost of the consolidation needed to maintain operational the various services and infrastructure for the LHC machine.

CONCLUSIONS

The HL-LHC is a very challenging project, aiming at improving a machine already very optimized. It requires a very high quality performance form the LHC Injector complex and a global revision of the machine parameters.

New concepts are applied to reach the upgrade goals, like the luminosity levelling, the ATS optics, the crab kissing scheme and the bunch rotation by means of CC. Novel advanced components will be used to dramatically improve the main performance of the two main accelerator technology: magnets and RF cavities. Superconducting magnets capable of up 12 T in very large bore (the IT quadrupoles) and very compact superconducting cavities capable to manipulate the proton bunch in the transverse space.

We have a solid plan to successfully finish the R&D for all various equipment and, thanks also to the new CERN schedule discussed during this workshop, we are optimist to be able to satisfy the installation schedule. The main uncertainty is at present, and probably will remain, the availability of adequate resources of personnel, in CERN and in all collaborating Institutes.

ACKNOWLEDGEMENTS

We warmly thank all people that are involved in the HL-LHC and that have provided useful information and material for this paper.

LS2 - 1 y (14 months access)		LS3 - 2 y (26 months access)					
	PIC		US1	US2	Cost (MCHF)		In kind
	LS2	*LS3*	*LS3*	*LS3*			in part
P4 new cryoplant	Y				15		
H SC link P7	Y				5		
IR (IT,D1, TAS)	%	Y			210		YES
P1-P5 cryoplant	%	Y			75		
SC link (EPC&DFBX on surface)	%	Y			40		
Collimators IR		Y			10		
Collimators MoGr	%	Y			15		
Collimators for INJ &TCLA Q4/Q5)		Y			5		
DS cryocoll.(11T) P2	Y				20	395	
LRBB comp.wires			Y		10		
DS cryocoll.(11T) P7			Y		25		
DS cryocoll (11 T) P1-P5			Y		40		
SC link (EPC&DFB on surface) for MS			Y		20	95	
MS new layout (P1-P5) and Q5 in P6				Y	30		YES
Machine & Magnet QPS (Availability)				Y	25		
CC cavity P1-P5				Y	95		YES
SCRF 2nd Harmonic				Y			
Crystal Coll				Y ?			YES ?
Halo control (e-lens)				Y ?			YES
High Band Feedback System				Y ?		150	
Studies					10		
Other systems (Studies, Vacuum, Diagnostics, Remote handling					30		
Infrastructure, Logistics, Integration,Installation HWC					130	170	
Total					**810**	**810**	

Figure 17: Implementation matrix and material cost, in CERN accounting system, of the HL-LHC project. See text for explanation. The symbol “Y” means Yes (full implementation) and “%” means partial implementation. The “?” is used to tag equipment that today are not in baseline.

REFERENCES

[1] C. Carli editor, Proceedings of Chamonix 2010 Workshop on LHC Performance, held in Chamonix 25-29 January 2010, report CERN-ATS-2010-026.

[2] S. Meyers and F.Zimmermann, “Chamonix’10 Summary”, in Proceedings of Chamonix’10, report CERN-ATS-2010-026, pp. 367-374.

[3] “The European Strategy for Particle Physics - Update 2013”, CERN-Council-S/106, approved in the Special Session held in Brussel, European Commission, on 30 May.

[4] HL-LHC Coordination Group, Minutes of Meeting 2nd Meeting, https://indico.cern.ch/conferenceDisplay.py?confId=192708

[5] S. Fartoukh, “Pile up at HL-LHC and possible mitigations”, talk at the Ecfa High Luminosity LHC Experiments Workshop, 1-3 October 2014, Aix-les-Bains, https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=252045

[6] L. Rossi, “LHC Upgrade Plans: Options and Strategy”, Presented at IPAC2011, San Sebastian (ES), published in the Proceedings on the Jacow website (pp. 908-912): http://accelconf.web.cern.ch/AccelConf/IPAC2011/papers/tuya02.pdf

[7] O. Bruning and L. Rossi, “High Luminosity Large Hadron Collider. A description for the European Strategy Preparatory Group”, CERN-ATS-2012-236.

[8] R. Tomás, O. Domingues and S. White, “HL-LHC alternatoves”, these proceedings.

[9] M. Brugger, “Radiation Damage to Electronics at the LHC”, IPAC 2012, published in Conf. Proc. C1205201 (2012) 3734-3736.

[10] A. Ballarino, “Development of Superconducting Links for the LHC Machine", presented at EUCAS 2013, Genova, Proceedings of SUST, Superconductor Science and Technology.

[11] R. Assmann et al., "Accelerator physics concept for upgraded LHC collimation performance," Proceedings of PAC09, held in Vancouver (CA), 2009. http://accelconf.web.cern.ch/AccelConf/PAC2009/papers/th5pfp008.pdf

[12] A. Marsili, R. Bruce, R. De Maria, S.D. Fartoukh, S. Redaelli, "Simulations of Collimation Cleaning Performance with HL-LHC Optics," Proc. of IPAC2013, Shanghai (China), 2013. http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/mopwo042.pdf

[13] L. Bottura, G. de Rijk, L. Rossi, E. Todesco, "Advanced Accelerator Magnets for Upgrading the LHC", IEEE Transactions on Applied Superconductivity, Vol. 22, Issue 3, June 2012, article 4002008.

[14] A. V. Zlobin et al., "Fabrication and test of a 1 m long single aperture 11 T Nb3Sn dipole for LHC upgrades", Proceedings of IPAC2013, Jacow website: http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/thpme044.pdf

[15] A. Bertarelli et al., "An experiment to test advanced materials impacted by intense proton pulses at CERN HiRadMat facility", Nucl. Instr. Meth. B (2013) http://dx.doi.org/10.1016/j.nimb.2013.05.007

[16] S. Redaelli, "The LHC collimation baseline for HL-LHC," presentation at the 3rd HiLumi annual meeting, Daresbury (UK), 2013. http://indico.cern.ch/event/257368

[17] L. Bottura and P. Fessia, "What could stop us and when", these proceedings.

[18] 1st HL-LHC Parameter and Layout Committee, http://indico.cern.ch/conferenceDisplay.py?confId=196571

[19] G. Ambrosio et al., "Progress in the Long Nb3Sn Quadrupole R&D by LARP", IEEE Transactions on Applied Superconductivity, Vol. 21, no. 3, pp. 1858-1862.

[20] E. Todesco et al., "Design Studies for the Low-Beta Quadrupoles for the LHC Luminosity Vol. 23, Issue 3, Part: 2, 2013.

[21] R. De Maria, S. Fartoukh, A. Bogomyagkov, M. Korostelev, "HLLHCV1.0: HL-LHC Layout and Optics Models for 150 mm Nb3Sn Triplets and Local Crab-cavities. TUPFI014, IPAC'13 Proceedings.

[22] E. Todesco et al., "A First Baseline for the Magnets in the High Luminosity LHC Insertion Regions", IEEE Trans. on Appl. Superc., Vol. 24, Issue 3, 2014.

[23] S. Fartoukh, "Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade", DOI: 10.1103/PhysRevSTAB.16.111002 and CERN-ACC-2013-0289

[24] R. de Maria, Gianluigi Arduini et al., "How to maximize the HL-LHC performance", these proceedings.

[25] Y-P Sun, R. Assmann, J. Barranco, R. Tomás, T. Weiler, F. Zimmermann, R. Calaga, R, A. Morita, "Beam dynamics aspects of crab cavities in the CERN Large Hadron Collider" Phys. Rev. Spec. Top. Accel. Beams 12 (2009) 101002.

[26] R. Calaga, "Crab Cavities for the LHC Upgrade", Proceedings of the Chamonix 2012 Workshop on LHC Performance, pp.363-372.

[27] L.S. Esposito, F. Cerutti, E. Todesco, "FLUKA Energy Deposition Studies for the HL-LHC", IPAC'13 Proceedings (Jacow website).

[28] J.P. Koutchouk, "Correction of the Long-Range Beam-Beam Effect in LHC using Electro-Magnetic Lenses", PAC '01 Chicago, IL, USA , 18 - 22 Jun 2001 and CERN-SL-2001-048-BI

[29] T.L. Rijoff, R.J. Steinhagen, F. Zimmermann, "Simulation Studies for the LHC Long-Range Beam-Beam Compensators", IPAC'12 (Jacow website).

[30] G. Stancari, "Progress towards the conceptual design of a hollow electron lens for the LHC", presentation at the 3rd Joint HiLumi LHC- LARP Annual Meeting, Daresbury (UK), 2013. http://indico.cern.ch/event/257368

[31] W. Scandale et al., "Strong reduction of the off-momentum halo in crystal assisted collimation of the SPS beam," Phys.Lett. B714 (2012) 231-236.

[32] O. Bruning et. al. (F. Ruggiero ed.), "LHC Luminosity and Energy Upgrade: A Feasibility Study", CERN LHC Project Report 626, December 2002.

Published by CERN in the Proceedings of RLIUP: Review of LHC and Injector Upgrade Plans, Centre de Convention, Archamps, France, 29–31 October 2013, edited by B. Goddard and F. Zimmermann, CERN–2014–006 (CERN, Geneva, 2014)

HL-LHC ALTERNATIVES

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Abstract

The HL-LHC parameters assume unexplored regimes for hadron colliders in various aspects of accelerator beam dynamics and technology. This paper reviews three alternatives that could potentially improve the LHC performance: (i) the alternative filling scheme 8b+4e, (ii) the use of a 200 MHz RF system in the LHC and (iii) the use of proton cooling methods to reduce the beam emittance (at top energy and at injection).

The alternatives are assessed in terms of feasibility, pros and cons, risks versus benefits and the impact on beam availability.

ALTERNATIVES AND MERITS

This section introduces three alternatives to the HL-LHC baseline considered in this report together with their merits and weak points. Electron cloud effects in the HL-LHC era could seriously hamper the luminosity upgrade. Therefore special attention is put in the evaluation of electron cloud effects for the different alternatives.

Filling scheme 8b+4e

By performing a double splitting instead of triple splitting in the PS it is possible to generate fewer and more intense bunches. Basically a PSB bunch is split into 8 bunches rather than 12. The usual 12 bunch structure is preserved keeping 4 empty bucktes in between the micro-batches of 8 bunches. For details on the generation of this scheme see [1]. Following the upgrade of the injector chain, the 8b+4e scheme would allow 1840 bunches to be injected into the LHC with 2.4e11 ppb if the LHC is filled without further changes to the bunch pattern.

The outstanding merit of this alternative is the huge reduction of electron cloud effects plus the fact that this filling scheme can be implemented from 2015 without any cost (8b+4e bunch population in 2015 might be $1.6{\times}10^{11}$ ppb). Figure 1 shows simulations of the heat load due to electron cloud per aperture in the LHC dipoles using the parameters as expected in 2015 for the baseline and for the 8b+4e scheme. A measurement of heat load during 2012 is shown in the figure as a pessimistic reference for tolerable levels of heat load. A large reduction factor in heat load thanks to the 8b+4e scheme is observed, allowing, in principle, operation with secondary emission yields as large as $\delta_{max} \approx 1.6$. Considering HL-LHC parameters the 8b+4e scheme also generates considerably lower heat load than the nominal 25 ns scheme, yet it requires $\delta_{max} \lesssim 1.4$, as illustrated in Fig. 2.

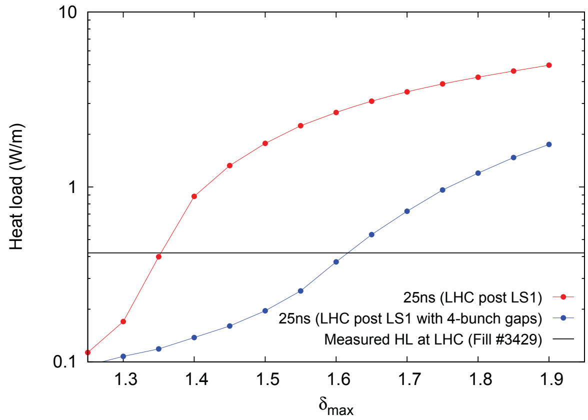

Figure 1: Heat load versus maximum secondary emission yield due to electron cloud per aperture in the LHC dipoles using the parameters as expected in 2015 for the baseline and for the 8b+4e scheme. The inferred heat load from measurements in 2012 is also shown.

During discussions in the RLIUP workshop on how to maximize the number of bunches in the LHC, a proposal was made to inject 7 instead of 6 PSB bunches into the PS. In the nominal filling scheme this would imply losing few (three or four) bunches at the end of the batch while extracting to the SPS, with the consequent transfer of trains made of 80 or 81 bunches. However, this option turned out to fit particularly well into the 8b+4e scheme, as 7 injections can be made from the PSB to the PS and no bunches would need to be removed at extraction thanks to the four empty buckets [2]. The SPS would be filled with the following bunch train structure:

$$4 \times (7 \times (8b + 4e) + 4e) + 572e \qquad (1)$$

This optimized scheme produces more luminosity thanks to the larger number of bunches but also yields slightly larger heat load due to electron cloud, see Fig. 2. A filling pattern in the LHC has been prepared using this scheme [3] yielding 1960 colliding bunches in the main interaction points (120 more than for the initial 8b+4e). This optimized scheme is used in the rest of the paper.

The feasibility and performance of the 8b+4e scheme should be experimentally assessed via beam tests starting in the LHC injector chain already in 2014.

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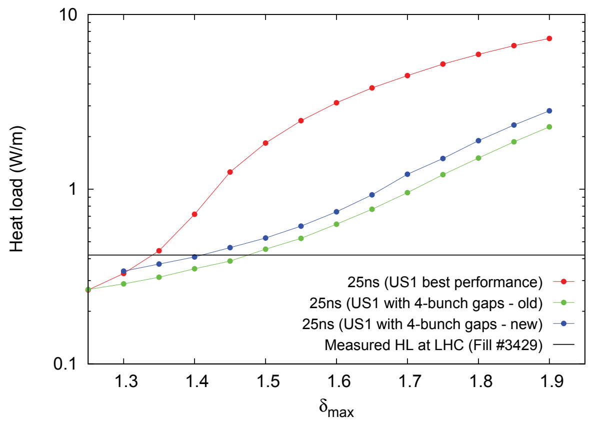

Figure 2: Heat load versus maximum secondary emission yield due to electron cloud per aperture in the LHC dipoles using the US1 parameters for the baseline and for the two 8b+4e filling schemes. The inferred heat load from measurements in 2012 is also shown.

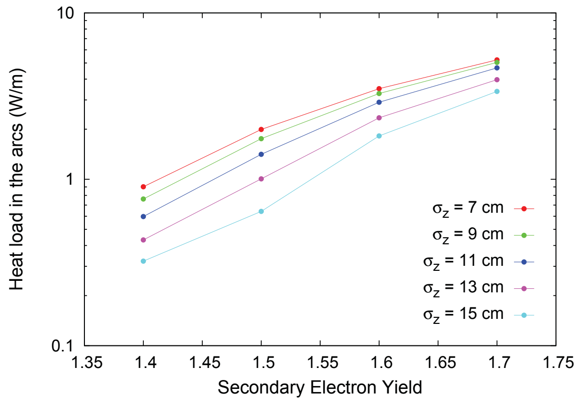

Figure 3: Heat load due to electron cloud in the arc dipoles at 7 TeV for the HL-LHC (US2) for different values of the bunch length with $N_b = 2.5 \cdot 10^{11}$ ppb. We can see how the heat load reduces monotonically with an increasing bunch length. In addition, the SEY multipacting threshold displaces towards higher values for longer bunch lengths.

Table 1: Possible configurations of the 200 and 400 MHz RF systems in the LHC [4], showing emittance, voltages and bunch length. The last row combines the possibility of using the 400 MHz system for bunch shortening or lengthening.

ϵ_s [eVs]	200 MHz [MV]	400 MHz [MV]	σ_z [cm]
3	0	16	8.77
3	3	0	15.7
2	6	0	12.6
2	6	3	10.8-15.5

200 MHz main RF in the LHC

Using a 200 MHz system as main RF throughout the LHC cycle allows to inject more intense and longer bunches into the LHC and to optionally level luminosity with bunch length. The possible RF operational modes at collision energy are shown in Table 1 [4]. A minimum voltage of 3 MV is required for the 200 MHz RF system. However this minimum voltage gives no operational margins to modify the bunch length. 6 MV is the preferred 200 MHz voltage. Bunch length luminosity leveling, in combination with β^* leveling, is considered to maximize the integrated luminosity with the possibility of full capture in the 400 MHz system during physics. Single steps of bunch length luminosity leveling were experimentally demonstrated in the LHC [5].

200 MHz normal conducting cavities have been already proposed [6] and manufactured for the LHC in order to optimize the beam capture at injection. However these cavities have not been installed and would not be sufficient to ramp the beam energy. Only recently a first compact design of 200 MHz superconducting cavities has been proposed [7] for the LHC.

A reduction of electron cloud is expected for longer bunches. This is shown in Fig. 3 by plotting simulated heat load in the dipoles for various bunch lengths versus secondary emission yield. A monotonic behavior is observed in the range of interest. Figure 4 compares the heat load for the HL-LHC baseline and the 200 MHz alternative. A significantly lower heat load due to electron cloud in the dipoles is observed in the 200 MHz case for $\delta_{max} < 1.6$.

The heat load due to electron cloud in the quadrupoles needs to be addressed for longer bunches. Nevertheless simulations show that head load in the arc quadrupoles is strongly reduced when increasing the bunch charge between $1.5{\times}10^{11}$ ppb and $2.2{\times}10^{11}$ ppb for secondary emission yields between 1.2 and 1.6 [8]. Measurements in the LHC with 25 ns bunch spacing during bunch lengthening by 40% in the energy ramp do not reveal any visible increase in the heat load [9]. Yet, there was one observation with 50 ns bunch spacing of a slight heat load increase in the triplets when increasing bunch length by 17% [10].

Another beneficial effect from the longer bunches is the reduction of the beam induced heating due to impedance. Figure 5 shows the beam induced heating versus the rms bunch length [11]. Reductions of a factor ≈ 5 for the upgraded injection kicker (MKI) and ≈ 2 for the 17.3 mm beam screen are expected when increasing the bunch length from 7.5 cm to 13 cm.

The main limitation arising from the lower RF frequency is a reduction of the TMCI threshold. The LHC impedance is dominated by collimators and one can assume the TMCI threshold to be driven by the tune shift of the mode 0. In this case it is possible to analytically estimate the maximum

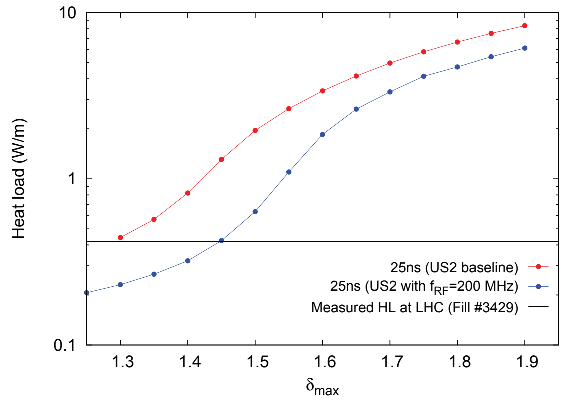

Figure 4: Heat load due to electron cloud in the arc dipoles at 7 TeV for the HL-LHC (US2) for the baseline scenario (red curve) and an alternative scenario using a 200 MHz system as main RF (blue curve).

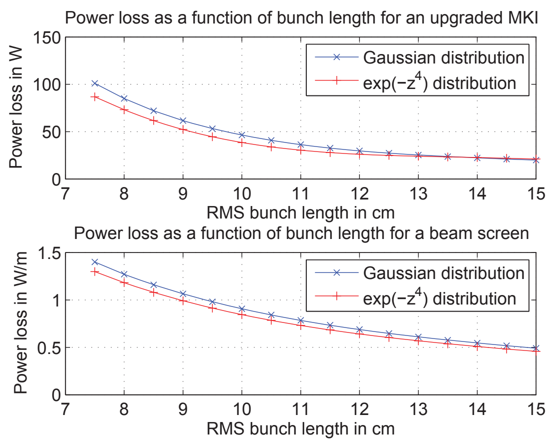

Figure 5: Heating due to impedance versus rms bunch length for the injection kicker (MKI) and the beam screen [11].

effective impedance by [12]

$$\Im Z_y^{eff}{}_{max} = \frac{4\pi(E_t/e)\tau_b Q_s}{N_b e \beta_y^{av}} \quad (2)$$

where E_t is the beam energy, τ_b is the bunch length in seconds, Q_s is the synchrotron tune, N_b is the bunch population and β_y^{av} is the average β-function. The TMCI threshold is therefore proportional to the bunch length and the synchrotron tune. Using a bunch length of 12.6 cm and $Q_s = 9 \times 10^{-4}$ for the 200 MHz scenario the relative reduction of the TMCI threshold is 1.36.

Figure 6 shows a simulation of the TMCI threshold at zero chromaticity for 200 MHz and 400 MHz main RF systems. The HL-LHC impedance model as presented in [13] is used in the eigenvalue solver code presented in [14] assuming Gaussian bunch densities. The degradation of about a factor 1.5 is confirmed and the threshold is decreased to 2.6×10^{11} ppb which is barely above the foreseen operational bunch charge. It is possible that multi-bunch effects slightly decrease this threshold bringing the operational bunch charge below the target. This could be of some concern for beam stability but it has been shown that the use of transverse damper and chromaticity relaxed intensity thresholds, for instance, in SOLEIL [15]. Alternative materials for the collimators are also under consideration which could significantly reduce their contribution to the global impedance of the machine and hence increase the TMCI threshold.

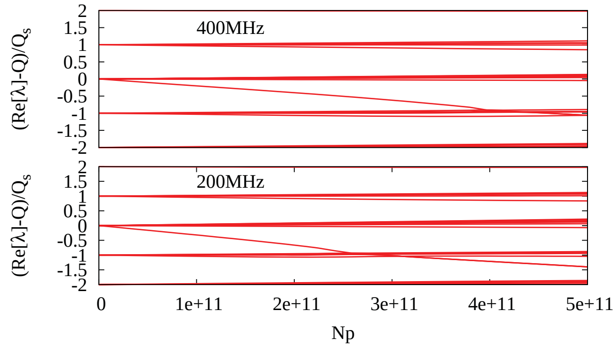

Figure 6: TMCI threshold at zero chromaticity for 200 MHz (bottom) and 400 MHz (top) main RF systems.

Another concern of the 200 MHz system is its compatibility with 400 MHz crab cavities. An illustration of the beams encounter at the IP is depicted in Fig. 7 for the baseline and the 200 MHz alternative. The core of the beam (1 σ corresponding to the red area) is basically unaffected by the crab cavity RF curvature. A similar situation was studied when 800 MHz elliptical crab cavities and β^*= 25 cm were considered for the luminosity upgrade without finding any problem in dynamic aperture [16] or strong-strong [17] simulations. Nevertheless these simulations should be revisited using the new configuration. Furthermore a reduction of the crab cavity frequency to 320 MHz has been considered after the RLIUP workshop [18]. This causes a negligible increase in integrated luminosity but a significant reduction of peak pile-up density, reaching 0.8 mm^{-1}.

The merits of the 200 MHz main RF system follow: (i) a significantly lower electron cloud, (ii) larger bunch charge (possibly 2.56×10^{11} ppb), (iii) factors between 2 and 5 lower heat-load coming from impedances and (iv) the possibility of leveling luminosity by reducing bunch length during the fill.

Cooling protons

Recently various cooling techniques have been proposed for protons in the LHC [19, 20, 21]. Most of these techniques require challenging hardware at top energy. However performing cooling at injection energy prior to the energy ramp would require a more affordable hardware and synergies could be established with the LHeC ERL test fa-

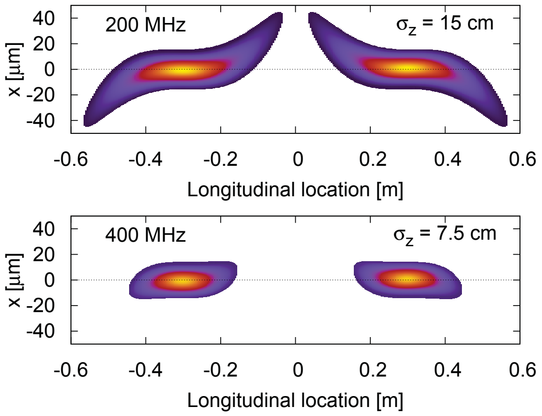

Figure 7: Illustration of the crab cavity RF curvature effect on the collision process for the nominal RF system (400 MHz) and the alternative of 200 MHz. The beams contours correspond to 2 σ envelope for a β^*= 15 cm.

cility. Nevertheless even assuming 1 hour of cooling at injection to halve the transverse emittances does not render any improvement in the integrated luminosity. This is due to the increased turn-around time and the presence of IBS during the fill, which blows up the cooled emittance. Possible future developments on cooling techniques should be followed up since an affordable cooling at collision energy will certainly improve the HL-LHC performance.

PERFORMANCE EVALUATION

In the following sections the various alternatives are compared in terms of integrated luminosity, length of the optimum physics fill, peak pile-up density (μ_{peak}) and beam-beam tuneshift ($\xi_{x,y}$). These are calculated via simulations of the physics fill evolution. The estimate of the integrated luminosity requires determining the luminosity evolution during a fill. The beam intensity evolution has been evaluated taking into account the burn-off due to luminosity considering a total cross-section of 100 mb. The emittance evolution has been determined including Intra-Beam Scattering (IBS) with a coupling of 10% and Synchrotron Radiation (SR) damping. The bunch charge and emittances are updated every 10 minutes according to the current luminosity burn-off, IBS growth rates and SR damping. The bunch length is either kept constant assuming the use of longitudinal emittance blow-up techniques or purposely reduced by increasing RF voltage and/or letting SR damp the longitudinal emittance.

The overlap luminosity integral including the crab cavity RF curvature is derived from [16] by adding the hour-glass effect. The peak pile-up density is evaluated as the density of physics events exactly at the IP (s=0).

The yearly integrated performance is computed assuming 160 days dedicated to proton physics (including the turn-around time of 3 hours) with a 50% efficiency. Efficiency is defined as:

$$N_{fills}\frac{T_{physics}+T_{turn-around}}{T_{run}}$$

where N_{fills} is the number of fills, $T_{physics}+T_{turn-around}$ is the sum of the time in physics and the time needed to come back to physics and T_{run} is 160 days. All the fills are assumed to have the same length. This could correspond to the optimum fill length or to 6 hours. Both cases are presented in the following to assess the sensitivity to the fill length.

US1 PERFORMANCE

The US1 scenario [22] sets a yearly integrated luminosity goal of 170 fb^{-1}. The baseline approach to reach this goal assumes the installation of the new large aperture triplet in the LHC but without crab cavities and without any modification of the matching section. A separation of 10 σ is assumed at the long-range encounters, which should be compared to the nominal 9.5 σ. Although β^* leveling would strongly mitigate the long-range interactions, it is not guaranteed that such separation can be achieved without degradation of the dynamic aperture during the whole fill due to the larger bunch population. Therefore the possibility of using long-range compensation wires is under study to allow for the 10 σ separation.

Table 2 compares the performance of the US1 baseline scenario to various alternatives. The first alternative simply considers a flatter beam at the IP by increasing the β^* function in the crossing plane. This reduces the integrated luminosity only by 7% while reducing the peak pile-up density from 1.5 mm^{-1} to 1.1 mm^{-1} (27% reduction).

The next two alternatives can be regarded as the back-up scenarios in case electron cloud makes 25 ns not operational. These are 8b+4e and 50 ns [23]. The 8b+4e gives 11% lower integrated luminosity than the baseline US1 with 20% lower peak-pile up density. The small performance degradation makes this option extremelly interesting. The 50 ns alternative features lower performance with almost twice longer fills, which makes it considerably less interesting.

It should be noted that head-on and long-range beam-beam effects should be reviewed for all scenarios to find appropriate compromises and that the 8b+4e alternative enhances the head-on beam-beam by about 15-20%.

The last alternative considered for US1 is using a 200 MHz main RF system in LHC. This proves to be the best performing option providing between 232 fb^{-1} and 240 fb^{-1} per year with peak pile-up densities between 1.1 mm^{-1} and 1.4 mm^{-1}, depending on the β^* in the crossing plane. This largely exceeds the goal of 170 fb^{-1} per year.

Figure 8 shows the evolution of the relevant machine and beam parameters during the fill for the baseline and the main alternatives 8b+4e and 200 MHz.

Table 2: Performance comparison of the US1 baseline to various alternatives. 200 MHz features the performance with significantly lower electron cloud than the baseline.

	N	ϵ	$\beta^*_{x,y}$	L_{year}[fb^{-1}]		Opt. fill	Pile-up	
	[10^{11}]	[μm]	[cm]	Opt.	6h	length [h]	total	[mm^{-1}]
US1	1.9	2.62	20,40	181	181	6.1	140	1.5
flatter	1.9	2.62	20,80	169	168	6.6	128	1.1
8b+4e	2.4	2.2	20,80	160	156	7.5	143	1.2
50ns	3.5	3.0	20,80	142	118	12	143	1.1
200MHz	2.56	3.0	20,80	232	224	8.1	138	1.1
200MHz	2.56	3.0	20,40	**240**	228	8.5	138	1.4

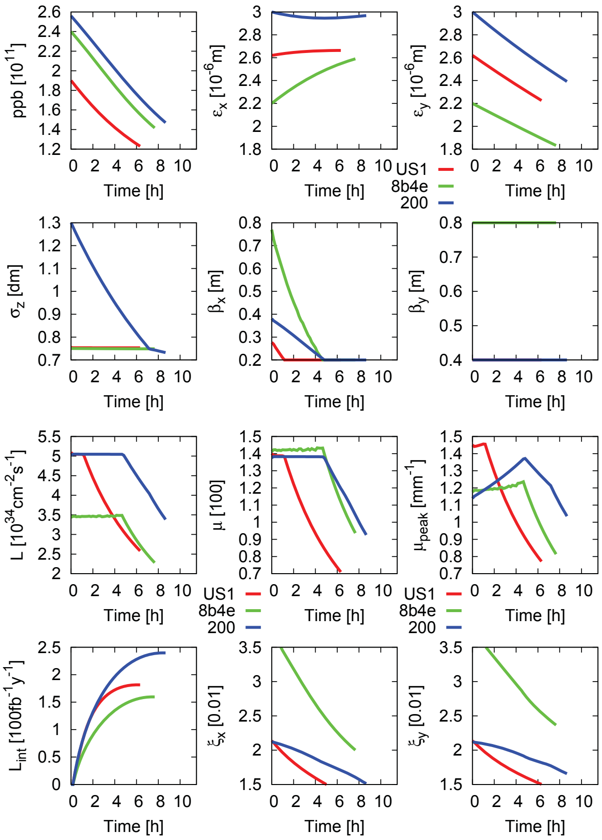

Figure 8: Comparison of the US1 baseline (red) to the 8b+4e (green) and 200 MHz (blue) alternatives. β_x is the beta function in the separation plane.

US2 PERFORMANCE

The US2 scenario [24] sets a yearly integrated luminosity goal of 250 fb^{-1}. The baseline approach to achieve this goal corresponds to the complete HL-LHC upgrade with crab cavities and a modified matching section allowing to achieve lower β^* than in US1. A more comfortable beam separation at the long range encounters of 12 σ is assumed for US2 throughout this report. For flat beams alternatives in US2 12 σ might again need the use long range wire compensators [25]. The main alternative to this scenario is the addition of the 200 MHz main RF system which increases the yearly integrated luminosity by 6% using 11 hours fills. Table 3 shows the performance of the US2 baseline, the 200 MHz alternative with 400 MHz crab cavities and a back-up solution in case crab cavities would not be operational in hadron machines. The detailed evolution of the various machine and beam parameters during the fill is shown in Fig. 9. Bunch length leveling is assumed in the 200 MHz alternatives for a maximum luminosity performance. This, in turn, produces a large peak pile-up density. Means to decrease the peak pile-up density are addressed in the next section.

PEAK PILE-UP DENSITY LEVELING

In general it is possible to level at constant peak pile-up density rather than at constant luminosity. This implies a reduction of the integrated luminosity. The first scheme including peak pile-up density leveling at 0.65 mm^{-1} is named “crab kissing” and it is described in [26, 27].

We consider two other ways to achieve an efficient peak pile density leveling. The first one is particularly interesting since it does not require any new hardware contrary to the crab-kissing which assumes crab-cavities also in the parallel separation planes. This consists in the usual β^* leveling with σ_z=10 cm but targeting peak pile-up density rather than luminosity.

The second one includes the use of 800 MHz RF cavities to flatten the longitudinal bunch distribution, see Fig. 10, and β^* leveling. Table 4 shows the performance for the US2 baseline and these two peak pile-up leveling techniques. Peak pile-up density can be effectively reduced to 1 mm^{-1} without any new hardware integrating 250 fb^{-1} per year. The 800 MHz RF system further reduces the peak pile-up density to 0.9 mm^{-1} slightly increasing the integrated luminosity to 252 fb^{-1}.

Peak pile-up density is also possible in the 200 MHz alternative scenario. The most convenient is to assume flat optics at the IP with a bunch length not shorter than 10 cm and using β^* leveling. Table 5 shows the performance of this option in 2 steps. A peak pile-up density of 1 mm^{-1} is

Table 3: Performance of US2 baseline and 200 MHz alternatives with 400 MHz crab cavities. 200 MHz with crab cavities gives the best performance with lower electron cloud and it is robust against non-working crab cavities.

	N $[10^{11}]$	ϵ $[\mu m]$	$\beta^*_{x,y}$ [cm]	$L_{year}[fb^{-1}]$ Opt.	6h	Opt. fill length [h]	Pile-up total	$[mm^{-1}]$
US2	2.2	2.5	15,15	261	232	9.3	140	1.3
200MHz	2.56	3.0	15,15	**276**	234	11	140	1.3
200MHz (no CC)	2.56	3.0	10,50	255	233	10	139	1.6

Table 4: Performance of the peak pile-up leveling techniques in the baseline scenario.

	N $[10^{11}]$	ϵ $[\mu m]$	$\beta^*_{x,y}$ [cm]	$L_{year}[fb^{-1}]$ Opt.	6h	Opt. fill length [h]	Pile-up total	$[mm^{-1}]$
US2	2.2	2.5	15,15	261	232	9.3	140	1.2
β^*-level	2.2	2.5	15,15	250	232	9.5	142	1.0
800MHz	2.2	2.5	15,15	252	232	9.1	141	0.9

Table 5: Performance of the peak pile-up leveling techniques in the 200 MHz scenario.

	N $[10^{11}]$	ϵ $[\mu m]$	$\beta^*_{x,y}$ [cm]	$L_{year}[fb^{-1}]$ Opt.	6h	Opt. fill length [h]	Pile-up total	$[mm^{-1}]$
200MHz	2.56	3.0	15,15	276	234	11	140	1.3
σ_z=10cm	2.56	3.0	7.5,30	272	233	11	140	1.1
β^*-level	2.56	3.0	7.5,30	272	233	10	141	1.0

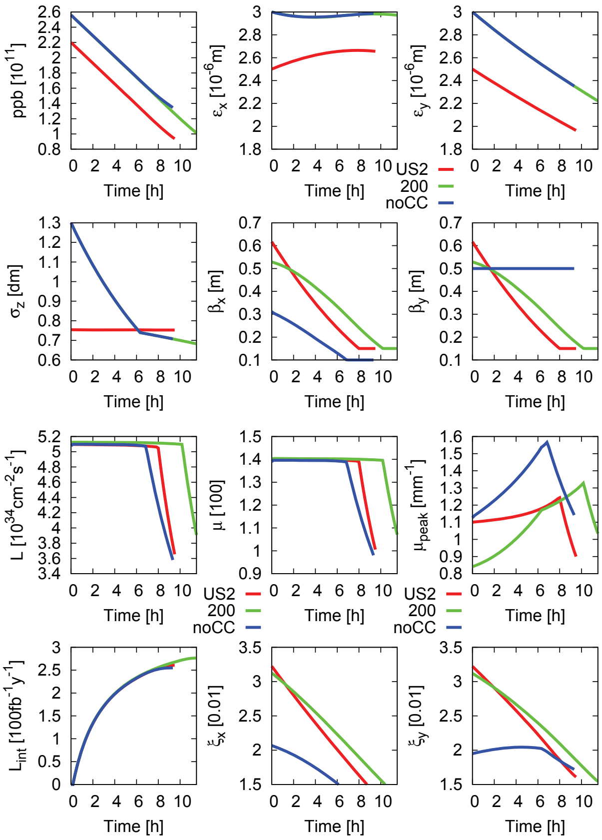

Figure 9: Fill evolution of the US2 baseline, 200 MHz alternative with 400 MHz crab cavities and a back-up option without crab cavities.

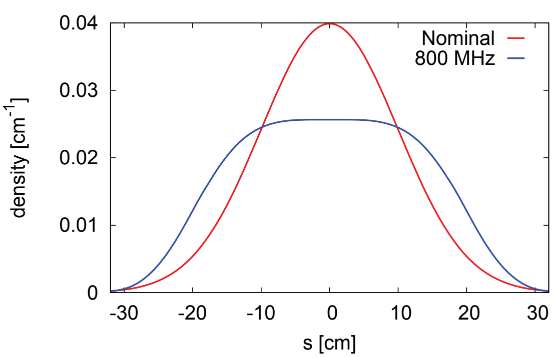

Figure 10: Longitudinal bunch distribution for a nominal bunch with σ_z= 10 cm and a flatter bunch using 8 MV 800 MHz system to provide 12.5 cm rms bunch length.

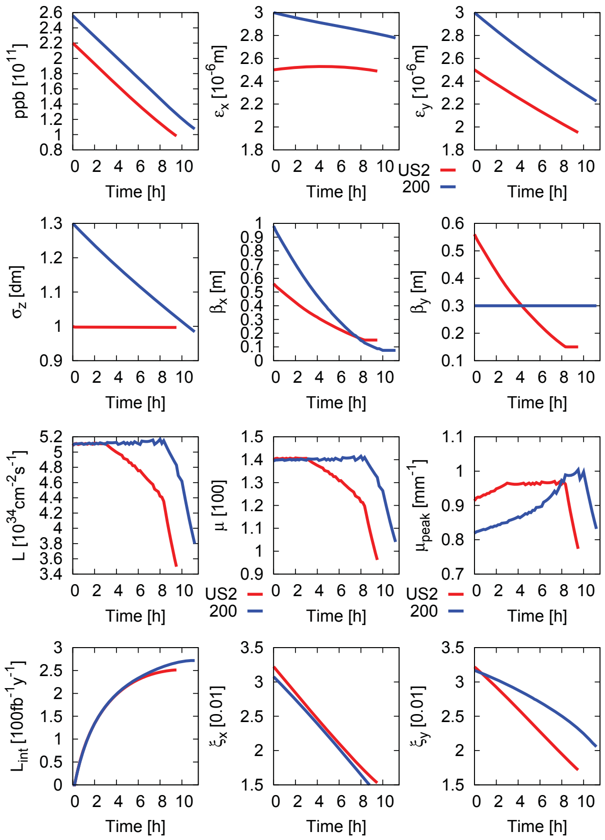

Figure 11: Fill evolution for the US2 baseline and the 200 MHz alternative with 400 MHz crab cavities using β^* for leveling peak pile-up density.

achievable with an integrated luminosity above 270 fb^{-1}.

Figure 11 compares the baseline and the 200 MHz alternative fills using leveling techniques to stay at maximum 1 mm^{-1} pile-up density.

Another effective means to reduce the peak pile-up density is to reduce the crab cavity frequency to 320 MHz or even 200 MHz [18]. Crab cavity voltage needs to increase proportionally to the reduction in crab cavity frequency. With 320 MHz crab cavity peak pile-up density is lowered to 0.8 mm^{-1}.

SUMMARY & OUTLOOK

Using 200 MHz as the main RF system in the LHC has been identified as a very promising alternative for achieving both the US1 and US2 performance goals. 200 MHz provides the best yearly integrated luminosity with a significantly reduced electron cloud and impedance heating. No obstacle is found to keep crab cavity frequency at 400 MHz. Actually, a reduction in the crab cavity frequency only improves the peak pile-up density [18]. The 200 MHz alternative is also very robust against non-working crab cavities. Nevertheless 200 MHz superconducting cavities require a completely new RF design never tested in circular accelerators. Further R&D efforts are required to evaluate the feasibility of this proposal.

If electron cloud makes it impossible to operate with 25 ns beams the filling scheme 8b+4e shows significant advantages over the 50ns. The 8b+4e alternative has no extra cost and can already be used in 2015.

Peak pile-up density leveling with β^* in US2 to $\lesssim$1 mm^{-1} is possible without any extra hardware and little performance degradation, for the baseline and for the 200 MHz alternative. A more uniform bunch distribution obtained with a double RF system (400+800 MHz or 200+400 MHz) can further reduce the pile-up density to $\approx$0.9 mm^{-1}. To reach lower pile-up densities the crab cavity frequency might be reduced (0.8 mm^{-1}) [18] at the cost of larger crab cavity voltage. The lowest pile-up density of 0.65 mm^{-1} is accessible via the crab-kissing scheme [26, 27], but being rather costly in terms of new hardware.

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REFERENCES

[1] H. Damerau, "LIU: Exploring alternative ideas", these proceedings.

[2] H. Bartosik, H. Damerau, B. Goddard and G. Rumolo, discussions during the RLIUP workshop and private communications thereafter.

[3] B. Gorini, private communication, December 2013.

[4] E. Shaposhnikova, private communication, November 2013.

[5] M. Lamont, J. Uythoven, "Summary of week 44" 8:30 meeting, November 5, 2012: lhc-commissioning.../news-2013/old-news/old-news.html

[6] D. Boussard, E. Chiaveri, H.P. Kindermann, T. Linnecar, S. Marque and J. Tuckmantel, "Design Considerations for the LHC 200 MHz RF System", LHC Project Report 268, CERN.

[7] R. Calaga et al, "A proposal for a compact 200 MHz SC-RF system for the LHC", to be published.

[8] G. Rumolo and G. Iadarola, "Evaluation of the electron cloud effect in the LHC", 5$^{\mathrm{th}}$ RLIUP Preparation meeting: https://indico.cern.ch/conferenceDisplay.py?confId=276999

[9] G. Rumolo, private communication, 2013.

[10] L. Tavian, "Cryogenics", Proceedings of Evian workshop 2012.

[11] Courtesy of Benoit Salvant.

[12] E. Métral F. Caspers, T. Kroyer, N. Mounet, F. Roncarolo, B. Salvant and B. Zotter, "Collimation-driven impedance", Collimation working group meeting,102$^{\mathrm{nd}}$ meeting, 2009: lhc-impedance.../LHCcollimation-driven-impedance.pdf

[13] N. Mounet, "Transverse impedance in the HL-LHC era", 3$^{\mathrm{rd}}$ joint HiLumi LHC-LARP annual meeting, 2013: https://espace.cern.ch/HiLumi/2013/SitePages/Home.aspx

[14] S. White, "Beam-beam and impedance", ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders (BB2013): http://indico.cern.ch/conferenceDisplay.py?confId=189544

[15] R. Nagaoka, "Transverse Feedback Systems at SOLEIL", Low Emittance Rings 2010: http://ler2010.web.cern.ch/ler2010/

[16] Y. Sun, R. Assmann, J. Barranco, R. Tomas, T. Weiler, F. Zimmermann, R. Calaga and A. Morita, "Beam dynamics aspects of crab cavities in the CERN Large Hadron Collider" Phys. Rev. ST Accel. Beams **12**, 101002, 2009.

[17] K. Ohmi, "Beambeam effect for collision with Large Piwinski angle scheme and high frequency crab cavity in LHC", CAREHHH, LHC beambeam and beambeam compensation workshop, 2008: http://indico.cern.ch/conferenceDisplay.py?confId=38353

[18] S. White, O. Dominguez, R. Tomás, "Impact of a 200 MHz RF system", LHC-CC13, 6th LHC Crab Cavity Workshop: http://indico.cern.ch/conferenceDisplay.py?confId=269322

[19] V.N. Litvinenko, Y.S. Derbenev, Proc. of 29th International FEL Conference, Novosibirsk, Russia, August 27-31, 2007, p.268, http://accelconf.web.cern.ch/accelconf/f07

[20] V. Lebedev, "Optical Stochastic Cooling", Joint Experimental-Theoretical Seminar FNAL, 2012: http://theory.fnal.gov/jetp/talks/OptStochCooling1.pdf

[21] D. Ratner, "Microbunched Electron Cooling for High-Energy Hadron Beams", Phys. Rev. Lett. **111**, 084802 (2013).

[22] O. Brüning, "HL-LHC: How to achieve Upgrade Scenario 1 goals in the LHC?", these proceedings.

[23] V. Kain, "50 ns back-up scenario", these proceedings.

[24] R. de Maria, "How to maximize the HL-LHC performance (HL-LHC)?", these proceedings.

[25] A. Valishev, "Weak-strong beam-beam simulation with crab-kissing" and S. Fartoukh, "The crab-kissing scheme: concept and motivation" in LHC-CC13, 6th LHC Crab Cavity Workshop: https://indico.cern.ch/conferenceOtherViews.py?confId=269322

[26] S. Fartoukh, "Pile-Up density management at HL-LHC and the crab-kissing scheme", HL-LHC brainstorming coordination meeting, July 2013. http://indico.cern.ch/conferenceDisplay.py?confId=263083

[27] S. Fartoukh, "Pile up density at HL-LHC with new shaping and leveling techniques", ECFA High Luminosity LHC Experiment Workshop, 1-3 October 2013, Aix-Les-Bains, France (2103): http://indico.cern.ch/conferenceDisplay.py?confId=252045

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LIU: EXPLORING ALTERNATIVE IDEAS

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Abstract

The baseline upgrade scenarios for the injector complex cover the connection of Linac4 to the PSB, the increase of the PSB-PS transfer energy from 1.4 GeV to 2 GeV and the major SPS RF upgrade during LS2. The achievable beam characteristics will nonetheless remain below the expectation of the HL-LHC project. Therefore, alternative or additional options like, e.g., special bunch distributions, the use of injection optics optimized for high space charge or extra RF systems will be discussed. The expected beam parameters, possible implementation and impact on beam availability for these more exotic options will be analysed and compared to the LIU baseline plan. Moreover, the potential interest of further batch compression schemes will be evaluated.

INTRODUCTION

The upgrades foreseen within the baseline plan of the LHC Injector Upgrade (LIU) project include the connection of Linac4 to the PSB, the increase of the PSB-PS transfer energy to 2 GeV and the 200 MHz RF upgrade in the SPS [1, 2]. Taking the various limitations in the injector chain into account, a bunch intensity of $N_b = 2 \cdot 10^{11}$ ppb with transverse emittances of slightly below 2 μm is expected at extraction from the SPS (round beams, $\varepsilon_x \simeq \varepsilon_y$). Figure 1 shows a summary plot of the brightness limit of the PSB with Linac4, together with the limitations from space charge in PS and SPS. The dashed vertical line indicates the maximum expected intensity per bunch after the RF power upgrade in the SPS (without beam quality deterioration with respect to present parameters). These beam parameters can be reached with the nominal production scheme of the LHC-type beams in the injector chain [3].

Alternative possibilities and additional improvements to this baseline which would allow to increase intensity or brightness of the beam available to the LHC have already been studied [4–6], not only in view of the foreseen upgrades within LIU. In particular LHC-beams with higher brightness were successfully commissioned and delivered to the LHC during the 2012 run using the batch compression merging and splitting (BCMS) scheme.

Various further alternative scenarios have been suggested and are studied in this paper, mainly targeted at reducing space charge effects in PS and SPS, as well as increasing intensity per bunch from the SPS (Table 1).

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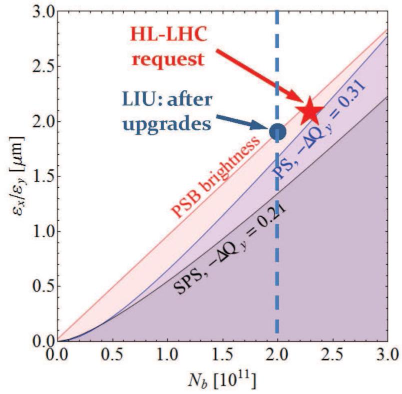

Figure 1: Brightness and space charge limitations following the baseline LIU upgrades. The dashed line marks the expected bunch intensity after RF power upgrade in the SPS.

The beam performance of these options is estimated and compared to the baseline upgrade path. It is important to point out that some considerations for the evaluation of beam parameters may be over-simplified due to the large variety of scenarios and possible combinations.

PERFORMANCE EVALUATION AND OPTIMIZATION

To compare alternative schemes in the LHC injector chain, their potential performance has been evaluated applying the same assumptions as for the baseline scenarios [7]. These constraints are summarized in Table 2. With the connection of Linac4 (L4) to the PSB, the brightness available to the PS will be doubled. In the PS, all RF manipulations are assumed to take place at a kinetic energy of 2.5 GeV, independent of the energy at PS injection. At this energy, the available RF voltages for the manipulations result in comfortably large bucket areas (doubled with respect to 1.4 GeV) and the synchrotron frequencies are still high enough for an acceptable duration. To minimize space charge at PS injection, the bunches at PSB-PS transfer are as long as possible. As consecutive bunches at PS injection may be produced by different rings of the PSB, an empty gap for the recombination kickers in the transfer line must be preserved between the tail of a given bunch and the head of the next. The duration of the switching time between rings (rise time of recombination kickers), 105 ns at 1.4 GeV and 110 ns at 2 GeV [8], defines the maximum bunch length at injection into the PS.

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Table 1: Upgrade options for the injector complex. Baseline choices of the LIU project are marked in *italics* (BCMS: Batch Compression Merging and Splitting; BCS: Batch Compression and Splitting; PBC: Pure Batch Compression). The potential intensity gain (i.e. the equivalent brightness gain) is shown for some options in the last column.

	Scheme	**Gain**
PSB	*Linac4 connection*	
	Faster recombination kickers (1.4 GeV)	
	Long. flat or hollow bunches	+25 %
	2 GeV at PSB→PS transfer	
PS	Double batch or $h = 5$ single-batch inj.	
	3-split, BCMS, BCS or PBC	
	$8b \oplus 4e$ together with 3-split or BCMS	
	Resonance compensation	
	Special injection optics	
	Long. flat or hollow bunches	+25 %
	28 GeV at PS→SPS transfer	+15 %
SPS	*Baseline SPS RF upgrade*	+50 %
	Extended SPS RF upgrade	
	Relaxed ε_l with 200 MHz in LHC	
	Q20 optics	+10 %
	Q20/Q26 split-tune optics	+5 %
	Special injection optics	

Table 2: Basic assumptions for performance comparison.

	Parameter	
L4 + PSB	Brightness, ε_x, ε_y per N_b (H$^-$ injection at 160 MeV)	$0.4\,\mu$m/10^{12}
PS	Beam loss	5 %
	Transv. emittance growth	5 %
	Tolerable tune shift, ΔQ_y	-0.31
	Maximum bunch length at inj.	Recomb. kickers
SPS	Beam loss	10 %
	Transverse emittance growth	10 %
	Tolerable tune shift, ΔQ_y	-0.21
	Bunch intensity at extraction after RF upgrade	$2 \cdot 10^{11}$

ALTERNATIVE SCHEMES IN THE PRE-INJECTORS

The connection of Linac4, in combination with the increase of the PSB-PS transfer energy, will double the available brightness for almost any scenario. The performance reach of the two pre-injector synchrotrons, PSB and PS, is however closely interlinked via the RF manipulation scheme applied in the PS. Firstly, the RF harmonic number at PS injection, together with the ring-to-ring switching time, constrains the maximum bunch length at transfer and hence the space charge conditions in the PS. Additionally the overall splitting ratio in the PS, r_{split}, defines the bunch intensity required at injection for a given intensity per LHC-type bunch at transfer to the SPS. At constant brightness from the PSB [7] the minimum transverse emittance becomes directly proportional to the splitting ratio.

Beam manipulation schemes in the PS

The nominal production scheme of the LHC-type beams [3] in the injector chain consists of injecting 4+2 bunches in two batches from the PSB into the PS. With an initial harmonic number of $h = 7$, one bucket remains empty for the PS extraction kicker gap. Each bunch is then triple split, accelerated on $h = 21$ and further split in four parts (total splitting factor, $r_{\mathrm{split}} = 3 \cdot 4 = 12$) on the flat-top to generate a batch of 72 bunches spaced by 25 ns. Up to four of these 72-bunch batches are then accumulated in the SPS and finally transferred at an energy of 450 GeV to the LHC.

For all different RF manipulation schemes in the PS, the beam is accelerated at the pivotal harmonic number of $h = 21$ to allow using the fixed-frequency 20 MHz, 40 MHz and 80 MHz RF systems for quadruple splitting and bunch rotation on the PS flat-top.

To reduce the space charge tune shift on the PS flat-bottom, the incoming bunches must not only be as long as possible, but they should also be distributed over the maximum fraction of the PS circumference. Only after an acceleration to an intermediate flat-top at a kinetic energy of 2.5 GeV, they can be compressed to a smaller fraction of the circumference [9] and brought to the acceleration harmonic, $h = 21$. Batch compression is the iterative increase of the principal harmonic number to reduce the spacing in between bunches, hence reducing the batch length [10]. Empty buckets are literally added at the azimuth of the batch gap.

Batch compression, merging and splitting (BCMS) Beams produced with the BCMS scheme have been commissioned in the injectors during the 2012 run and successfully delivered to the LHC [11, 12]. The RF manipulation in the PS is illustrated by the mountain range density plot in Fig. 2 (measured data). In total 8 bunches are double-batch transferred from the PSB into $h = 9$ buckets in the PS. Following an acceleration to the intermediate flat-top, the harmonic number is incrementally increased to $h = 14$ (batch-compression). Pairs of bunches are subsequently merged together (main harmonic: $h = 7$) and finally triple split as with the nominal beam. The resulting splitting ratio on the intermediate flat-top of 1.5 becomes, after the usual quadruple splitting at 26 GeV, $r_{\mathrm{split}} = 6$ for the BCMS beam. This means that for an LHC-type bunch with a given intensity at PS extraction, the injected bunch from the PSB is only half the intensity compared to the nominal production scheme, resulting in at best twice smaller transverse

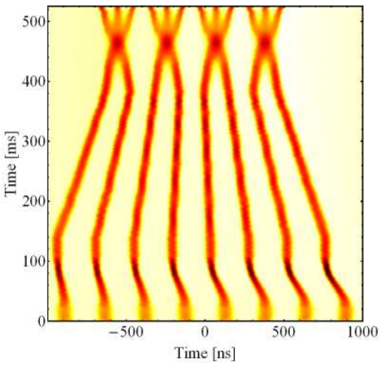

Figure 2: Batch compression, merging and splitting (BCMS).

emittance. This improvement has been confirmed by emittance measurements at SPS extraction, as well as by a luminosity increase in the LHC experiments [11].

Figure 3 shows the limit plot for the BCMS scheme. The

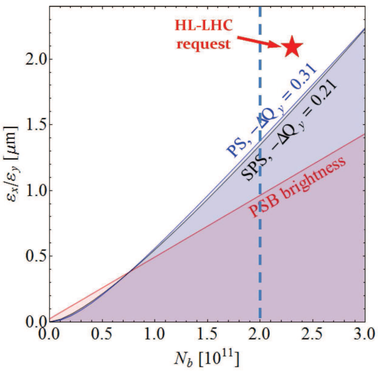

Figure 3: Limit plot for the BCMS beam (Linac4, PSB-PS at 2 GeV, 25 ns bunch spacing).

space charge tune shifts in both, PS and SPS, are perfectly matched for beams produced with the BCMS scheme. The brightness reach is beyond the HL-LHC request though the requested intensity cannot be fully reached; however, Linac4 and PSB could deliver even higher brightness incompatible with space charge in the PS and SPS. Due to the reduced splitting factor, each PS batch contains only 48 bunches (25 ns spacing) instead of 72, which propagates as a reduction of the total number of bunches per LHC ring by about 6 % and a 20 % longer LHC filling time.

Pure batch compression Even higher brightness can be achieved with the pure batch compression (PBC) scheme. As for the BCMS manipulation, twice 4 bunches are again transferred from the PSB into $h = 9$ in the PS. The acceleration to an intermediate flat-top on $h = 9$ is followed by a batch compression incrementally scanning through all harmonic numbers up to $h = 21$ (Fig. 4). The batch of 8 bunches is then accelerated to the flat-top where each bunch is again split in four, resulting in a 32-bunch batch with 25 ns spacing ($r_{\text{split}} = 4$).

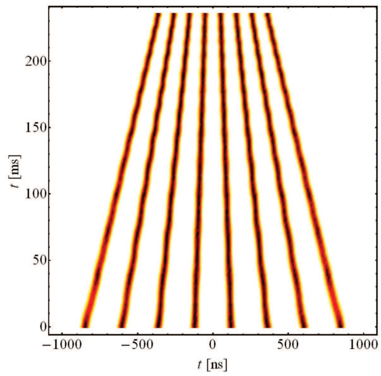

Figure 4: Pure batch compression (PBC).

The corresponding limit plot in Fig. 5 indicates that up to PS extraction a brightness well beyond the assumed SPS space charge limit can be produced. Unless this limitation

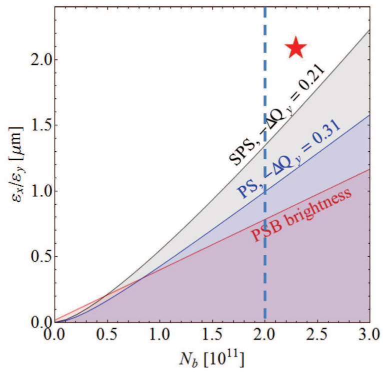

Figure 5: Limit plot for the PBC scheme (Linac4, PSB-PS at 2 GeV, 25 ns bunch spacing).

can be mitigated, the pure batch compression scheme will not provide any advantage with respect to BCMS. As the PS batches are only 32 bunches long, it even results in longer filling time and about 13 % fewer bunches in the LHC [6].

This alternative scheme will hence have its interest in exploring the limitations of the SPS. Pure batch compression will already become technically feasible after LS1, following the controls upgrade of the PS low-level RF. With the experience of the BCMS beam, its commissioning should be straightforward.

8b⊕4e bunch pattern schemes Schemes resulting in short batches in the LHC will become important in case there are issues with electron cloud (e-cloud) instabilities [13]. An extreme case, which is expected to significantly reduce e-cloud formation in the LHC, is $8b \oplus 4e$ micro-batches produced in the PS.

Replacing the triple splitting in the PS by a direct $h = 7 \to 21$ bunch pair splitting results in pairs of bunches with an empty bucket in between. On the flat-top each bunch and empty bucket subsequently split in four ($r_{\text{split}} = 8$). In combination with nominal injection of $4 + 2$ bunches into $h = 7$ buckets in the PS, the bunch pattern from the PS becomes $6\otimes(8b\oplus4e)\oplus12e$ (Fig. 6, top), with the corresponding limit plot shown in Fig. 7. Possibly even $4 + 3$ bunches

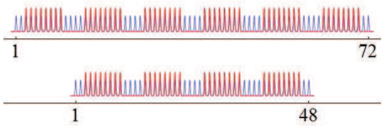

Figure 6: Bunch patterns of $8b \oplus 4e$ option (red) compared to the patterns of regular batches (blue). The first pattern (top) is achieved by changing the triple splitting to an $h = 7 \to 21$ double splitting, while the second pattern (bottom) is generated in combination with the modified BCMS scheme.

could be injected into the PS, yielding a $7\otimes(8b\oplus4e)$ pattern at extraction [14,15]. The remaining gaps of 4 empty buckets (about 100 ns) between the micro-batches are expected to be sufficiently long for the PS ejection kicker. Since the

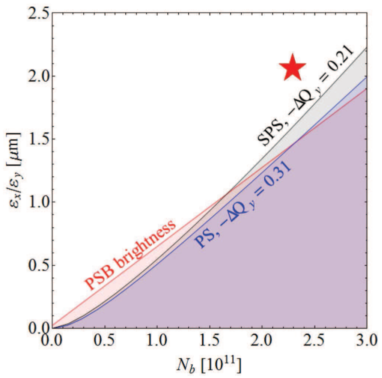

Figure 7: Limit plot for $8b \oplus 4e$ scheme (Linac4, PSB-PS at 2 GeV, 25 ns bunch spacing).

bunch splittings in the PS are lossless manipulations, the 8 bunches could theoretically have 50 % more intensity. As will be shown below, such an intensity cannot be digested by the SPS.

A derivation of the BCMS manipulation could be imagined by replacing merging and triple splitting by a regrouping of bunches with a direct hand-over from $h = 14$ to $h = 21$ ($r_{\text{split}} = 4$), but keeping in mind that the nominal $8b\oplus4e$ scenario already pushes the SPS to the space charge limit, such a scheme would have no further benefit for the LHC.

Potential additional improvements

In addition to the main alternative scenarios in the pre-injectors mentioned above, further potential options reducing space charge have been investigated. They can be applied in combination with the RF manipulation schemes in the PS. In the longitudinal plane the bunches can be stretched or made longitudinally flat to reduce their peak line density. In the transverse plane the available space for the space charge necktie in the working point diagram can be increased by compensating resonances, while the space charge necktie can be reduced by applying a special optics at low energy, e.g., by introducing vertical dispersion [16], to keep the physical beam size as large as possible.

Space charge reduction from longitudinal improvements Longitudinally flat bunches can be generated by two techniques. A higher-harmonic RF system can be added to the main RF system to reduce the peak line density. This technique is applied in the PSB [17]. However, the transfer of a flat-bunch generated by this technique requires double-harmonic RF systems in both the sending and receiving accelerators. Bunches with a longitudinally flat profile can also be achieved by depleting the central part of the distribution in longitudinal phase space [18, 19]. This technique has the advantage of requiring only a single-harmonic RF system. Hence a flat bunch can be easily transferred from PSB to PS [7], and the flat bunch is even expected to preserve its distribution through certain RF manipulations like batch-compression or bunch pair splitting and merging. The reduction of the space charge tune shift achieved by longitudinal flat or hollow bunches corresponds to the reduction of peak line density and the increase of the momentum spread, and is of the order of 25 %.

Increasing bunch length can also be a means to reduce the longitudinal density and space charge. At PSB-PS transfer the maximum bunch length is given by the minimum gap between two consecutive bunches, which is constrained by the switching time between the different rings of the PSB. Figure 8 illustrates the double batch transfer of $4 + 2$ bunches into $h = 7$ buckets or $4 + 4$ bunches into $h = 9$ buckets in the PS [12]. Assuming that the

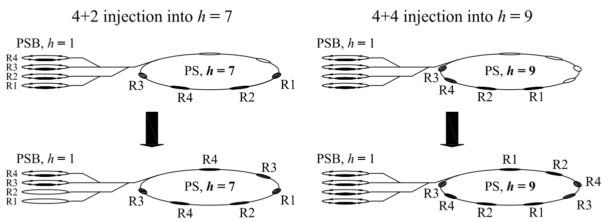

Figure 8: Beam transfer between PSB and PS.

rise time of the recombination kickers can be reduced by 50 ns, the bunch length at PS injection could be increased by this amount. The effect of the corresponding mitigation of the space charge limit is shown in Fig. 9, resulting in a reduction of about 15 % at 1.4 GeV. However, reducing the recombination kicker switching times by 50 ns would be a challenging task already for the kick strength required at a transfer energy of 1.4 GeV. Additionally the gain from this option becomes marginal after the upgrade of the PSB-PS transfer energy to 2 GeV.

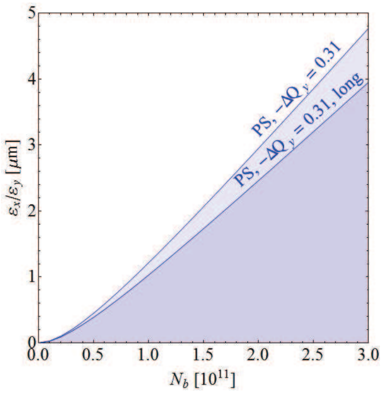

Figure 9: Brightness limit improvement of longer bunches with faster recombination kickers (Linac4, PSB-PS at 1.4 GeV, 25 ns bunch spacing).

Space charge reduction from transverse improvements Studies to compensate lattice resonances with skew sextupole magnets for LHC-type beams in the PS have started in 2013, following the installation of 4 sextupole magnets during the winter stop. At the nominal (fractional) working point of $q_x = 0.21$ and $q_y = 0.24$ the closest 4th order resonance is excited by space charge itself and cannot be easily compensated. Successful compensation of the $2q_x + q_y = 1$ and $3q_y = 1$ resonance lines has nonetheless been demonstrated [20] and a study program with the objective of simultaneous compensation of multiple resonances will continue after LS1.

Space charge effects may also be reduced by maximizing the physical beam size at low energies. The regular lattice of the PS features 10 lattice super-periods with 10 magnet units each [21]. The vertical dispersion, D_y, is ideally zero all around the ring. Introducing perturbations using the already existing skew quadrupoles, an irregular lattice with non-zero vertical dispersion (fully coupled optics) can be obtained [16]. Beta functions and dispersion around the PS circumference for an extreme case are plotted in Fig. 10. This would ideally provide a Laslett tune-

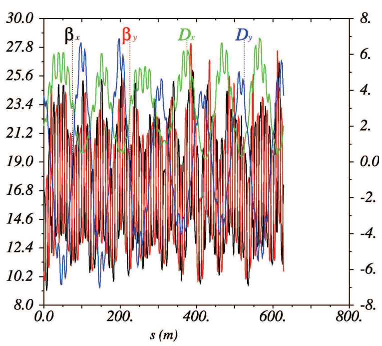

Figure 10: Lattice functions for the case of an extreme optics with vertical dispersion.

shift reduction of a factor of 1.5 in both planes. It is important to point out that extensive upgrades of various skew quadrupoles and their power converters would be required to reach such a configuration. As the optics functions are very irregular, simulations including space charge should be performed; especially the sensitivities with respect to coupling resonances remain to be studied. Assuming that no show-stoppers are identified by these simulations, first beam studies to evaluate the potential benefit of non-zero vertical-dispersion optics can be initiated after LS1.

Alternatives for special cases of limited upgrades

In the unlikely case of Linac4 connection before the upgrade of the PSB-PS transfer energy, space charge on the PS flat-bottom will become the most stringent limitation in the injector chain, essentially independent from the RF manipulation scheme. Figure 11 presents a limit plot for an injection energy into the PS of 1.4 GeV. The brightness deliverable by the PSB and acceptable for the SPS becomes almost twice the brightness which the PS can digest and almost nothing would be gained for LHC-type beams with Linac4.

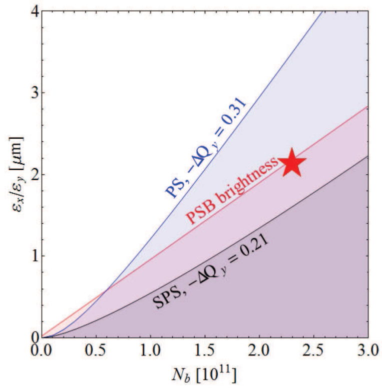

Figure 11: Limit plot for double-batch injection of 8 bunches into $h = 9$ and subsequent generation of 64 bunch batches (Linac4, PSB-PS at 1.4 GeV, 25 ns bunch spacing). The bunches are double split on the flat-bottom and again twice on the flat-top, $r_{\text{split}} = 8$ [5].

To profit in this case from the significantly higher brightness with Linac4, single-batch transfer of 4 bunches into $h = 5$ buckets in the PS has been suggested [22]. As becomes clear from Fig. 12, the space charge limit in the PS matches again with the brightness deliverable by the PSB with Linac4.

After injection, each bunch is double split twice, resulting in 16 bunches at harmonic $h = 20$. Following a single harmonic number hand-over to $h = 21$ (Fig. 13), the 16 bunches are accelerated to the flat-top where each of them passes through the usual quadruple splitting ($r_{\text{split}} = 16$), hence the PS produces batches of 64 bunches. These shorter batches would reduce the total number of bunches in the LHC by only about 3 %, but with reduced filling time thanks to the one third shorter cycle in the PS.

The lowest harmonic number, $h = 5$ (2.18 MHz), re-

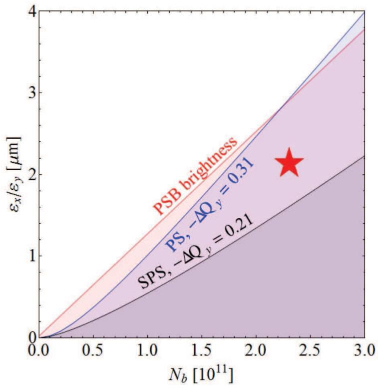

Figure 12: Limit plot for single-batch injection into $h = 5$ and subsequent generation of 64 bunch batches (Linac4, PSB-PS at 1.4 GeV, 25 ns bunch spacing).

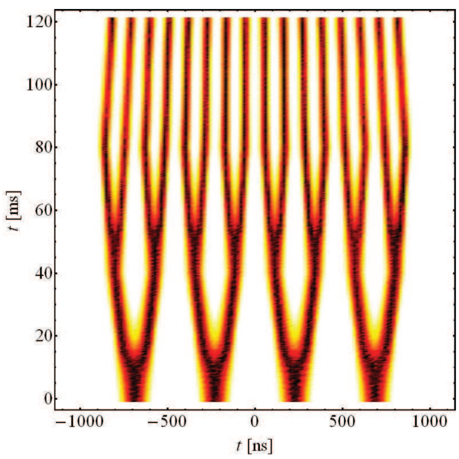

Figure 13: Single-batch injection of 4 bunches from the PSB into $h = 5$ in the PS.

quired with this alternative scheme at injection, is below the lower limit of the frequency range of the main RF cavities, but the development of a dedicated or the modification of an existing cavity could be envisaged.

ALTERNATIVE SCHEMES IN THE SPS

In the framework of the LIU upgrades the integer working point of the SPS has recently been moved from $Q_h/Q_v = 26$ to 20, operating with a new low transition energy optics which significantly improves longitudinal and transverse beam stability for LHC-type beams, but requires higher RF voltage [23]. The future baseline upgrades include measures against e-cloud instabilities and a major upgrade of the main 200 MHz RF system of the SPS. The latter mainly foresees the regrouping of the traveling wave cavities into four 3-section and two 4-section cavities [24, 25], the installation of two additional 1.6 MW RF power amplifiers and an upgrade of the beam control system.

Beyond this baseline, even further splitting to a larger number of shorter cavities has been considered, as well as the effect of the $8b\oplus4e$ scheme or a possible 200 MHz main RF system in the LHC. As part of the upgrade baseline, the successful mitigation of electron cloud instabilities by amorphous carbon coating [26] or scrubbing of the SPS beam pipe is assumed.

RF power considerations at extraction to LHC

At transfer to the LHC, the 200 MHz RF system in the SPS has to provide sufficient RF voltage to keep the bunch length below 1.7 ns (4σ Gaussian fit) to fit into the 2.5 ns long buckets of the LHC. Two effects determine the RF voltage and power requirements which are beam loading and longitudinal beam stability.

At fixed maximum RF power the voltage generated by the traveling wave accelerating cavities of the SPS [27] decreases with increasing beam intensity [28] due to beam loading. This voltage decrease at given RF power is illustrated for different RF system configurations in Fig. 14. The grey curve shows the voltage decrease for the present

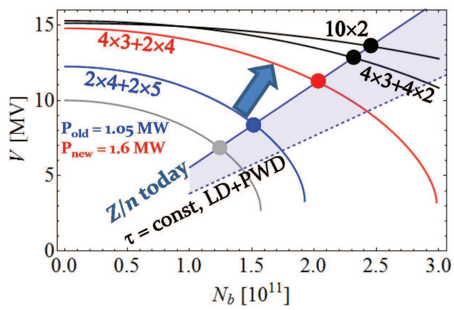

Figure 14: Beam loading (25 ns bunch spacing) and single bunch stability limits for various arrangements of the 200 MHz cavities [25].

cavity configuration (two 4-section and two 5-section cavities) and an RF power of 0.7 MW per cavity. Pulsing the RF amplifiers with the revolution frequency following the upgrade of the LLRF system allows a power increase to about 1.05 MW per amplifier (blue curve). Following the LIU baseline upgrade, two new transmitters with an RF power of 1.6 MW each will become available. Together with the planned re-grouping of the cavity sections to four 3-section cavities and two 4-section cavities, the available voltage is increased significantly (red curve). Thanks to the addition of two more sections (in total 20 instead of 18 section), low- and high-intensity beams will profit from the baseline upgrade.

Alternatively, the same number of total cavity sections can be assembled to more but shorter cavities. The black curves of Fig. 14 show the available RF voltage for extreme cases of four 3-section with four 2-section cavities (two additional 1.6 MW RF transmitters compared to the baseline upgrade), as well as ten 2-section cavities (four additional transmitters). Essentially no further voltage gain can be achieved for lower intensity beams.

To finally estimate the voltage requirements at a fixed bunch length at transfer to LHC, longitudinal instabilities must be taken into account. Considering only the voltage reduction by potential-well distortion (PWD) and the single-bunch instability due to loss of Landau damping (LD), a scaling law for the minimum longitudinal emittance emittance assuring stability can be derived [29, 30]. Assuming constant bunch length τ, it can be shown that the RF voltage must increase proportionally to the bunch intensity. The nominal LHC beam with 25 ns with an intensity of $1.3 \cdot 10^{11}$ ppb and a longitudinal emittance of $\varepsilon_l \simeq 0.35$ eVs can be taken as a reference case for the linear increase of RF voltage with intensity. Measurements have shown that it is indeed close to the longitudinal stability limit on the flat-top in the SPS [25]. Combining the intensity dependent voltage requirement with the available voltage at fixed RF power results in an estimation of the maximum intensity for the different RF system configurations (Fig. 14).

The grey point again indicates the present cavity configuration (two 4-section and two 5-section cavities). With a maximum voltage of about 7 MV an intensity of $1.3 \cdot 10^{11}$ ppb has been achieved on the flat-top. Upgrading the low-level RF system to operate the cavities in pulsed mode increases the available RF power per amplifier from 0.7 MW to 1.05 MW, allowing a maximum intensity of $1.5 \cdot 10^{11}$ ppb. A major improvement will be introduced by the re-grouping of the cavities as foreseen within the LIU baseline. Without any increase of bunch length, an intensity of $2.0 \cdot 10^{11}$ ppb can be obtained. It is important to point out that the contribution from loss of Landau damping to the gradient of the line in Fig. 14 scales with $\varepsilon_l^{-5/2}$ and is directly proportional to the broadband impedance, Z/n. Permitting only 10 % longer bunches at transfer to the LHC increases the maximum intensity estimate to $2.5 \cdot 10^{11}$ ppb.

The effect of further shortening the RF cavities is shown in Fig. 15, indicating the maximum achievable intensity per bunch versus total RF power. Clearly, the step for the baseline upgrade from two 4-section and two 5-section to four 3-section and two 4-section cavities, adding two 1.6 MW amplifiers, results in the most efficient intensity increase.

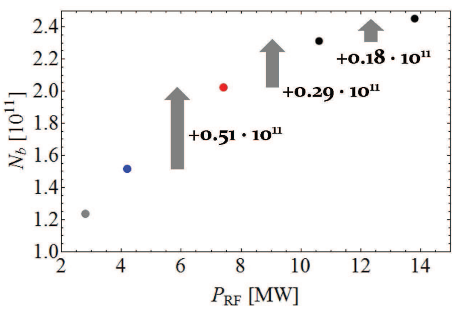

Figure 15: Total RF power versus maximum bunch intensity (25 ns bunch spacing). The colours correspond to those of Fig. 14.

The next step to four 2-section and four 3-section cavities, requiring two more additional power amplifiers, gains only half of the previous step. Moving to an extreme case of ten 2-section cavities demands for excessive RF power with little effect on maximum intensity per bunch.

8b⊕4e bunch pattern schemes At fixed bunch intensity, the line density averaged over 300 ns is reduced by $2/3$ using the $8b \oplus 4e$ bunch pattern schemes. With a filling time of the RF cavities in the SPS of about twice that duration, one can expect 50 % higher bunch intensity for the same voltage as illustrated in Fig. 16. However, as potential well distortion and loss of Landau damping are single-bunch effects, no scaling is applied to the instability line (with respect to Fig. 14). The potential gain with the $8b \oplus 4e$ schemes is thus below 50 % and to reach a bunch intensity of $3 \cdot 10^{11}$ ppb with the baseline RF upgrade would require an impedance reduction by approximately 50 % (Fig. 16, blue shaded area).

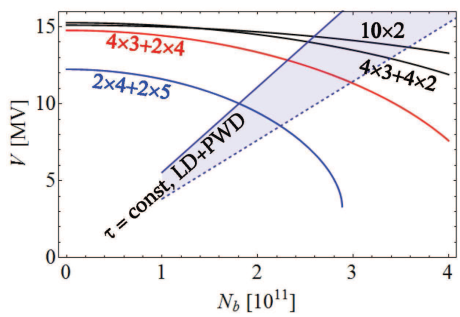

Figure 16: Improvements with the 8b+4e bunch pattern scheme (25 ns bunch spacing).

Proof-of-principle beam tests of the $8b \oplus 4e$ scheme in the whole accelerator complex will become possible after LS1 at reduced performance level to evaluate its potential gain with respect to the nominal filling scheme.

200 MHz RF system in the LHC The major constraint of short bunches at transfer from SPS to LHC is relaxed with a 200 MHz RF system in the LHC. Further benefits of a lower frequency main RF system in the collider are discussed in [15]. While the beam loading curves remain unchanged (Fig. 17), the single bunch instabilities are well suppressed thanks to the strong dependence of the loss of Landau damping on longitudinal emittance. Assuming a longitudinal emittance of 1 eVs, the RF voltage for matched transfer into a 200 MHz/3 MV bucket in the LHC requires an intensity independent voltage of 7.5 MV in the SPS. In conjunction with the baseline RF upgrade the maximum intensity per bunch on the SPS flat-top is estimated at above $2.5 \cdot 10^{11}$ ppb, clearly highlighting the benefit of a 200 MHz RF system in the LHC for the injectors.

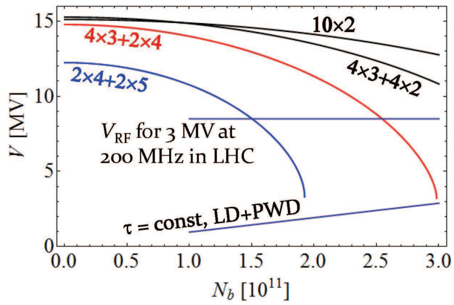

Figure 17: Larger longitudinal emittance anticipating a 200 MHz RF system in the LHC (25 ns bunch spacing).

Performance during acceleration in the SPS

Next to the constraints at transfer to the LHC, the available RF power also limits the maximum intensity during the acceleration ramp. Assuming the present cavity configuration and magnetic cycle for LHC-type beams, the bucket area during the first part of the cycle is limited to $A_b = 0.6$ eVs at an intensity of, e.g., $1.2 \cdot 10^{11}$ ppb (Fig. 18). Without reducing the ramp rate and hence stretching the acceleration cycle, this leaves little margin for further intensity increase.

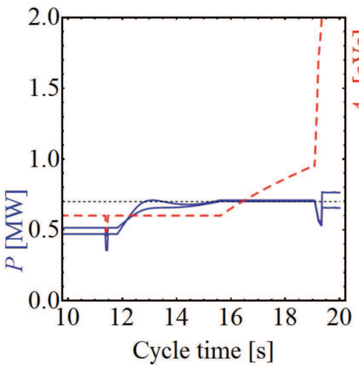

Figure 18: RF power and resulting bucket area along the LHC cycle in the SPS for the present configuration with a bunch population of $N_b = 1.2 \cdot 10^{11}$ (25 ns bunch spacing). The different blue curves show the RF power for the 4-section and 5-section cavities.

Already the baseline RF upgrade will provide a larger bucket area ($A_b = 0.75$ eVs at the start of acceleration with margin for increase during the cycle) for an intensity of $2.3 \cdot 10^{11}$ ppb (Fig. 19), beyond the limitation at transfer to the LHC discussed above. In combination with the $8b \oplus 4e$ scheme, an intensity of up to $3.0 \cdot 10^{11}$ ppb is expected to be accelerated, thanks to the 50 % reduction of the average line density. Clearly, the baseline RF upgrade remains indispensable to profit from the benefit of a new 200 MHz RF system in the LHC.

Extending the upgrade to four 2-section cavities and four 3-section cavities (in total four new 1.6 MW RF amplifiers), the intensity reach for the 25 ns beam could be pushed above $3 \cdot 10^{11}$ ppb. Figure 20 illustrates RF power and bucket area for a bunch population of $3.2 \cdot 10^{11}$ ppb.

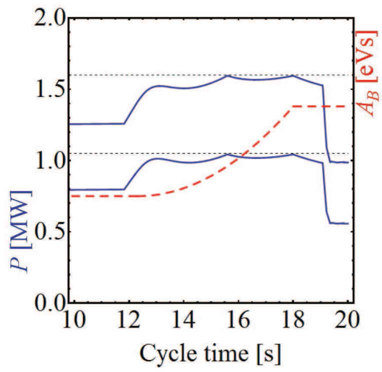

Figure 19: RF power and resulting bucket area along the LHC cycle in the SPS for the baseline upgrade configuration with a bunch population of $N_b = 2.3 \cdot 10^{11}$ (25 ns bunch spacing). The blue traces indicate the power of a new amplifier connected to a 4-section cavity (top) and an existing amplifier connected to 3-section cavity (bottom).

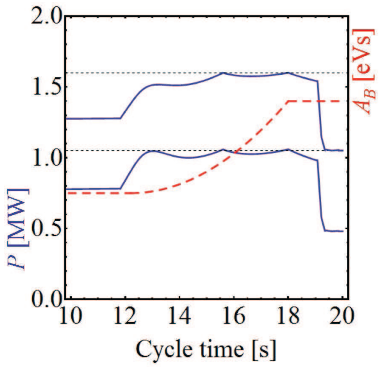

Figure 20: RF power and resulting bucket area along the LHC cycle in the SPS for in total 8 cavities (4 additional power plants) configuration with a bunch population of $N_b = 3.2 \cdot 10^{11}$ (25 ns bunch spacing). The two blue curves show again the power with new (top) and existing (bottom) RF amplifiers.

As shown above, the baseline upgrade of the 200 MHz including the re-grouping of cavity sections and the construction of two new power amplifiers represents a major gain in bunch intensity during acceleration, as well as at transfer to the LHC. Alternative options to further split the cavities, and add even more RF power, may be beneficial, but the incremental gain becomes less significant.

Transverse improvements

In terms of alternative improvements in the transverse plane, the SPS offers less possibilities and flexibility than the pre-injectors. Firstly, similar to the increase of the extraction energy of the PSB, the PS may have a small margin to extract above the present (total) energy of 26 GeV. At its initial commissioning in the late 1950s, a flat-top energy of 28 GeV had been reached [31], but such beams were not extracted. Even though the PS ejection elements, as well as the SPS injection elements have not been designed for this high energy, the LHC-type beams have small transverse emittances compared to fixed target beams. Hence slightly too small kick angles at PS ejection and SPS injection are not expected to cause losses and can most likely be corrected. Raising the transfer to 28 GeV results in a space charge tune shift reduction in the SPS of 15 % with an immediate gain for all schemes limited by the SPS space charge. First studies to extract beams above 26 GeV from the PS are planned for 2014.

Secondly, instead of moving both horizontal and vertical integer tunes from $Q_h/Q_v = 26$ to 20, a split-tune optics with $Q_h = 20$ and $Q_v = 26$ has been proposed [32]. Figure 21 illustrates the normalized space charge tune shifts at SPS injection versus transverse emittance. The most favorable situation can be achieved with the split-tune optics.

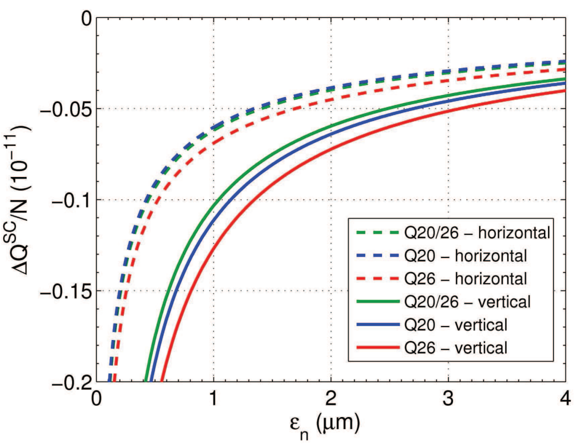

Figure 21: Normalized horizontal and vertical space charge tune shift versus transverse emittance for Q20, Q26 and split-tune optics.

Additionally, the kick strength required at injection is reduced when moving from $Q_v = 20$ back to $Q_v = 26$, leaving some margin for the injection at energies above 26 GeV. Transverse instability thresholds can be slightly increased by the reduction of the vertical beta function for $Q_v = 26$.

Finally, as in the PS, a lattice with non-zero vertical dispersion could be envisaged in the SPS. However, important changes to the cabling and the supply of the skew quadrupole magnets, which are presently grouped in families, would be required.

CONCLUSIONS

No magic alternative to the present baseline upgrades, including Linac4, the increase of the PSB-PS transfer energy to 2 GeV and a major RF upgrade in the SPS, has been identified. The flexibility of the pre-injectors allows an important number of different production schemes to increase bunch intensity and beam brightness. Some of these schemes deliver sufficiently high brightness to push the SPS to its space charge limit.

The acceleration and transfer to LHC of bunches with larger longitudinal emittance and higher intensity in the SPS will become possible following the major RF upgrade. A new RF system at 200 MHz in the LHC would additionally have beneficial effects for the injectors as it further relaxes the constraints on bunch length and longitudinal emittance at transfer from the SPS, estimating a maximum bunch intensity beyond $2.5 \cdot 10^{11}$ ppb and shifting possible limits to the lower energy part of acceleration. However, the brute-force approach of adding even more than two 1.6 MW power amplifiers has only limited reach as the absolute intensity gain when moving from 6 to 8 cavities is half of the extra intensity reach when moving from 4 to 6 cavities.

A number of interesting alternatives have been identified which will be accessible to machine development studies after LS1 to validate their potential benefits:

- **PSB:** hollow bunches,
- **PS:** flat or hollow bunches, special flat-bottom optics, PBC, $8b \oplus 4e$ schemes, PS-SPS transfer energy above 26 GeV,
- **SPS:** split-tune optics, higher intensity at transfer to the LHC with slightly longer bunches.

Even more combinations of the various alternatives can be imagined.

Finally, the flexibility of producing a wide range of beam parameters represents an important asset of the injector chain which allows to quickly react to requests from the LHC in case of unforeseen issues. The $8b \oplus 4e$ scheme is one example of an alternative in case of persistent electron cloud issues in the LHC with 25 ns bunch spacing after LS1. This flexibility of CERN's injector chain should be preserved in the future.

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APPENDIX

Many alternative options have already been studied by numerous authors and have therefore not been reconsidered in the present report. Table 3 gives a non-exhaustive list of these alternative options.

Table 3: Non-exhaustive list of further alternative options studied by other authors.

	Alternative scheme	Remark	Reference
PSB	Vertical painting at PSB injection with Linac4	Minor improvement	[33]
	Replacement of the PSB by a Rapid Cycling Synchrotron	Study not continued	[34]
PS	H^- injection from SPL-like Linac into the PS	Together with 40 MHz RF	[4, 35, 36]
	40 MHz-based main RF system	Needs Linac for 40 MHz structure	[4]
	Separated function lattice with 30 GeV energy	Essentially new accelerator in PS tunnel	[37]
SPS	Low frequency (40 MHz capture cavity in the SPS)	Issues with beam stability	[38]
	Splitting or merging	Would require low-frequency cavity	
	Slip stacking to increase bunch intensity	Issues with beam loading and ε_l	[39]

REFERENCES

[1] R. Garoby et al., "Plans for the Upgrade of the LHC Injectors", IPAC2011, San Sebastián, Spain, 2011, p. 2517-2519.

[2] H. Bartosik et al., "Can we Ever Reach the HL-LHC Requirements with the Injectors (LIU)?", *these proceedings.*

[3] M. Benedikt et al., "The PS Complex as Proton Pre-Injector for the LHC", CERN 2000-03, CERN Geneva, Switzerland, 2000.

[4] C. Carli, "Other Scenarios for a Partial Upgrade of the Injector Complex", Chamonix 2010 LHC Performance Workshop, Chamonix, France, pp. 247-252, 2010.

[5] C. Carli et al., "Alternative/complementary Possibilities", Chamonix 2011 LHC Performance Workshop, Chamonix, France, pp. 361-367, 2011.

[6] H. Bartosik et al., "Performance Potential of the Injectors after LS1", Chamonix 2012 LHC Performance Workshop, Chamonix, France, pp. 268-275, 2012.

[7] G. Rumolo et al., "Expected Performance in the Injectors at 25 ns without and with LINAC4", *these proceedings.*

[8] L. Sermeus, *private communication*, 2013.

[9] R. Garoby, "Analysis of Batch Compression in the PS", High Intensity Proton Working Group Meeting (HIP), CERN, Geneva, Switzerland, 2003, `https://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-10Dec03-RGaroby.ppt`.

[10] R. Garoby, "New RF Exercises Envisaged in the CERN-PS for the Antiprotons Production Beam of the ACOL Machine", PAC1985, Vancouver, British Columbia, Canada, pp. 2332-2334, 1985.

[11] S. Hancock, "Batch Compression Makes Sense", *unpublished presentation at LIU Day 2013*, CERN, Geneva, Switzerland, 2013, `http://indico.cern.ch/getFile.py/access?contribId=9&sessionId=2&resId=1&materialId=slides&confId=238152`.

[12] H. Damerau et al., "RF Manipulations for Higher Brightness LHC-type Beams", IPAC2013, Shanghai, China, pp. 2600-2602, 2013.

[13] O. Domínguez et al., "Electron Cloud Studies for Alternative Train Configurations and Bunch Spacings at the HL-LHC", CERN-ATS-Note-2013-036 TECH, CERN, Geneva, Switzerland, 2013.

[14] H. Bartosik, H. Damerau, B. Goddard, G. Rumolo et al., *discussions during RLIUP.*

[15] R. Tomás et al., "HL-LHC: Exploring alternative ideas", *these proceeding.*

[16] Y. Papaphilippou, *private communication*, 2013.

[17] A. Hofmann, F. Pedersen, "Bunches with Local Elliptic Energy Distributions", PAC1979, San Francisco, California, U.S.A., pp. 3526-3528, 1979.

[18] R. Garoby, S. Hancock, J. L. Vallet, "PS Machine Development Report", PS/RF/Note 92-8, CERN, Geneva, Switzerland, 1992.

[19] C. Carli, "Creation of Hollow Bunches using a double harmonic RF System", CERN/PS 2001-073 (AE), CERN, Geneva, Switzerland, 2001.

[20] R. Wasef et al., "Resonance Compensation", *unpublished presentation in LIU-PS meeting*, CERN, Geneva Switzerland, 2013, `https://indico.cern.ch/getFile.py/access?contribId=0&resId=1&materialId=slides&confId=241210`.

[21] R. Cappi et al., "Optics Studies in the CERN Proton Synchrotron: Linear and Nonlinear Modelling Using Beam Based Measurements", PAC2003, Portland, Oregon, U.S.A., pp. 2913-2915, 2003.

[22] S. Hancock, *private communication*, 2013.

[23] Y. Papaphilippou et al., "Operational Performance of the LHC Proton Beams with the SPS Low Transition Energy Optics", IPAC2013, Shanghai, China, pp. 3945-3947, 2013.

[24] E. Shaposhnikova, "SPS Collective Effects and Limitations", LIU-2011 Event, CERN, Geneva, Switzerland, 2011, `https://indico.cern.ch/getFile.py/access?contribId=17&resId=1&materialId=slides&confId=160434`.

[25] E. Shaposhnikova, "SPS Intensity Limitation Without the 200 MHz Upgrade", *unpublished presentation in LIU-SPS Beam Dynamics Working Group meeting*, CERN, Geneva, 2013, `http://paf-spsu.web.cern.ch/paf-spsu/meetings/2013/m11-07/SPSRF_US1_BD.pptx`.

[26] J. M. Jimenez, "Electron Clouds in the SPS: Progress in the Analysis of Cures/mitigation Measures and Potential Schedule of Implementation", Chamonix 2011 LHC Performance Workshop, Chamonix, France, pp. 355-358, 2011.

[27] G. Dôme, "The SPS Acceleration System Traveling Wave Drift Tube Structure for the CERN SPS", LINAC76, Chalk River, Ontario, Canada, pp. 138-147, 1976.

[28] T. Bohl, "The 200 MHz Travelling Wave Cavities in the SPS", Chamonix 2000 SPS and LEP Performance Workshop, Chamonix, France, pp. 58-60, 2000.

[29] E. Shaposhnikova, "Longitudinal Stability of the LHC Beam in the SPS", SL-Note-2001-031 HRF, CERN, Geneva, Switzerland, 2001.

[30] E. Shaposhnikova, "Longitudinal Beam Parameters During Acceleration in the LHC", LHC Project Note 242, CERN, Geneva, Switzerland, 2000.

[31] J. B. Adams, "The CERN Proton Synchrotron", Nature, Vol. 185, pp. 568-572, 1960.

[32] H. Bartosik et al., "Increasing Instability Thresholds in the SPS by Lowering Transition Energy", IPAC12, New Orleans, Louisiana, U.S.A., pp. 3096-3098, 2012.

[33] C. Bracco et al., "Studies of Transverse Painting for H^- Injection in the PSB", IPAC11, San Sebastián, Spain, pp. 3544-3546, 2011.

[34] K. Hanke et al., "PS Booster Energy Upgrade Feasibility Study First report", EDMS Document no. 1082646 v.3, CERN, Geneva, Switzerland, 2010, `https://edms.cern.ch/file/1082646/3/PSBUpgrade_Feas_Study_v3.pdf`.

[35] R. Garoby, M. Vretenar, "Proposal for a 2 GeV Linac Injector for the CERN PS", PS/RF/Note 96-27, CERN, Geneva, Switzerland, 1996.

[36] M. Vretenar et al., "Report of the Study Group on a Superconducting Proton Linac as a PS Injector", CERN/PS 98-063 (RF-HP).

[37] Y. Papaphilippou, *private communication*, 2013.

[38] E. Shaposhnikova, "Low Frequency RF System in the SPS?", *unpublished presentation in SPSU-BD working group meeting*, CERN, Geneva, Switzerland, 2011.

[39] T. Argyropoulos , E. Shaposhnikova, "Possible Increase of Bunch Intensity in the SPS for HL-LHC", *unpublished presentation in LIU & HL-LHC brainstorming meeting*, Crozet, France, 2011.

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HOW TO REACH THE REQUIRED AVAILABILITY IN THE HL-LHC ERA

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Abstract

The HL-LHC has ambitious integrated luminosity goals in the region of 250 fb^{-1} per year. This level of performance will required excellent machine availability. After a definition of terms and assumptions, the availability to date is reviewed while noting the importance of accurate and reliable tracking. Other possible areas of improvement and future challenges which could impact the overall availability are then discussed. Estimates based on extrapolation from present experience are given. Injector availability will also be important for the overall LHC performance and the need for sustained, well-planned consolidation is recalled.

INTRODUCTION

Definition of terms

Scheduled proton physics time (SPT) is the time scheduled in a given year for high luminosity proton physics. It does not include initial re-commissioning, special physics runs, ions, MD, and technical stops. It does include the intensity ramp-up following re-commissioning at the start of the year. One could include special physics runs, operation with ions, and MD in the scheduled time but we single out proton physics because we eventually want to make luminosity predictions. Note that high luminosity running involves a number of challenges not present in other modes of operation and different availability can be expected.

Availability is the scheduled proton physics time minus the time assigned to faults and fault recovery expressed as a percentage of the SPT. Edge effects (recovery from access, the precycle) tend not, at present, to be fully included in the assigned fault time.

The **turnaround time** is defined as time taken to go from Stable Beam mode back to Stable Beam mode in the absence of significant interruptions due to fault diagnosis and resolution.

Physics efficiency is the fraction of the scheduled physics time spent in Stable Beams.

Recall 2012

The overall faults statistics for 2012 [1] are shown in figure 1. Subsequent re-analysis of 2012's SPT gave a total of 1411 hours or 58.8 days of fault time or approximately 71% availability for a 201 day physics run [2]. Even given the caveat of incomplete assignment of fault recovery time noted above, this is an excellent result given the complexity and relative youth of the LHC.

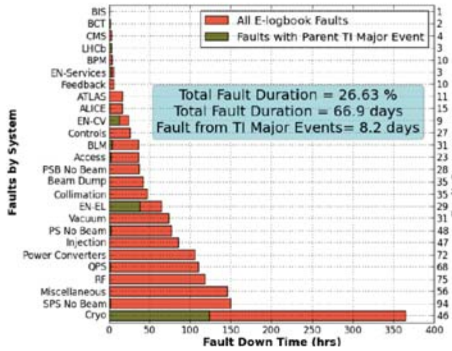

Figure 1: 2012 LHC fault analsysis taking into account all scheduled operation. Figure courtesy Alick Macpherson.

Technical infrastructure major events generated 8.2 days of fault time with some major knock-on effects to cryogenics. Recovery from major events has been helped by experience, procedures, and buy-in from the concerned equipment groups. The importance of injector complex availability can be clearly seen. Miscellaneous comes in third suggesting the need for more refined tracking.

Overhead of a fault

Faults cover an enormous range from a simple front-end reboot to the loss of a cold compressor with corresponding loss of time to operations ranging from 10 minutes to potentially days.

The impact of a typical fault requiring tunnel access was considered. It showed the following sequence of steps from the occurrence of the original fault through to full recovery.

- Premature beam dump in Stable Beams.
- Original diagnosis of fault by control room operator. Contact expert.
- Remote diagnosis by expert.
- Access required and prepared. Travel of expert to site. Travel of radiation protection piquet to site.
- Intervention, on-site diagnosis and repair by expert.
- Recovery from access.
- Recovery from the impact of the fault (for example, cool-down following quench).
- Re-establish machine state: precycle, injection etc.

It can be seen that besides the cost to fix a fault, there is also significant overhead.

- Faults often dump the beam. For those with long recovery times this is almost incidental, but for the rest the cost is a premature dump of a fill.

- There is need for diagnosis of the problem both by the control room and the expert.
- Preparation for the intervention can require magnet switch off, radiation survey, and access.
- There is travel time for the expert and, if required the radiation protection piquet.
- Recovery from the intervention can be problematic. Things do not like being switched off and there can be knock-on faults.

The clear message is that fixing the fault is only part of the cost. Fault resolution and recovery should be accounted for as such. This is not at present the case.

The cost in time of turnaround and its fault recovery component is now examined in a little more detail.

TURNAROUND

The turnaround time is defined above as time taken to go from Stable Beam mode back to Stable Beam mode. Before examining potential issues, the ideal case is presented.

7 TeV turnaround

A breakdown of the foreseen HL-LHC turnaround time is shown in table 1.

Table 1: Breakdown of turnaround with estimated minimum times shown

Phase	Time [minutes]
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	20
Ramp preparation	5
Ramp	25
Squeeze	30
Adjust/collisions	10
Total	180

From table 1, one can see that realistically a three hour minimum turn around time may be assumed. The main components are the ramp-down from top energy; the injection of beam from the SPS; the ramp to high energy; and the squeeze. The ramp-down, the ramp, and the squeeze duration are given by the current rate limitations of the power converters. Of note is the 10 A/s limit up and down for the main bends; and the need to respect the natural decay constants of the main quadrupoles, the individually powered quadrupoles and the triplets during the ramp-down and the squeeze. These quadrupoles are powered by single quadrant power converters and take a considerable time to come down. A faster precycle via upgrades to the power converters might be anticipated. Two quadrant power converters for the inner triplets for example would remove them as a ramp-down bottle neck.

In practice, the turnaround has to contend with a number of issues which could involve lengthy beam based set-up and optimization. Typical beam based optimization might include: the need to re-steer the transfer lines; occasional energy matching between the SPS and LHC; the need for the SPS to adjust scraping during the injection process. Injector and LHC tuning and optimization are accounted for in the average turn around time.

Turnaround time 2012

The fastest turnaround in 2012 was 2 hours 8 minutes. This was close to the theoretical minimum for 4 TeV operation. The average for the year was around 5 hours 30 minutes. What is going on?

- Clearly the main component of the turnaround is the nominal cycle outlined in the previous section: injection, ramp, squeeze, ramp-down/precycle.
- Also included are test ramps and squeezes which do not result in Stable Beams. These have to be counted as justifiable (at this stage) allowing as they do clean set-up of parameters and understanding of beam based issues.
- Transfer and injection optimization and general wrestling with the injection process (respecting tight demands on beam quality etc.).
- Unrecorded faults and problem resolution which are fixed on the fly possibly even with beam in the machine. Typically these could include: controls and data acquisition problems; kicker overheating; problems in the injectors; etc. etc.
- As mentioned above fault recovery such as access recovery, precycle and so on are not costed to the originating fault.
- Fills lost in the ramp and squeeze to beam induced problems (instabilities) or, for example, feedback system faults are not separated out. The machine in principle effectively stays “available”.

There is definitely a case for a more detailed break-down of the turnaround time which could include appropriate allocation of time to: test fills; lost fills; recovery time; etc.

LOST FILLS

One also must consider overheads and the pain of losing a fill (in ramp, in squeeze, in physics...). The list of premature dumps above 450 GeV in 2012 [3] are shown in figure 2. 70% of all fills are terminated by a fault. It is worth considering the table in some detail and asking what will still be an issue in the HL-LHC era.

The number one cause of lost fills, beam loss, was in fact not fault related and could be regarded as somewhat self-inflicted courtesy the choice of pushing instantaneous performance via tight collimator settings, low β^*, and high bunch intensity. Does it matter? 58 fills were lost to beam losses in 2012. If we simply assigned a 3 hour turnaround

Dump Cause	#	Dump Cause	#
Beam: Losses	58	BPM	8
Quench Protection	56	Operations: Error	6
Power Converter	35	SIS	4
Electrical Supply	26	LBDS	4
RF + Damper	23	TOTEM	4
Feedback	19	CMS	3
BLM	18	BCM	2
Vacuum	17	Water	2
Beam: Losses (UFO)	15	Access System	2
Cryogenics	14	LHCb	2
Collimation	12	ALICE	2
Controls	12	Beam: Orbit	1

Figure 2: Premature dumps above 450 GeV in 2012. Table courtesy Ben Todd et al [3]

to each we have around 180 hours or 7.5 days lost. In 2012 this would have equated to a loss of around 1.3 fb^{-1} maximum. This is insignificant on the grand scale of things and probably worth it for the instruction. However it would be clearly unacceptable in HL-LHC era and operationally robust choices of parameters will be required.

Number 2 and 3 on the list are the QPS and power converters respectively. These are, of course, huge distributed systems with direct exposure to the radiation field of the beam. Correspondingly there is a significant fraction of beam dumps attributed to Single Event Effects (10% of total dumps). This issue is being addressed by the Radiation to Electronics (R2E) effort and is discussed in more detail below.

Besides the usual mix of equipment faults operations is exposed to some other problems before Stable Beams is established. Noticeably in 2012:

- orbit feedback problems - the resolution time is usually short but if the problem provokes a dump the cost is a full turnaround (around 13 dumps);
- instabilities and beam loss in squeeze and adjust caused 32 dumps (addressed above).

FILL LENGTH

Both the average fill length and fill length distribution will play an important role in the overall exploitation of the LHC. They will also be key factors in any estimates of future performance.

Some simple arithmetic:

- Reduced the schedule physics time SPT by the availability factor.
- Assume an average turn around and average fill length in the time thats left and reduce available time by number of fills times turn around to get the time spent in Stable Beams - previously defined as Physics Efficiency (PE).

The physics efficiency may thus be expressed as:

$$PE = (A \times SPT - N_f \times T_{\text{around}}) \tag{1}$$

where A is the availability, SPT is the scheduled physics time, T_{around} the average turn-around time, and N_f the number of fills which may be expressed as:

$$N_f = \frac{A \times SPT}{T_{\text{fill}} + T_{\text{around}}} \tag{2}$$

$$PE = A \times SPT \times \left(1 - \frac{T_{\text{around}}}{T_{\text{fill}} + T_{\text{around}}}\right) \tag{3}$$

The 2012 data shown in table 2 can be used as an illustration.

Table 2: Overall operational performance 2012

Scheduled physics time	201 days
Availability	71%
Average fill length	6.0 hours
Average turn around	5.5 hours
Mean luminosity delivery rate	12.97 pb^{-1}/hour
Peak luminosity delivery rate	$\approx$ 25 pb^{-1}/hour

Given a time in Stable Beams the obvious question is how much luminosity might one hope to produce in said time. It is not luminosity as a function of time in a fill integrated over the average fill length multiplied by the number of fills because of the impact of the fill length distribution. An average fill length of 6 hours sounds pretty good but theres a difference between the distribution shown in figure 3 and the 2012 distribution shown in figure 4.

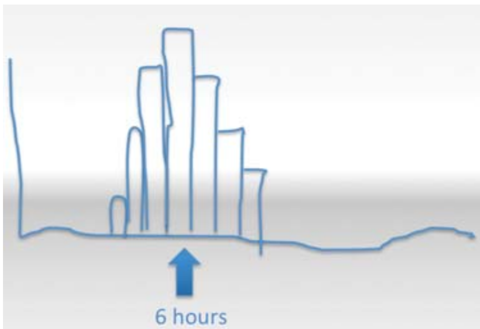

Figure 3: Hypothetical and far from realistic fill length distribution.

Inspection of figure 4 reveals a lot of short unproductive fills and some not so productive long fills. The cost of the short fills is a corresponding number of extra turnarounds which fold directly into lost time for physics.

A brief analysis of the causes for lost fills during the first two hours of stable beams is shown in table 3. It can be seen that the large distributed systems again play an important role and are clear candidates for careful, considered consolidation with a view to high availability in what will be tough conditions. The higher loss fill rate in the first two hours is at least in part due to challenging beam conditions. These will include: peak losses in collimator regions; peak losses in the interaction regions coming from luminosity

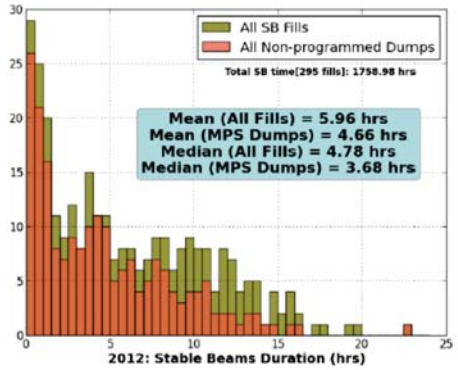

Figure 4: Fill length distribution in 2012. Figure courtesy Alick Macpherson.

debris; peak beam loading for the RF; peak beam induced heating. Given that the HL-LHC plans, with levelling, to maintain these conditions for as long as possible, all possible efforts should be made to address the causes of the premature beam dumps.

Table 3: Systems responsible for most of the fills lost in first two hours of Stable Beams 2012. * includes SEUs

System	No. fills lost
Power converters*	17
Tests	10
QPS*	8
Vacuum	8
UFO	6

REQUIRED AVAILABILITY

The fill length distribution can be visualized in a different way. Figure 5 shows the integrated time for fills terminating between 0 and 1, 1 and 2 hours etc. As might be expected the short fills contribute a low amount of integrated time.

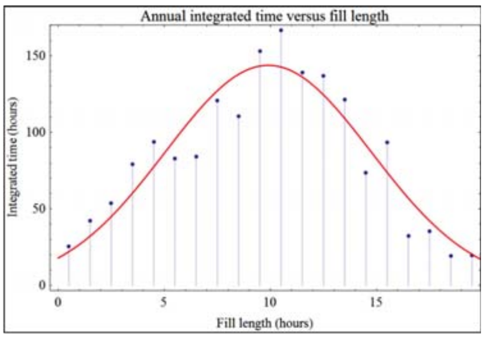

Figure 5: Integrated time per given hour in fill in 2012

Integrating across the hours to get the total time in the year delivered per given hour of a fill we get the result shown in figure 6.

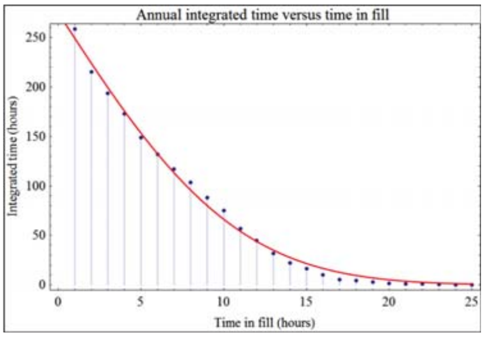

Figure 6: Integrated time per given hour in fill in 2012

An appropriate fit motivated by the Gaussian fit of figure 5 is the complementary error function. Given this fit it is then trivial to calculate the integrated luminosity per year assuming any (average) luminosity profile through a fill.

For example, assume:

- 2012 fill time distribution and naively scaled it to 160 days (this implies the same availability and average turnaround time);
- 5 hours levelling at 5×10^{34} cm^{-2}s^{-1};
- 5 hour luminosity lifetime after the levelling period;
- dump any fill that survives that long after 13 hours.

The result of this particular set of assumptions is shown in figure 7. Integrating over fill length, the total luminosity for a HL-LHC year given 2012's availability and turnaround time is around 210 fb^{-1}.

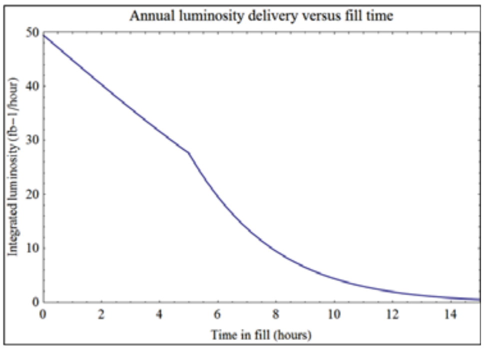

Figure 7: Integrated yearly luminosity versus time in fill given assumptions above.

A Monte Carlo approach which also extends the 2012 figures to the full HL-LHC (and assumes the average turnaround time is increased from 5.5 to 6.2 hours) gets a figure of 213 fb^{-1} [4]. The team also simulates the impact on the integrated luminosity of SEUs, UFOs, quenches and gives a range of 180 to 220 fb^{-1} in simulations that attempt to take these factors into account.

The details of the calculations are unimportant but what is clear is that given 2012's availability and turnaround

around 85% of the HL-LHC annual target would be achieved. This is encouraging but clearly the already good availability must be maintained and improved if the ambitious goals of the HL-LHC are to be reached.

WHAT CAN BE DONE?

In the above discussion some main areas that might be targeted in the interest of improved availability and operational efficiency have been identified.

- Reduce number of faults (hardware and software) - this would be the standard target of improved availability.
- Reduce time to fix faults, reduce intervention times, reduce number of interventions (for example by universal remote reset functionality or improved remote diagnostics or increase redundancy).
- Reduce number of beam induced faults (R2E, beam induced heating, vacuum issues).
- Reduce the mean turn around time (besides reducing number of unwanted dumps before stable beams). Here one could imagine targeting optimization, test runs, the nominal cycle.

What has been done

It is clear that the groups involved have been working hard to target areas of improved availability with some success. The groups implicated include: cryogenics; QPS; power converters; vacuum; BLMs; RF; collimation; injection; beam dump system; feedbacks; controls; technical infrastructure.

One notable thrust has been the major combined effort to alleviate the serious problem of single event effects coordinated by the R2E team. R2E has done a vitally important job so far including the development of test facilities, links with external companies and so on. It is extremely important for the HL-LHC era that this effort continues.

The long term strategy is wide reaching and includes: superconducting links with feed-boxes and main power converters on the surface. 120 A, 60 A converters will remain exposed in tunnel and there is power converter R&D ongoing for radiation tolerant design. Given the results the decision about what else to bring up will be made. Radiation tolerant solutions are being developed for QPS and cryogenics that remains in tunnel and RRs with some 10,000 units that will remain in the tunnel. A robust solution is required for equipment in both radiation and no radiation areas with stringent demands on MTBF. Beam instrumentation is also targeting radiation-tolerant design and upgrades.

Having built up considerable knowledge and expertise in the area of testing and radiation-tolerant design the R2E team worry about knowledge continuity through LS3.

What will have been done

2012 is, of course, only partially representative of the foreseen HL-LHC operational regime and extrapolation must be tempered with caution. However, on the positive side the next runs through to 2023 will see:

- 10 years or so of debugging, consolidation, understanding and flushing out of system problems.
- 10 years of beam dynamics, understanding, control, instrumentation, diagnostics, combat tools at 6.5 to 7 TeV with 25 ns beam.
- Certainly to be quantified in the next 8 years or so
  - Higher energy operation: power converters, cryogenics nearer limits, beam induced quenches
  - Training de-training after thermal cycling
  - E-cloud, scrubbing, conditioning,de-conditioning after LS
  - UFOs: Conditioning, thresholds adjustment, clean MKI

Cryogenics [5]

As regards availability the cryogenics team achieved: 90% for the 5 weeks in 2009, 90% in 2010, 89% in 2011 (impacted by SEUs), 95% in 2012-13. This includes MDs and physics, with typical operational period of 260 days/year. The teams forecasts would be for post-LS1: 90% in 2015, 92% in 2016, 95% in 2017 considering: correct understanding of cryo process and equipment (now well tuned and with procedures), experienced staff and shift organisation; that “quick” fixes will be required, but not often and with pre-defined protocols, therefore with minor impacts on integrated availability. Considerations for post-LS1 beam operation parameters with respect to the “reduced parameter set” pre-LS1 will include: for sure increased heat loads, in particular higher “dynamic””(resistive-RI2 and beam related) with respect to static conditions. However operation should still in the range of “nominal mode with respect to design” and below the “installed capacity”.

The baseline target is 95% for HL-LHC era while noting the addition of 3 additional cryogenics facilities.

Less faults

An ongoing, committed effort from the equipment groups concerned will be required. Some potential target areas are:

- more rigorous preventive maintenance and appropriate technical stops to allow said;
- sustained, well-planned consolidation of injectors;
- installation of plant redundancy e.g. back-up cooling pumps, fully reliable UPS;
- updated system design for reliability, targeted radiation-tolerance, robust, redundant system upgrades given experience and testing.

Reduced fault overhead

There is certainly scope for reducing the overhead of fixing a fault. Possible measures include:

- better diagnostics;
- less tunnel interventions via remote resets, redundancy, remote inspection;
- relocation of hardware to the surface;
- the use of 21st century technology;
- faster interventions, for example by using TIM for radiation surveys, visual inspections and the like.

Operational efficiency

One would anticipate fully and robustly establishing all necessary procedures required in HL era. Possible examples would include:

- BLM thresholds completely optimized across all time scales;
- compress the cycle e.g. combined ramp and squeeze, reduced injection time (dedicated singe batch injection);
- more efficient and fully optimized set-up in place: injectors; transfer and injection; collimators, squeeze, optics;
- less test ramps and squeezes;
- use of optimum fill length strategy;
- precycle:, optimized pre-cycles/dynamic use of model
- upgraded system performance: e.g. 2Q triplet power supplies.

Concerns

It will be a mature system but with major upgrades operating with unprecedented bunch and beam intensities.

Potential concerns include:

- ageing, long-term radiation damage;
- robustness of systems such as QPS, power converters (that remain in tunnel);
- increased intervention overheads because of higher radiation levels (cool-down requirements and remote handling requirements); radiation protection in the HL era should be fully study across the full intervention space;
- the cost in time of recovering from de-conditioning (UFOs, electron-cloud) following long shutdowns.

Fault tracking

In order to fully track availability and to be able to be target weaknesses it is vital that an adequate fault tracking tool be developed and implemented for the LHC restart after LS1. This tool should provide:

- a new LHC fault tracking tool and fault database;
- means of fully assigning the downtime due to a fault including the fault recovery time;
- metric to reflect lost integrated luminosity due to a fault;
- a defined and agreed reference metrics to consolidate views on definitions used in availability calculations;
- reliability tracking of the critical elements of the machine protection systems to ensure that LHC machine protection integrity is acceptable.

CONCLUSIONS

The HL-LHC will place challenging demands on availability and operational efficiency if the ambitious integrated luminosity goals are to be met. The machine availability in 2012 was encouraging but there are still a number of known unknowns to be evaluated e.g. electron-cloud, UFOs, 7 TeV operations. 10 years more years of operations will surely see a concerted effort to address these issues. Unknown unknowns wait to be discovered, among these will be the operability of the LHC with very high bunch populations, very high total beam current, with a novel optics providing a challenging final β^*.

R2E will continue to be very important and continued system improvements across the board will be necessary to get close to the required level of availability. Radiation protection and associated issues will be critical and must be anticipated.

A more formal approach to availability and the proposed developments for coherent tracking and accounting should be fully supported.

There would appear to some room for improved operational and fault fixing efficiency. Certainly the HL-LHC will have to take full advantage and work hard on all possible fronts.

REFERENCES

[1] A. Macpherson, “LHC Availability and Performance in 2012, proceedings of the LHC Beam Operation Workshop, Evian, December 2012.

[2] A. Apollonio, M. Jonker, R. Schmidt, B. Todd, S. Wagner, D. Wollmann, M. Zerlauth, “HL-LHC: integrated luminosity and availability”, Proceedings of the 4th International Particle Accelerator Conference, Shanghai, 2013.

[3] B. Todd, A. Apollonio, A. Macpherson, J. Uythoven, D. Wollmann, “A look back on 2012 LHC availability”, proceedings of the LHC Beam Operation Workshop, Evian, December 2012.

[4] A. Apollonio, D. Wollmann, “Updated projections for HL-LHC and post LS1 operation with Monte Carlo simulations”, LHC Machine Protection Panel, 08 November 2013.

[5] S. Claudet, private communication.

Published by CERN in the Proceedings of RLIUP: Review of LHC and Injector Upgrade Plans, Centre de Convention, Archamps, France, 29–31 October 2013, edited by B. Goddard and F. Zimmermann, CERN–2014–006 (CERN, Geneva, 2014)

50 ns BACKUP SOLUTION

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Abstract

The baseline bunch spacing for LHC high luminosity proton-proton operation after LS3 is 25 ns to maximize the integrated luminosity while keeping the pile-up low. The success of this mode of operation is not guaranteed. Electron cloud, UFOs, long-range beam-beam, heating and other effects might make 25 ns operation in the LHC and/or the injectors difficult. This talk will review possible showstoppers in the LHC and injectors for 25 ns operation and discuss possible remedies. An alternative would be re-considering 50 ns operation. An estimate of the 50 ns performance will be given. The question of whether a different upgrade path would have to be chosen in case of 50 ns operation will also be addressed.

INTRODUCTION

The integrated luminosity goal during the LHC High Luminosity (HL) era is 275 fb^{-1} per year. The standard scenario to achieve this ambitious goal is to run with a levelled luminosity of 5×10^{34} $cm^{-2}s^{-1}$ with 25 ns bunch spacing. This configuration respects the HL LHC experiments‘ limit of event pile-up of μ = 140. The HL LHC parameters with 25 ns can almost give this performance with a physics efficiency slightly increased with respect to the 2012 efficiency [1].

This paper will investigate whether there could be showstoppers for 25 ns operation in the LHC or in the injectors and what the possible mitigations could be. The main topic will then be whether 50 ns could be a valid alternative to 25 ns and whether there would be any differences in the upgrade path if 50 ns beam had to become the operational beam.

The LHC configuration and beam parameters assumed for 25 ns and 50 ns in this paper are the standard HL parameters, see Table 1.

INJECTOR PERFORMANCE AFTER LS2

Figures 1 and 2 show the expected performance in the SPS at 450 GeV as normalized emittance for a given bunch population in the case where all proposed injector upgrades are implemented (after LS2). The white zones in the plots show the achievable combinations of emittance versus bunch intensity and the coloured areas refer to exclusion zones due to various instabilities in the injectors and other limitations. The injector upgrades include Linac4 connection, upgrade of PSB extraction energy to 2 GeV, full SPS uprade and e-cloud suppression [2].

25 ns after LS2

An emittance growth of 20 % and intensity loss of 5 % through the LHC cycle is assumed. Thus the HL 25 ns target parameters at the end of the injector chain are supposed to be a bunch intensity of $N_b = 2.32 \times 10^{11}$ p+ and a normalized emittance of 2.08 μm. According to Fig. 1 the expected performance after LS2 is 2×10^{11} p+ in an emittance of 1.88 μm. The main limitation for reaching the target parameters is the available SPS RF power. It appears however that this is not necessarily a hard limit [3] and that the required bunch intensity is almost within reach.

Table 1: HL parameters for 25 and 50 ns

Parameter	25 ns	50 ns
N_b [$\times 10^{11}$]	2.2	3.5
n_b	2808	1404
ε_n [μm]	2.5	3
Bunch length [cm]	7.5	7.5
Crossing angle [μm]	590	590
Events per crossing	140	140

50 ns after LS2

Valuable experience with 50 ns has been gained during LHC run 1 with bunch intensities up to 1.8×10^{11} protons. The remarkable 50 ns performance in the injectors in 2012 is shown in Fig. 2.

The target HL performance of the injectors for this beam is 3.68×10^{11} p+ per bunch in an emittance of 2.5 μm. As can be seen in Fig. 3 the achievable parameters for 50 ns in the injectors with all the upgrades in place are 2.7×10^{11} p+ in an emittance of 1.95 μm. The bunch intensity will only be about 70 % of the target value, limited by PS longitudinal stability.

POSSIBLE SHOWSTOPPERS FOR 25 ns IN THE LHC

With the HL beam parameters for both 25 ns and 50 ns, the LHC will become more challenging to operate than what was experienced during LHC run 1 or will be experienced during LHC run 2. A number of possible issues specifically for 25 ns will be discussed in the following section. According to the experience with the LHC so far, the only real threat for 25 ns beams will be electron cloud.

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Machine Protection Absorbers

The energy deposition in material is proportional to the energy density of the beam

$$\Delta E \propto \frac{N_b \cdot n_b}{\varepsilon} \quad (1)$$

where N_b is the number of protons per bunch, n_b the number of bunches and ε the normalized transverse emittance.

Energy deposition studies for the injection protection absorbers have shown that the current design choice of materials for transfer line collimators and the TDI injection absorber would not survive the LIU 25 ns beams after LS2. The energy density will be increased by about a factor 4. The main limitation comes from tensile stresses for shallow impact parameters.

The solution for the transfer line collimators could be disposable collimators with quick plug-in supports, as full beam impact on these devices is supposed to be rare and has not happened so far. For the TDI injection absorber however a material has to be found that can survive beam impact. It is designed to protect against injection kicker failures and these failures occur several times per run. The beam was lost 3 times on the TDI in 2012.

50 ns LIU beams would have the advantage of 50 % less energy density in a full injected SPS batch and hence provide significant margin with respect to 25 ns LIU beams for the design choice of protection absorbers.

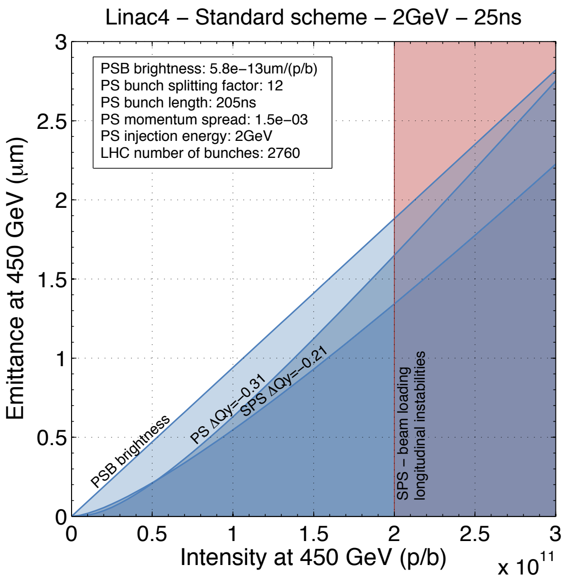

Figure 1: 25 ns performance after LS2.

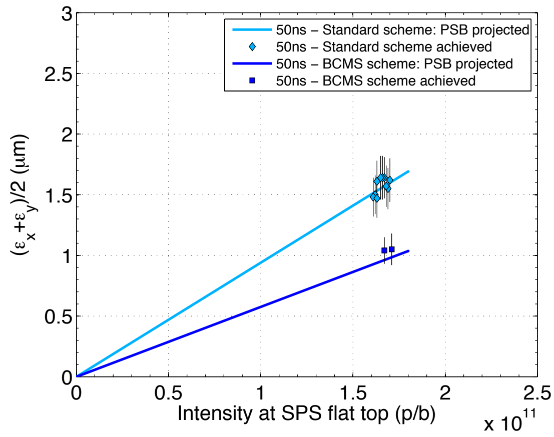

Figure 2: Emittance and intensity for 50 ns beams in the injectors at the exit of the SPS. This plot shows the remarkable performance of the 50 ns beam in the LHC injectors during LHC run 1. The projection from the PSB includes the emittance growth and intensity loss budget through the chain.

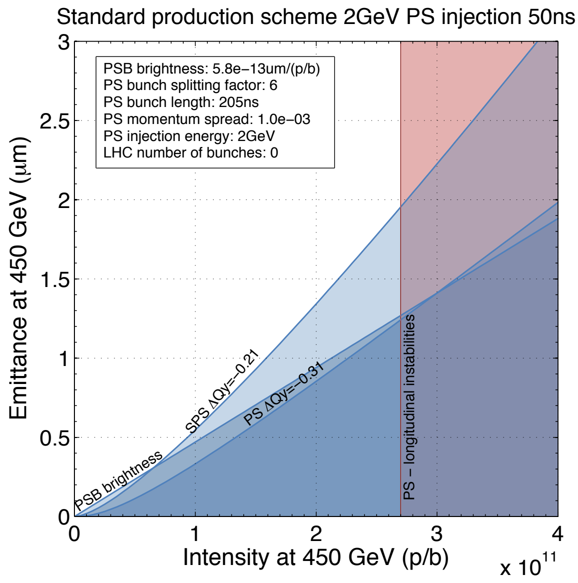

Figure 3: 50 ns performance after LS2.

Beam Induced Heating

The power loss from beam is proportional to the N_b^2. The number of bunches contributes differently depending on narrow band or broad band impedances. In the case of a broad band impedance the power loss is proportional to

$$P_{loss} \propto M \times N_b^2 \quad (2)$$

where M is the number of bunches. In the case of a narrow band impedance (peaked at a multiple of 20 or 40 MHz) the power loss is proportional to

$$P_{loss} \propto (M \times N_b)^2 \quad (3)$$

The power loss will be much increased for the high luminosity beams. 50 ns beams will be slightly worse

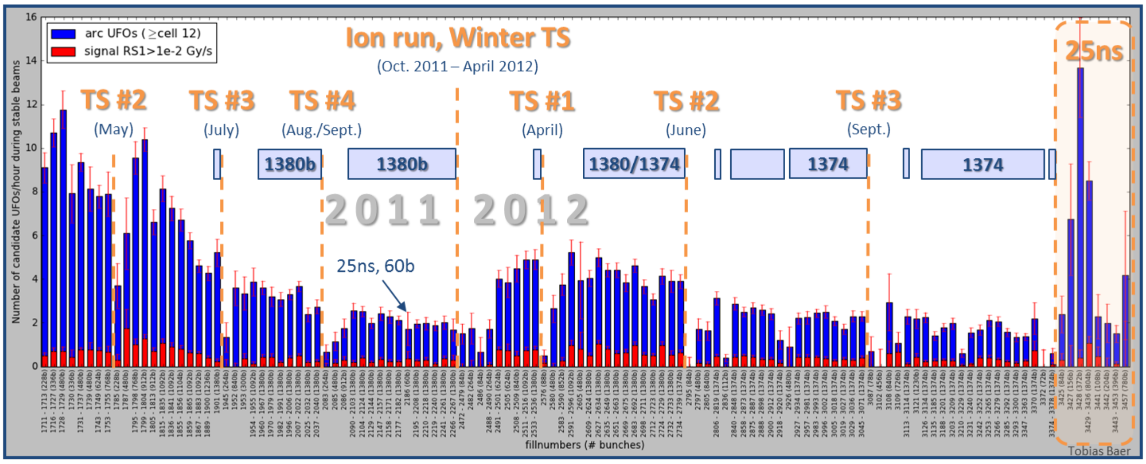

Figure 4: Evolution of number of arc UFOs during stable beams for the years 2011 and 2012. *Courtesy T. Baer*.

for broad band impedance, but 25 ns significantly worse for narrow band ones. A summary is given in Table 2.

Table 2: Power loss scaling with respect to 2012 50 ns beam (1374 bunches, 1.6 × 10^{11} ppb)

	25 ns nominal	50 ns 2012	50 ns HL- LHC	25 ns HL-LHC
Broad band	×1.05	×1	×4.9	×3.9
Narrow band	×2.1	×1	×5	×7.9

UFOs

The evolution of the UFO events detected during stable beams was monitored during the physics production runs 2011/2012 [4]. In 2012 there were periods with 50 ns and 25 ns physics. A summary is given in Fig. 4. Extrapolating from 2012 using the same assumptions for quench limits and hence beam loss thresholds, roughly 100 beam dumps a year from UFOs can be expected at 7 TeV*.

With 25 ns beams the LHC might see even more UFOs. During the 25 ns operation in 2012, the UFO rate increased by factor 5 to 10 in the arcs. However a fast conditioning back to the 50 ns rate levels was observed. The mechanisms involved are not fully understood.

To give realistic predictions for the HL era, UFO rate data from LHC run 2 with 25 ns physics at 6.5 TeV is required.

* The results from the 2013 quench tests indicate that the assumed quench limits for the UFO-like time scales might have been too pessimistic.

Beam-beam effect

The bunch spacing of 25 ns will create more long-range beam-beam encounters than the LHC run 1 physics beam with 50 ns bunch spacing. Large crossing angles of 590 μrad for HL 25 ns as well as 50 ns with its high bunch intensity are foreseen. Simulations suggest that enough dynamic aperture can be guaranteed with this crossing angle. β*-levelling and different optics (e.g. flat beams instead of round beams) will offer sufficient flexibility to optimise performance, see Fig. 5.

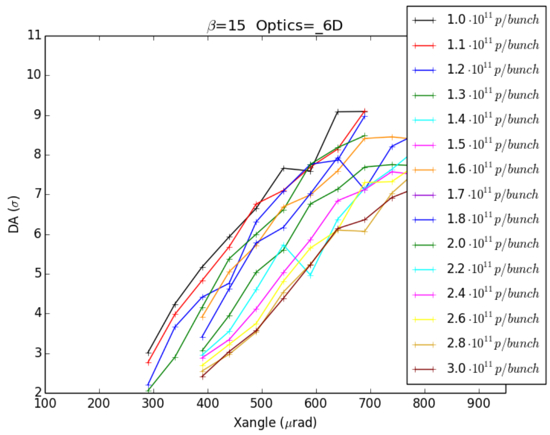

Figure 5: Dynamic aperture with beam-beam at β*=15 m, round optics, as a function of crossing angle for different bunch intensities. The collimators will be at 7 σ (beam sigma). The dynamic aperture with beam-beam should be larger than the collimator aperture. With β* levelling, 15 m β* is reached only with smaller bunch intensities and 590 μrad crossing angle should hence be sufficient. (Imperfections have not been taken into account for this simulation.) *Courtesy T. Pieloni, D. Banfi and J. Barranco.*

With the HL design parameters the head-on beam-beam tune shift ξ will be very high. And HL 50 ns ξ_{50} will be even higher than ξ_{25} for HL 25 ns.

$$\frac{\xi_{50}}{\xi_{25}} = \frac{\frac{N_{50}}{\varepsilon_{50}}}{\frac{N_{25}}{\varepsilon_{25}}} \approx 1.3 \qquad (4)$$

A total tune shift of $\xi \sim 0.02$ to 0.03 was achieved in the LHC during experiments without deterioration of the beam [5]. Long-range effects were however not present. With the HL parameters, a tune shift of $\xi \sim 0.0098$ per IP for 25 ns and $\xi \sim 0.013$ per IP for 50 ns can be expected. In case of problems with the very high tune shift, one could resolve to offset levelling for IP 8 instead of β* levelling to reduce the total tune shift. Presently no insurmountable problems are expected from beam-beam.

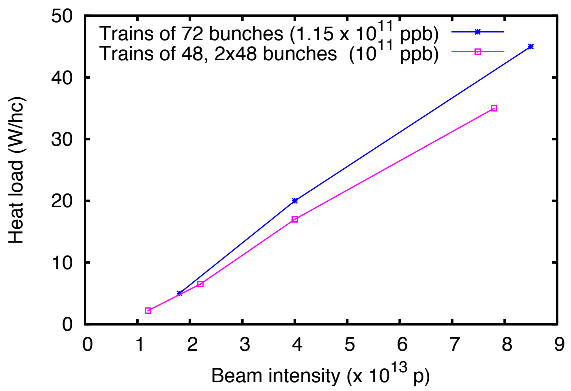

Figure 6: Heat load per arc half cell as function of beam intensity for different bunch train structures.

Electron Cloud

Substantial experience with e-cloud and scrubbing could be gained during LHC run 1, specifically during 2012. A résumé of the 2012 results with 50 ns and 25 ns beams is given in the following:

- Scrubbing has been demonstrated to be efficient at 450 GeV. It lowers the e-cloud in the dipoles. Scrubbing is less evident in the quadrupoles due to a significantly lower threshold SEY.
- Despite the 2-beam-50 ns operation in the triplet for 2 years (very high electron dose), the electron cloud is still present in the triplets.
- A significant increase (~ factor 4) of the heat load from electron cloud was observed in the arcs during the ramp. It only comes from the e-cloud in the dipoles and does not decrease over time at flattop. Scrubbing at flattop does not seem to take place. The underlying mechanism still needs to be understood.
- The heat load increases ~linearly with the number of bunches (less effect from bunch intensity above threshold intensity), see Fig. 6. This could put a limit to number of 25 ns spaced bunches in the LHC.

If the electron cloud in the arcs from the dipoles at flattop cannot be suppressed, the 25 ns total number of bunches could be limited to about half the nominal number of bunches due to the limited cooling power available in the arcs, see Table 3. Different electron cloud mitigation possibilities have been discussed. The most promising one would obviously be scrubbing at 450 GeV to "completely" remove the electron cloud in the dipoles. A special scrubbing beam - the so-called doublet beam - with partly even shorter bunch spacing than 25 ns - will be tested in 2015 [6]. Simulations suggest that this beam will increase the e-cloud significantly and thus enhance the scrubbing efficiency. In case the electron cloud from the dipoles can be removed completely, no cooling power limitation in the arcs is expected, see Table 4.

Table 3: Heat load per arc half-cell. Projection to the HL era

	Available cooling [W]	Fill 3429 meas [W]	HL 7 TeV, 25 ns, 2012 SEY [W]
Arc half-cell	255	45	438

Table 4: Heat load per arc half-cell. Projection to the HL era with full suppression of e-cloud in dipoles

	Available cooling [W]	HL 7 TeV, 25 ns [W]
Arc half-cell	255	4.4

If it turns out that it is not possible to scrub the LHC dipoles sufficiently, an upgrade of the cooling power for the LHC arcs by a factor 2 would have to be considered assuming the degradation of the beam quality due to electron cloud is still acceptable.

New equipment to be installed in the LHC for the HL era should foresee e-cloud mitigation. E.g. the new triplets should be equipped with electron clearing electrodes or be coated.

THE 50 ns ALTERNATIVE

An estimate of the performance with 50 ns beams as alternative to the 25 ns scheme during the HL era will be given.

Assumptions

The following assumptions and definitions have been used to give an integrated luminosity estimate:

- The efficiency parameter used for the calculations and simulations in this paper is "physics efficiency" ε_{SB}. It corresponds to the ratio of the total time spent in stable beams T_{SB} over the total allocated time for operation T_{run}. The 2012 efficiency was 37 %.

$$\varepsilon_{SB} = \frac{T_{SB}}{T_{run}} \quad (5)$$

- An exponential fill length distribution is assumed. The fill lengths of the fills in 2011 and 2012 followed exponential distributions [7][†]. The average fill length in 2012 was ~ 6 h.
- Assumed luminosity lifetime: 9 h (const.)
- 160 days of physics operation
- Pile-up limit of μ = 140 as for 25 ns. The level luminosity for 50 ns is thus half the level luminosity for 25 ns.

Estimated performance with HL 50 ns

The yearly expected integrated luminosity has been simulated according to the assumptions in the previous paragraph. Figure 7 summarizes the results for 50 ns and 25 ns with and without crab cavities as integrated luminosity per year versus physics efficiency. An efficiency of ~ 47 % would be needed to meet the target of 275 fb^{-1} per year for 25 ns with crab cavities. For HL 50 ns the required efficiency would be ~ 80 % due to the long optimum levelling times and the low level luminosity. Running with or without crab cavities does not change the result significantly with efficiencies < 50 % for 50 ns. Expecting a physics efficiency of > 50 % is very certainly unrealistic. On a short term basis 50 % efficiency could be achieved in 2012, see Fig. 8. To reach 50 % efficiency on average for the entire run is already a challenge. Assuming now 50 % efficiency, the runs would still have to be longer by > 50 % to reach the integrated luminosity goal with 50 ns beams, see Fig. 9.

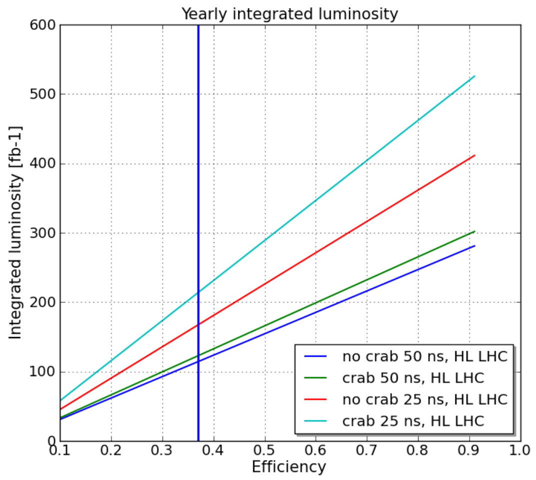

Figure 7: Integrated luminosity per year for 25 ns and 50 ns HL beams with and without crab cavities as function of physics efficiency. The blue vertical line indicates the 2012 achieved efficiency. The HL goal is 275 fb^{-1} per year.

[†] A uniform fill length distribution increases the performance estimate for integrated luminosity per year by ~ 15 %.

Additional upgrades for 50 ns?

All the previous performance estimates were assuming the 50 ns HL target parameters. With the currently foreseen injector upgrades the achievable parameters at the exit of the SPS will only be 2.7×10^{11} in an emittance of 1.95 μm, as already stated earlier. Figure 10 compares the performance for HL 25 ns, HL 50 ns and 50 ns as achievable after injector upgrades after LS2 with and without crab cavities. With the assumptions from above for fill length distribution and efficiency but an emittance growth through the LHC cycle of 40 % instead of 20 % due to the higher brightness, the integrated luminosity per year with crab cavities for the achievable 50 ns beam would be ~ 113 fb^{-1}, compared to 123 fb^{-1} for the 50 ns HL target parameters and crab cavities. The difference is less than 10 % and does not justify another upgrade scenario in the injectors in case of 50 ns operation.

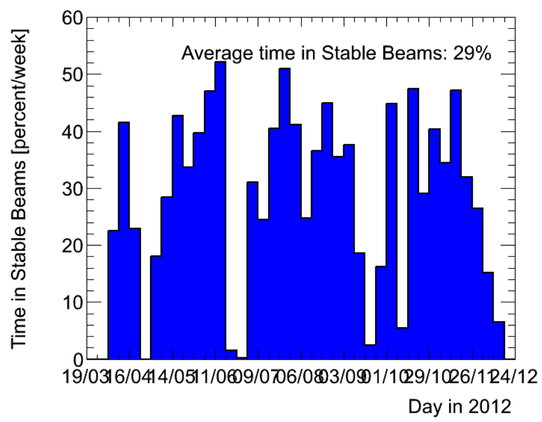

Figure 8: Average time in stable beams per week in 2012. 50 % physics efficiency per week was reached twice in 2012. *Courtesy ATLAS*

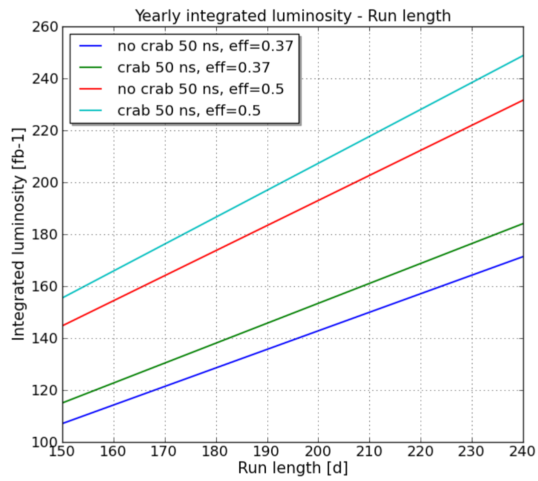

Figure 9: Integrated luminosity per year versus run length for 50 ns with and without crab cavities for efficiency of 37 % and 50 %. To reach the integrated luminosity goal of > 250 fb^{-1} per year, the runs would have to be at least 50 % longer in case of 50 % efficiency.

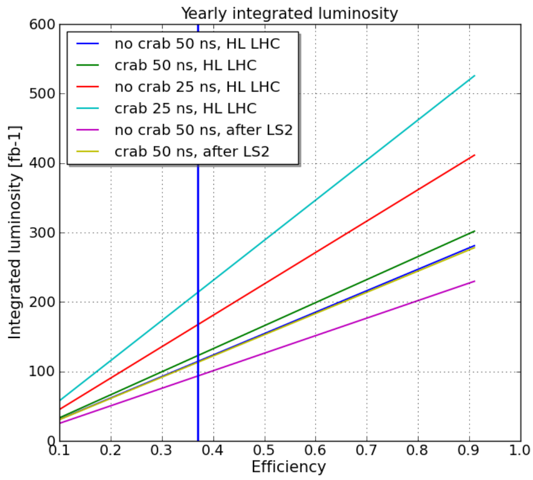

Figure 10: Integrated luminosity per year as a function of physics efficiency for 25 ns HL target parameters, 50 ns HL target parameters and 50 ns parameters as achievable after LS2 with and without crab cavities. The vertical line indicates the efficiency achieved in 2012.

Remark: Can we operate with HL 50 ns bunch intensities?

In 2012 the LHC was operating with 50 ns bunch spacing and bunch intensities up to 1.8×10^{11} p^+. Beam stability had become a permanent concern during 2012 operation with tight collimator settings. Fig. 11 shows the result of a stability classification analysis of all fills during 2012 based on logged data of BBQ amplitudes, emittance growth and losses. The red dots indicate fills with instabilities and the black ones without instabilities. In the second half of 2012 the fills were systematically suffering from instabilities at the end of the betatron squeeze degrading the beam parameters and creating increased loss rates at the collimators. The underlying mechanism is not understood. The additional impedance from the collimators with the smaller gaps in 2012 most probably played an important role together with beam-beam.

With the 50 ns HL bunch intensities, understanding the LHC stability limitations and the impedance model will become even more important. Beam instabilities with high bunch intensities might be a possible limitation for the HL 50 ns beam and could make it even less attractive with its already reduced performance compared to 25 ns.

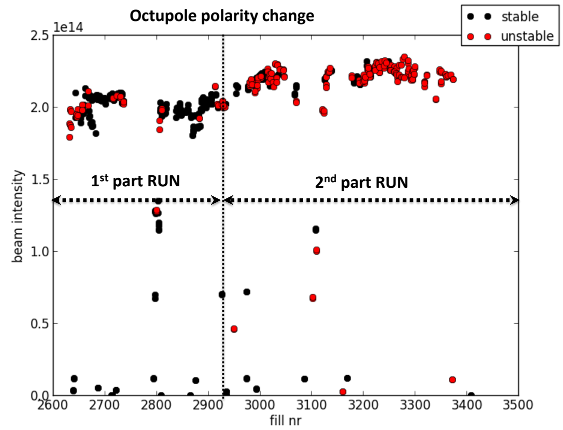

Figure 11: Stability classification of all LHC fills during 2012. Signatures of instabilities are detected from the logged data of losses, BBQ amplitudes and emittance growth. *Courtesy T. Pieloni and D. Banfi.*

CONCLUSIONS

The performance goal during the high luminosity era of the LHC will be to deliver 275 fb^{-1} of integrated luminosity a year. The 25 ns option with the high luminosity beam parameters, a fill length distribution as in 2012 and physics efficiency of close to 50 % could deliver this performance within the pile-up constraints given by the LHC experiments. Electron cloud could however be a showstopper and mitigation possibilities will have to be found in the next LHC run to prepare for the high luminosity era.

A bunch spacing of 50 ns could be an alternative. Valuable experience with this beam has been gained during LHC run 1 with bunch intensities up to 1.8×10^{11} protons. For the high luminosity ear after LS3 the 50 ns beam has significant disadvantages. With a fixed pile-up limit of 140 for the LHC experiments, only about 50 % of the integrated luminosity compared to 25 ns would be collected per year. In order to become comparable to 25 ns, unrealistic physics efficiencies of 70 – 80 % would be required.

Intermediate schemes with more bunches than the 50 ns scheme, but less electron cloud than for 25 ns, could be more attractive than 50 ns. An example is the 8b-4e beam as mentioned in [3].

No alternative upgrade paths have been identified in case 50 ns became the only valid option to operate the LHC with during the high luminosity era. Even more emphasis would however have to be put on understanding the LHC beam stability limits with high bunch intensities and the LHC impedance model. The proposed high luminosity 50 ns bunch intensities might be close to the bunch intensity limits of the LHC.

REFERENCES

[1] A. Apollonio et al., “HL-LHC: Integrated Luminosity and availability”, TUPFI012, proceedings of IPAC’13.

[2] B. Goddard et al., “Can the proton injectors meet the HL-LHC requirements after LS2“, Chamonix 2012 workshop on LHC performance, Chamonix, France.

[3] H. Damerau et al., ”LIU: Exploring alternative ideas”, these proceedings.

[4] T. Baer, “Very fast losses of the circulating LHC Beam, their mitigation and machine protection“, CERN-THESIS-2013-233.

[5] W. Herr et al., “Head-on beam-beam tune shifts with high brightness beams in the LHC“, CERN-ATS-Note-2011-029 MD.

[6] H. Bartosik et al., “Can we ever reach the HL-LHC requirements with the injectors (LIU)?”, these proceedings.

[7] J. Wenninger, “Simple models for the integrated luminosity“, CERN-ATS-Note-2013-033 PERF.

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HEAVY ION PLANS: EXPERIMENTS PERSPECTIVE

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Abstract

An outlook of the experiments needs for Heavy Ion physics for the next ten years is given, including a summary of required beam types and configurations (e.g. p-Pb and collision energies other than the nominal 13 TeV). We discuss which, if any, other ion species than Pb are being considered. The experiment expectations in terms of integrated luminosities are discussed, along with the impact - usefulness, or otherwise, of different scheduling options for the Ion physics program. Different ion running scenarios, as well as the interest of an extended ion run, in light of the upgrade plans and goals are discussed in terms of integrated luminosity and physics targets.

INTRODUCTION

The LHC as a hadron collider is used to study the properties of nuclear matter at the very high temperatures produced in the collisions. The prevailing theoretical framework to model such properties is the Quark Gluon Plasma (QGP). QGP exhibits the properties of a very hot and dense quantum fluid where the partons (quarks and gluons) are neither free nor in a bound state but behave dynamically like a fluid whose properties are defined by the strong interaction. Heavy Ion physics uses the arsenal of particle physics (leptons, jets, heavy flavours and “onia” bound states) which are produced in the center of the Ion-Ion “fireball” as probes to measure the medium properties as it is traversed.

The LHC experiments already produced a wealth of new results using collider data from the PbPb runs in 2010 and 2011. Important results came also from the pPb run in 2012, which provided an invaluable cross check of results, a control experiment without a hot medium.

The LHC can produce today the largest, hottest, longest-lived QGP. This will allow, combined with the upgrades of the detectors in the next decade, to carry out a rich program of physics, from the detailed verification of the theory to the precise determination of the properties of hot nuclear matter.

HEAVY ION PARAMETERS FOR RUN 2

In a total of about 8 weeks of LHC operation in the two Pb-Pb runs of 2010-11, the peak luminosity has reached twice the design, and 15-18% (depending on the experiment) of the overall long-term Pb-Pb luminosity goal of 1 nb^{-1} was delivered.

A lot was learne from the 2011 Pb-Pb run, including a better understanding of the performance limits of the LHC as a heavy-ion collider. The operation of the LHC as a proton-Lead collider was proven and the performance in this configuration exceeded expectations.

As prospects for exceeding the design luminosity L>10^{27} $cm^{-2}s^{-1}$ after LS1 now appear very good and ALICE is considering an upgrade in LS2 to handle peak luminosities L ~ 6 10^{27} $cm^{-2}s^{-1}$, it will be important to study upgrade measures that may achieve these luminosities in 2019.

A missing factor 2-3 in peak luminosity might be achieved by increasing the number of bunches in the ring (reducing the minimum spacing to 50 ns, for example). Alternatively, all, or some fraction, of such an increase could come from measures taken in the LHC, e.g. reduced β* in collision.

The option of running with different ion species will also become available.

General Physics Goals

The general goal of the HI run 2 will be collecting large statistics for in-depth study of the medium properties, in order to achieve a better classification of the theoretical predictions. According to their specific characteristics, each experiment will focus on slightly different aspects. ALICE will focus on low-pT heavy-flavor production, fragmentation, and resonances and the study of elliptic flow, as well as the study of very low-pT and low mass dileptons. ATLAS and CMS will be more focused on hard probes (jets, with or without b-tagging, dijets, photon-jet and Z-jet production at very high-pT), as well as multi-differential studies of Y states. All the experiments, including LHCb, are interested in collecting large integrated luminosity with pPb, to disentangle cold nuclear matter effects from QGP effects and for use as a control experiment to reduce systematic uncertainties.

ALICE

Table 1 specifies the beam and collision characteristics required by ALICE in run 2.

Table 1: ALICE HI parameters

Year	System	Luminosity
2015	pp-min bias (24 wk) Pb-Pb (4 wk)	10^{29}-10^{30} $cm^{-2}s^{-1}$ 10^{27} $cm^{-2}s^{-1}$ – leveled
2016	pp rare triggers (24 wk) Pb-Pb (4 wk)	5-10 10^{30} $cm^{-2}s^{-1}$ 10^{27} $cm^{-2}s^{-1}$ – leveled
2017	pp rare triggers (24 wk) pPb min bias (2 wk) pPb rare triggers (2 wk)	5-10 10^{30} $cm^{-2}s^{-1}$ 0.5-1 10^{28} $cm^{-2}s^{-1}$ – leveled 10^{29} $cm^{-2}s^{-1}$ – leveled
2018	LS2	

http://dx.doi.org/10.5170/CERN-2014-006.153

To be noticed in particular is the need for a 4-5 orders of magnitude luminosity reduction in IP2. No filling scheme tricks will be available at 25ns bunch-spacing, and basically all bunches will collide in ALICE (except for the effect of the abort gap). A larger β^* is not a viable option due to aperture issues in IP2, hence, a separation of order 5σ will be needed. Whether the level of background in IP2 will be lower than the expected signal remains an open question, and will largely depend on the quality of the vacuum achieved after the LS1 intervention.

ALICE studied the beam-gas background conditions in LSS2-L assuming a 5 10^{-9} vacuum. The result is a rather strong MB trigger contamination (~50%) at L=1 10^{29}. On the other hand the contamination at L=1 10^{30} is ~10%, at the price of a higher pileup of order 10 in the TPC.

Further studies of optimization will be performed based on these results.

ATLAS and CMS

Both ATLAS and CMS assume a HI run at the end of each year as in the baseline LHC schedule. A leap of one year, although not desirable, could be acceptable to ATLAS if helping with overall efficiency. For both experiments, the ultimate goal is to collect 2-3 nb-1 before LS3. For 2015-2016, the two collaborations request PbPb at 5 TeV c.m. energy, and a corresponding amount of intermediate energy reference pp data. CMS would consider having the second high luminosity PbPb run at the same energy as the first one (i.e. 5 instead of 5.5), depending on the impact on setup time and achievable instantaneous luminosity – as this would require a single set of reference pp data, which will also be useful for pPb. For 2017 both collaborations request pPb at high luminosity. Running pPb at the same c.m. energy as PbPb instead of the top energy (8.2) is an option for CMS as it would allow to minimize the number of pp reference data sets needed. More studies are needed to balance the gain in high p_T statistics vs availability of reference data. ATLAS definitely favors one pPb run at 8.2 TeV before LS3. Concerning reference pp data at intermediate energy, a data set equivalent to the Pb+Pb data set (a pp integrated luminosity of ~3-4·10^4 the Pb-Pb one) is considered absolutely necessary and needs to be kept in sync with Pb+Pb $\int Ldt$ "steps". Therefore, it is not possible to concentrate all reference pp data taking in a single period during 2015-2022.

LHCb

Due to the huge track multiplicity in Pb-Pb collisions in the forward direction ($2 < \eta < 5$), the LHCb collaboration plans to participate only in a pPb run, as in 2013, and considers preferable to have p-Pb run not at the end of the HI program of run 2. The goal is to collect at least 10 times the integrated luminosity of 2013, when the experiment operated at ~5x10^{27}/cm^2/s. Assuming another p-Pb run would last also about 4 weeks, a luminosity greater than 5x10^{28}/cm^2/s should be provided to LHCb. The compatibility of this luminosity with machine limitations in the pPb scheme needs to be verified.

Experience has shown that a pp data sample at the corresponding pPb energies, i.e. at 5 TeV and/or 8.2 TeV. is important for LHCb

Conclusions

All experiments agree that HI run periods should not be grouped, and that the general goal is to collect as much integrated luminosity as possible for PbPb and pPb, with the general goal of collecting at least 1 nb^{-1} with one HI run period per year between 2015 and LS2.

Concerning the beam energy, one clear advantage in choosing a single value of √sNN is the pp reference sample just keeps adding up, and all experiments seem to consider running PbPb again at 5 TeV acceptable. Physics considerations must be weighed against the obvious advantages for reference pp samples in considering keeping the same (lower) energy also for the next pPb run.

Since ALICE requires leveling during PbPb and pPb running before LS2, ATLAS and CMS might need to be also leveled to guarantee constant luminosity to ALICE in the presence of large burn-off. Delivering the same luminosity to all IPs, although slightly penalizing for IP1/5, would be the easiest option.

The request of LHCb for a factor 10 more luminosity in IP8 requires squeezing of the 4 IPs, and at the time of writing it is not clear how technically difficult this is.

The generally agreed schedule would then look like this:

2015: PbPb at 5.02 TeV

2016: PbPb at 5.02 (5.5) TeV

2017: pPb at 5.02 (8.2) TeV

Concerning the use of ion species other than lead before LS2, only ATLAS expresses a slight preference for a possible ArAr run. In any case no request is made for different species during the same year.

BEYOND LS2

The general expectation of the HI community is to collect 2-3 nb^{-1} before LS3, with an ultimate goal and a physics case for collecting ≥ 10 nb^{-1} by the end of the LHC program.

Upgrades

ALICE will install its major detector upgrade during LS2 in 2018. The upgrade aims at precision measurements of the Quark Gluon Plasma, with a factor 100 gain in statistics (x10 luminosity, x10 via pipelined readout), with the aim of a Pb-Pb recorded luminosity ≥ 10 nb^{-1}, or 8 x 10^{10} events (Run2+3). The upgrade will also allow an increased pp capability, aiming at a recorded luminosity ≥ 6 pb^{-1}, or 1.4 x 10^{11} events. A new, ultra-low mass silicon tracker will be installed around a very small beam-pipe (ID 34.4 mm). The upgrade of the

TPC with GEM detectors will allow continuous (un-gated) readout, while the electronics upgrade of the other sub-detectors will permit the read out of all Pb-Pb interactions at a maximum rate of 50kHz (i.e. L = $6x10^{27}$ $cm^{-1}s^{-1}$) with a minimum bias trigger. Processing such rates will require a major upgrade of the online systems, with data reduction based on reconstruction of clusters and tracks.

ATLAS will add a pixel layer during LS1, then an entirely new tracker will be installed in LS3: this will dramatically improve the tracking and b-tag capabilities. A fast tracking trigger will be installed in LS2 to aid high-multiplicity tracking. Calorimeter and muon upgrades in LS2 will improve the electron, γ identification, as well as improve the muon triggers efficiency in the presence of large pileup. The upgraded TDAQ system will allow higher L1 rates and larger data volumes.

CMS L1 trigger upgrade, implemented during LS1, will enable the experiment to tolerate an interaction rate of up to ~50kHz for PbPb. Then the complete upgrade of trigger and DAQ in LS2 will include an HI-specific development to reach the necessary L1 rejection at 95%, from 50 kHz to <3 kHz (HLT). The new pixel tracker, installed before LS2, then new tracker in LS3, will preserve and improve the tracking and b-tagging capabilities of the experiment in the presence of large pileup. In LS2 the forward muon system will be extended to improve muon acceptance.

The LHCb detector upgrade, including new vertexing and tracking detectors, will also take place in LS2. Although not specifically focused on HI physics, it will clearly benefit it. The HI (pA) physics community in LHCb is still small, but might build up during Run2.

Heavy Ion Operations After LS2

The main interventions on the accelerator related to HI physics will concern the upgrade of the SPS injection system, and the installation of collimators in the dispersion suppression region around IR2 (possibly also in IR7) for ions. The ATLAS and CMS collaborations remark that in case the magnet quench limits should be reached in IP1/5, the installation of dispersion suppression collimators as in IP2 would be desirable.

To increase instantaneous luminosity, all experiments support going to a 100 ns bunch spacing as early as possible, as long as the development of the SPS injection kickers does not distract from pp upgrades. In view of this, the LHC vacuum in the LSS around IP2 needs to be improved by an order of magnitude to mitigate background.

HI operation after LS2 will still focus on PbPb a pPb. However, running with lighter species, namely ArAr and pAr, is considered important, in particular to better study jet quenching, since the lower underlying event multiplicity reduces the systematic error on the measurements. It is also deemed that running with ArAr collisions will potentially deliver a higher N_{coll}- weighted luminosity.

The LHCf collaboration has expressed interest in collisions with Nitrogen ions, which would be the best for modeling of cosmic-ray interaction in the atmosphere, while using Oxygen would also be acceptable.

Run 3 Scenarios

As anticipated, the general goal of the Run 3 is to collect at least 3 nb^{-1} of integrated luminosity. The basic assumption for scheduling is to continue the pattern of one month of HI operation of the LHC per year.

Besides ATLAS and CMS, ALICE will require the collection of reference pp data at intermediate energy (5.5 TeV). Although D and B cross sections can be scaled in √s with pQCD, large scaling uncertainties result for charm at low pT (>50%). Furthermore, there is no robust theoretical guidance for interpolating quarkonia production rates, and jet energy scale calibration depends strongly on √s. For all these reasons, ALICE will require approximately 10 $pb^{-1}$of pp reference data to achieve a statistical error negligible wrt Pb-Pb (e.g. 1/√2). This can be achieved e.g. by running for 10^6 s at 200 kHz (with L leveled at $6x10^{30}$). ATLAS and CMS need to match the PbPb yields at high pT for 10 nb^{-1} of PbPb collisions which will require an ultimate reference pp sample of 300 pb^{-1}.

The priority of operating with ArAr and pAr after LS2 will be defined based on the outcome of analysis of high statistics PbPb and pPb from Run 2.

A possible scenario for Run 3 HI operation could therefore be the following:

2019 – PbPb 2 nb^{-1} (and/or ArAr as per ATLAS request…?) + pp 60 pb^{-1} (ATLAS/CMS), 3 days (ALICE) ...

2020 – PbPb 2 nb^{-1}+ pp 60 pb^{-1} (ATLAS/CMS), 3 days (ALICE) …

2021 – pPb/pAr? (1/2 each) + complete pp reference run

2022/2023 LS3

AFTER LS3

The HI groups in the collaborations, and in particular the ALICE collaboration, are working on a physics case for running the upgraded LHC with heavy ions (HL-HI-LHC). The general goal would be to collect more than 10 nb^{-1} in a single run, thus allowing the study of QGP properties with unprecedented precision.

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PERFORMANCE OF THE INJECTORS WITH IONS AFTER LS1

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Abstract

We review the performance of the ion injector chain at the light of the improvements which will take place during LS1, and we derive the expected luminosity gain for Pb-Pb and p-Pb collisions in the LHC. We suggest a baseline plan of upgrades that will allow the requirements of the ALICE experiment after LS2 to be reached. An alternative plan is also presented. Finally, we examine the possibility for different ions species for which some of the other experiments have expressed an interest. The main outcomes of the presentation 'Work effort in the injector complex (including the Linac4 connection)' will be reminded with emphasis on their consequences on the ion operations.

INTRODUCTION

The Pb^{82+} ion beam brilliance, as delivered from the injectors in February 2013 at the end of the first LHC p-Pb run [1], exceeded the design value [2] by a factor three, as shown in table 1. A Pb-Pb run under those conditions would have delivered about 2.3×10^{27} cm^{-2} s^{-1} of peak luminosity at 6.5 ZTeV. Since the peak luminosity requested by the ALICE experiment for the HL-LHC era [3] is of the order of 6-7$\times10^{27}$ cm^{-2} s^{-1} at 7 ZTeV, a missing factor of about 3 is still to be found. The retained solution is to increase the number of bunches in the collider, as the bunch brilliance is already a limiting factor on the flat bottom of the SPS, due to space-charge and intra-beam scattering [4]. Increasing the bunch intensity would also decrease the luminosity lifetime due to larger burnoff [5].

Table 1: Pb^{82+} ion beam properties at SPS extraction in 2013, compared to design values.

	Pb^{82+} 2013	**Pb^{82+}design**	
N_B	22	9	10^7 Ions/bunch
ε_H	1.1	1.2	μm (norm. RMS)
ε_V	0.9	1.2	μm (norm. RMS)
N_B/ε	22.1	7.5	10^7 Ions/μm

BASELINE SCHEME

The baseline scheme, summarized in Fig. 1 below, assumes up to the LEIR machine, a similar performance as achieved in February 2013, with no significant improvement in the bunch intensity extracted from LEIR. The 2 bunches of 5.5×10^8 Pb^{54+} ions each, are transferred to the PS in two adjacent buckets of harmonic $h = 16$. A batch compression is performed in the PS on harmonics $h = 16$-18-21, yielding a bunch spacing of 100 ns at the end of acceleration. After rebucketing to $h = 169$, the two-bunch batch is transferred to the SPS through the TT2-TT10 line where full stripping to Pb^{82+} takes place. Twelve such transfers are needed to produce a full train. In order to maximize the number of bunches, the batches are injected next to each other, with a batch spacing of 100 ns, thanks to a new ion injection system [6]. The trains supplied by the injector chain to the LHC then consist of 24 bunches, spaced by 100 ns.

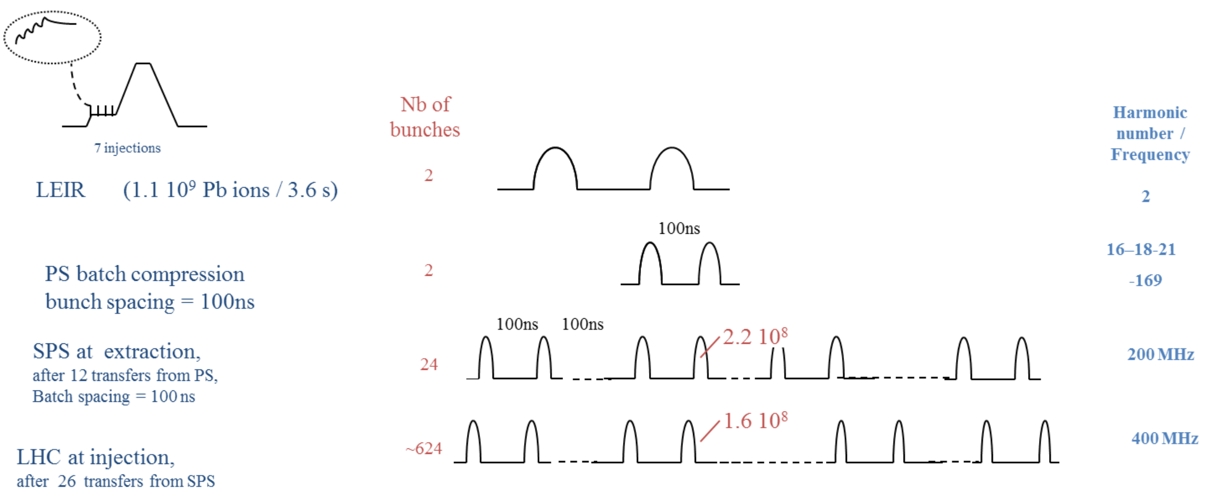

Figure 1: Proposed baseline scheme

Up to 26 such trains can be sent to each LHC ring, totalling 624 bunches per ring. Assuming LHC operation at 7 ZTeV, a peak luminosity of 4×10^{27} cm^{-2} s^{-1} is within reach. The main investment consists in an upgrade of the SPS injection scheme, using a septum recuperated from the PSB extraction line, after its upgrade to 2GeV, and a faster pulser which had already been foreseen at the time of design [7]. A faster, 50 ns injection system had been considered [8] but had to be discarded due to impedance and resources considerations.

Table 2 summarizes the beam parameters across the injector chain for the baseline scheme.

Table 2: Baseline beam parameters

Parameter	Unit	Linac 3	LEIR	PS	SPS
Pb charge state (1)		29+/54+ (1)	54+	54+/82+ (1)	82+
Output Energy	[GeV/u]	0.0042	0.0722	5.9	176.4
Output Bρ	[T.m]	2.12/1.14 (1)	4.8	86.7/57.1 (1)	1500
Injections into the next machine		6	1	12	26x2
Bunches/ring			2	2	24
Extracted intensity/pulse	Ions	4.6x10^{8}	1.1x10^{9}	7x10^{8}	1.9x10^{9}(3)
Total extracted charge	Charges	2.5x10^{10}	6.0x10^{10}	3.8x10^{10} / 5.7x10^{10} (1)	1.6x10^{11}(3)
Ions/bunch at injection	Ions		5.5x10^{8} (4)	3x10^{8}	2.2x10^{8}(2)
Ions/LHC bunch at extraction	Ions		4x10^{8}	2.5x10^{8}	2x10^{8}(2) 1.6x10^{8}(3)
Bunch spacing at extraction	[ns]	N/A	350	100	100
Normalised transverse rms emittance	[μm]	0.25	0.70	1.0	1.2
Longitudinal emittance	[eVs/u]		0.025	0.045	0.125
4σ Bunch length	[ns]		200	3.9	1.8
2σ Momentum spread		0.4x10^{-3}	1.2x10^{-3}	1.1x10^{-3}	3.2x10^{-4}
Repetition time	[s]	0.1	3.6	3.6	49.2
Space charge ΔQ on flat bottom			0.09 (4)	0.15	0.18 (2)

(1) stripper stages between Linac3 & LEIR, then between PS & SPS; parameters before/after stripping
(2) corresponding to the maximum bunch intensity
(3) average intensity taking into account the distribution of bunch intensities along the train
(4) at the end of the flat bottom, just before acceleration.

POSSIBLE IMPROVEMENTS

Splitting in the PS

In order to further increase the bunch number in the LHC, one would have to split the beam in the PS, whose RF system cannot accelerate on 20MHz. Hence, splitting down to a 50 ns bunch spacing would have to be done at high energy, close to transition. So, not only new cavities would have to be installed in the PS machine for the RF gymnastics themselves, but also a new gamma-jump scheme, specific to ions, would have to be designed and implemented. For the same reason, a batch compression down to 50 ns bunch spacing at high energy would be impractical. Hence, only splitting to 100 ns bunch spacing in the PS will be considered in the following, using the same bunch structure as already planned for the nominal beam in the design report [9].

Increasing the LEIR bunch population

In order to deliver a similar performance as in table 1 in spite of splitting, the beam intensity out of LEIR should be increased, ideally by a factor 2. However, assuming the splitting allows to double the number of bunches in the LHC, breakeven for the peak luminosity is reached by a factor $2^{1/2}$ only, i.e. an increase of 40%.

Due to a loss that occurs at the beginning of the acceleration ramp (Fig. 2), the intensity extracted out of LEIR is currently limited to about 6×10^{10} charges, corresponding to 5.5×10^{8} Pb^{54+} ions per bunch. A thorough machine development programme has started in order to try and understand, then lift or mitigate this limitation [10]. Provided it is possible, the Linac3 current output needs to be pushed up.

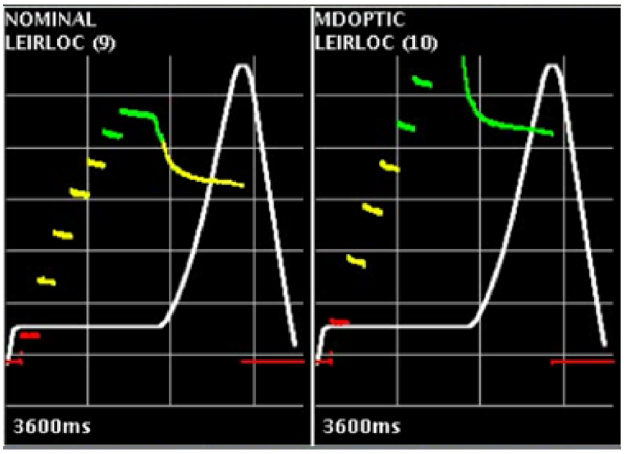

Figure 2: Loss at acceleration on the LEIR nominal and development cycles.

Increasing the LINAC3 current

Compared to the design values, a factor two is missing from the current output of Linac3. A rematching campaign is being performed to try and optimise the beam transmission in the LEBT.

The possibility of accelerating up to three charge states in Linac3 to double the intensity as originally planned at the time of design [11] is now abandoned, as it is likely that the off-central charge states would not transmitted into the LEIR machine, due to their large momentum error.

Aside from new developments on the ECR source itself, the most promising path consists in doubling the repetition rate from 5 to 10 Hz [12]. The investment will be relatively modest as the source itself is already pulsing at 10 Hz, and the Linac3 has been designed for operating at 10 Hz as well. The LEIR injection system has also been tested at 10 Hz, so only a few magnets and power supplies in the Linac-to-LEIR transfer lines will have to be replaced or upgraded.

Momentum slip-stacking in the SPS

As bunch-splitting or batch compression to reach a bunch spacing of 50 ns both prove difficult to perform in the PS, elegant RF gymnastics in the SPS have been proposed, which will be made possible by the planned upgrade of the SPS radio frequency systems. Momentum slip stacking [13] consists in capturing two trains of bunches with independent beam controls, and by detuning them in momentum, bringing them closer together. Those gymnastics, originally proposed to increase bunch densities [14], can be applied in our case to interleave the bunches (Fig. 3):

- The PS transfers two times 6 batches of four bunches to the SPS, with a batch spacing and a bunch spacing of 100 ns, leaving a gap large enough for two independant RF systems to capture each of them on the same frequency.
- The two trains are detuned in momentum by opposite amounts
- They start slipping towards each other
- Once the bunches are interleaved they are recaptured at average frequency and filament in a large bucket

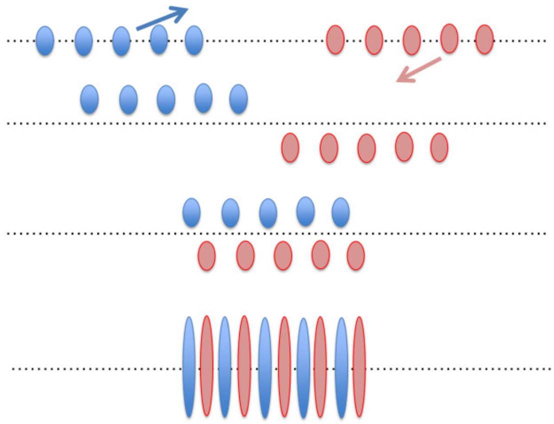
Figure 3: Schematic for halving the bunch spacing using momentum slip stacking.

One issue is the larger resulting longitudinal emittance, but early simulations indicate the bunch length would still be within the accepted limits of the LHC RF at injection [15]. This issue can be completely dismissed in case of the addition of 200 MHz cavities in the LHC.

Putting it all together

Assuming (Fig. 4):

- a reasonable increase (~50%) of the bunch density in LEIR,
- splitting the two bunches in the PS in order to send 4-bunch trains into the SPS with 100 ns bunch spacing,
- a new 100 ns rise time injection scheme into the SPS
- momentum slip stacking in the SPS,

one gets a total number of bunches of 1248 bunches in each one the LHC rings, bringing the peak Pb-Pb luminosity at 7 ZTeV over $\mathcal{L}_{peak} = 6.0\times10^{27}$ cm^{-2} s^{-1}. Table 3 summarizes the beam parameters in the injectors for this scheme.

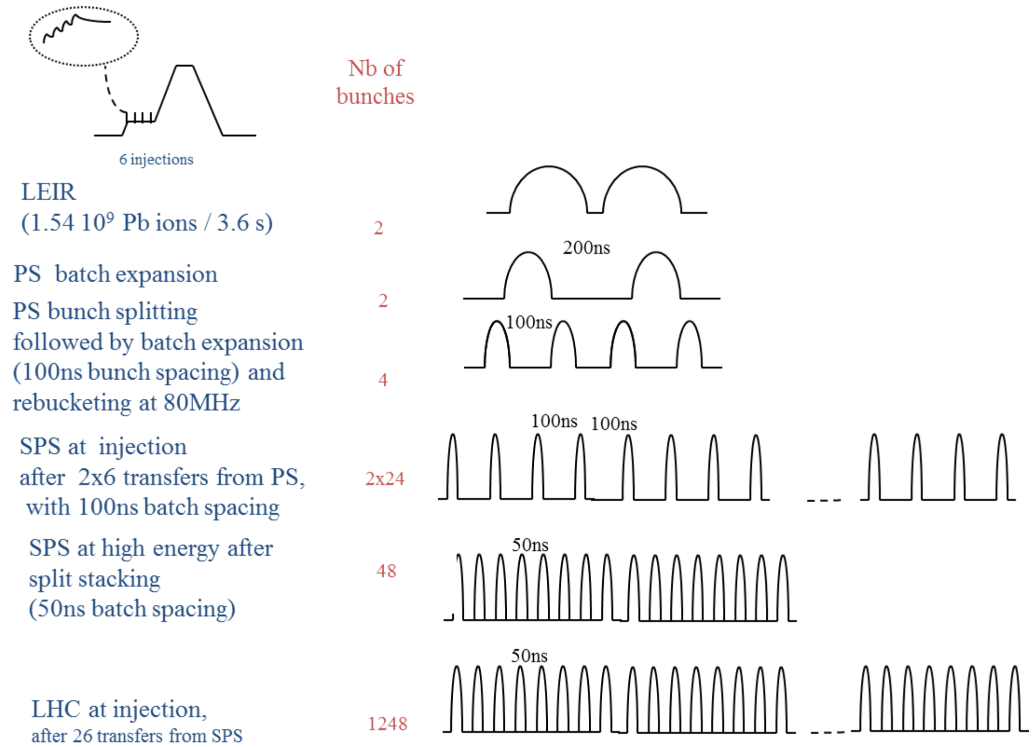

Figure 4: Fully upgraded scheme, with momentum slip stacking in the SPS

Table 3: Tentative beam parameters for the fully upgraded scheme

Parameter	Unit	Linac 3	LEIR	PS	SPS
Pb charge state (1)		29+/54+ (1)	54+	54+/82+ (1)	82+
Output Energy	[GeV/u]	0.0042	0.0722	5.9	176.4
Output Bρ	[T.m]	2.12/1.14 (1)	4.8	86.7/57.1 (1)	1500
Injections into the next machine		6 (or more)	1	6+6	26
Bunches/ring			2	4	48
Extracted intensity/pulse	Ions	$1.3x10^{9}$	$1.6x10^{9}$	$7.2x10^{8}$	$5.2x10^{9}$(3)
Total extracted charge	Charges	$7.2x10^{10}$	$8.6x10^{10}$	$3.9x10^{10}$ / $5.9x10^{10}$ (1)	$4.3x10^{11}$(3)
Ions/bunch at injection	Ions		10^{9} (4)	$8x10^{8}$	$1.8x10^{8}$(2)
Ions/LHC bunch at extraction	Ions		$4x10^{8}$	$1.8x10^{8}$	$1.5x10^{8}$(2) $1.1x10^{8}$(3)
Bunch spacing at extraction	[ns]	N/A	350	100	50
Normalised transverse rms emittance	[μm]	0.25	0.70	1.0	1.2
Longitudinal emittance	[eVs/u]		0.025	0.045	0.24
4σ Bunch length	[ns]		200	3.9	1.8 (5)
2σ Momentum spread		$0.4x10^{-3}$	$1.2x10^{-3}$	$1.1x10^{-3}$	$6.4x10^{-4}$ (5)
Repetition time	[s]	0.1	3.6	3.6	49.2
Space charge ΔQ on flat bottom			0.13 (4)	0.23	0.13 (2)

(1) Stripper stages between Linac3 & LEIR, then between PS & SPS; parameters before/after stripping
(2) Corresponding to the maximum bunch intensity
(3) Average intensity taking into account the distribution of bunch intensities along the train
(4) At the end of the flat bottom, just before acceleration.
(5) Assuming 7.5MV RF voltage.

Expectations for 2015

For the first Pb-Pb run, currently planned for November 2015, batch compression RF gymnastics, already tried and tested in 2012, will be implemented in the PS, bringing the spacing between the two bunches down to 100 ns. Up to twelves such two-bunch batches will be accumulated for every cycle of the SPS, with a batch spacing of 225 ns. After 36 injections from the SPS, assuming once again the same performance (intensity per bunch and transverse emittances) as in February 2013, this scheme delivers up to 432 bunches of 1.6×10^{8} Pb^{82+} ions per LHC ring, corresponding to a peak luminosity at 6.5 ZTeV of $\mathcal{L}_{peak} = 2.8\times10^{27}$ cm^{-2} s^{-1}.

DIFFERENT IONS SPECIES

In the coming years, the ion production complex (Linac3, LEIR, PS, SPS) will need to deliver argon and xenon ions to the North Area for fixed target experiments, mainly NA61/SHINE [16]. The argon beam will be commissioned in the whole injector complex up to the SPS in 2014, with a fixed target run planned for 2015. The experience gained in handling the argon beam will be useful to predict the luminosity of Ar-Ar or p-Ar collisions in the LHC, for which the heavy ion community part of the ATLAS collaboration has already expressed interest [17].

The current planning foresees xenon to be available by 2016 in the SPS for a fixed target run in 2017, but neither Xe-Xe nor p-Xe collisions have been mentioned by any of the LHC experiments so far.

Finally, oxygen is used as a support gas for the production of Pb ions at the level of the source. Switching the source to oxygen production at the beginning or at the end of a Pb-Pb or p-Pb run in the LHC would allow a short O-O or p-O run for forwards physics, as requested by LHC-f [18]. However some commissioning time for the oxygen beam in the injectors would have to be budgeted.

SCHEDULE

Connecting the LINAC4 to the PSB during a 9 month proton stop "LS1.5" in the middle of Run2 could be used for a (maximum) 3.5 month ion run: Pb-Pb collisions in the LHC, primary fixed target Xe ions in the North Area, and machine developments towards high luminosity in the whole injector chain [19]. This would also move xenon out of the way as it would allow a fixed target xenon run during the preceding year, in lieu of the Pb-Pb run in the LHC. However, this solution has been rejected by the heavy ion community in the collider experiments, as their data taking periods have to be regularly spaced, at a rate of one month per year [20].

CONCLUSION

- With the current scheme, the present injector performance would deliver $\mathcal{L}_{peak} = 2.3\times10^{27}$ cm^{-2} s^{-1} at 6.5 ZTeV
- A robust baseline scheme is presented, which ensures bringing the peak Pb-Pb luminosity at 7 ZTeV to $\mathcal{L}_{peak} = 4.0\times10^{27}$ cm^{-2} s^{-1} with feasible upgrades in the injectors, mainly a new ion injection scheme in the SPS.
- Until the SPS injection is upgraded, new RF gymnastics in the PS (demonstrated in 2012) already bring a 22% increase to $\mathcal{L}_{peak} = 2.8\times10^{27}$ cm^{-2} s^{-1} at 6.5 ZTeV for the first LHC run after LS1.
- A promising slip stacking scheme is being investigated, which would bring the performance up to the expectations of the experiments.
- Colliding other ions such as Ar, Xe, or even O, in the LHC can be envisaged but are currently neither scheduled, nor specified.
- The proposal of an extended ion run during the connection of LINAC4 to the PSB in the middle of Run2 has been rejected by the experiments.

ACKNOWLEDGMENTS

This report is a brief summary of the work performed by the whole LIU-ION team. In particular, the author would like to thank Theodoros Argyropoulos, Thomas Bohl, Heiko Damerau, Roland Garoby, John Jowett, Elena Shaposhnikova, and Michaela Schaumann, for their precious help in the preparation of the talk.

REFERENCES

[1] D. Manglunki et al., "The first LHC p-Pb run: performance of the heavy ion production complex", WEPEA061, IPAC'13, Shanghai, China.
[2] LHC design report, Vol I, Chap. 21, "The LHC as a Lead Ion Collider".
[3] The ALICE Collaboration, "Upgrade of the Inner Tracking System Conceptual Design Report", CERN-LHCC-2012-013 (LHCC-P-005), September 2012
[4] D. Manglunki et al., "Plans for the Upgrade of CERN's Heavy Ion Complex", WEPEA060, IPAC'13, Shanghai, China.
[5] J. M. Jowett et al, "Future heavy-ion performance of the LHC", these proceedings
[6] M.Benedikt (ed), "LIU-SPS 50ns Injection review", EDMS 1331860, https://edms.cern.ch/file/1331860/1.0/LIU-SPS_50ns_Injection_review_ExecutiveSummary_22Nov2013.pdf, November 2013,
[7] LHC design report, Vol III, Part 4, Chap. 38, "The LHC Ion Injector Chain: SPS".
[8] B. Goddard et al, "A New Lead Ion Injection System for the CERN SPS with 50 ns Rise Time", MOPFI052, IPAC13, Shanghai, China.

[9] LHC design report, Vol III, Part 4, Chap. 37, "The LHC Ion Injector Chain: PS and transfer line to SPS".
[10] M. Bodendorfer, "Chromaticity in LEIR performance", CERN-ACC-NOTE-2013-0032.
[11] LHC design report, Vol III, Part 4, Chap. 34, "source and Linac3".
[12] D. Küchler, D Manglunki, R. Scrivens, "How to run ions in the future?", these proceedings.
[13] R. Garoby, "RF Gymnastics in a synchrotron", in Handbook of accelerator physics and engineering, World Scientific ed., 1999, pp 286-287.
[14] D. Boussard and Y. Mizumachi, "Production of Beams with High Line-Density by Azimuthal Combination of Bunches in a Synchrotron", CERN-SPS/ARF/79-11
[15] T. Argyropoulos, Th.Bohl, E. Shaposhnikova, private communication.
[16] N. Abgrall et al, "NA61/SHINE facility at the CERN SPS: beams and detector system", CERN-PH-EP-2014-003, January 2014
[17] The ATLAS Collaboration, "Future of the ATLAS heavy ion program", ATL-PHYS-PUB-2012-002, August 16, 2012.
[18] H. Menjo et al., "The results from LHCf: very forward measurements for cosmic ray interactions", 33rd International Cosmic Ray conference, ICRC2013, Rio, Brazil, July 2013, http://www.cbpf.br/~icrc2013/papers/icrc2013-0376.pdf
[19] B. Mikulec et al., "Work effort in the injector complex for the upgrade scenarios", these proceedings.
[20] E. Meschi, B. Gorini, "Heavy ion plans: experiments perspective", these proceedings.

Published by CERN in the Proceedings of RLIUP: Review of LHC and Injector Upgrade Plans, Centre de Convention, Archamps, France, 29–31 October 2013, edited by B. Goddard and F. Zimmermann, CERN–2014–006 (CERN, Geneva, 2014)

HOW TO RUN IONS IN THE FUTURE?

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Abstract

In the light of different running scenarios potential source improvements will be discussed (e.g. one month every year versus two month every other year and impact of the different running options [e.g. an extended ion run] on the source). As the oven refills cause most of the down time the oven design and refilling strategies will be presented. A test stand for off-line developments will be taken into account. Also the implications on the necessary manpower for extended runs will be discussed.

INTRODUCTION

The heavy ions for the CERN heavy ion accelerator chain are delivered from Linac3 (see Figure 1) and the GTS-LHC ion source [1].

Operational conditions

To create the lead beam isotopically enriched ^{208}Pb is used (purity 99.6%). After the separation of the charge states Pb^{29+} is accelerated in the linac, which is converted to Pb^{54+} by the stripper.

The GTS-LHC ion source is an electron cyclotron resonance ion source (ECRIS) [2]. It is running in the so called afterglow mode, using the 14.5 GHz microwave plasma heating with 10 Hz repetition rate, 50 % duty cycle, where at the end of each heating pulse, a burst of approximately 1 ms in length of highly charged ions is emitted from the source. In the linac a pulse length of 200 µs is used, with a repetition rate of up to 5 Hz for LEIR filling.

Present performance

Up to now the following record values have been achieved: 215 eµA of Pb^{27+} after the charge state separation in the spectrometer (FC2) and 31 eµA of Pb^{54+} at the end of the linac (TRA25, with 120-130 eµA of Pb^{29+} in FC3). However, both values were not achieved at the same time, neither is it possible to produce them for long term operation, or even on demand. Maximizing the ion current at the output of the spectrometer very often leads to a poor transmission in the rest of the linac. This issue is part of an ongoing study.

For routine operation 100-120 eµA of Pb^{29+} out of the RFQ (FC3) and 20-25 eµA of Pb^{54+} at the end of the linac (TRA25) are available. The current at the end of the linac corresponds to less than 50 % of the design value.

OPTIONS TO STUDY

To overcome limitations of the machine and to further improve the operation, a number of options have to be studied.

The extraction system of the source may be improved by the re-design of the extraction electrodes. A new design may allow to extract the beam with a lower emittance. Adding an einzel lens directly after the extraction may help to optimize the beam transport. One can also think of a higher extraction voltage. This may allow to extract more beam from the source (if the plasma is not emission limited) and improve the transmission. A higher beam energy would need a new RFQ.

The Low Energy Beam Transport (LEBT), before the separation of a single lead charge state is strongly influenced by space-charge, with the space-charge forces still existing to a lesser extent after the spectrometer. If one could reduce the space charge in this region one may be able to improve the beam quality and to reduce the losses. A possible method would be the control of the creation of compensating electrons with the help of the control of the pressure of the background gas in the line.

The present LEBT is very long, and a new, shorter LEBT adapted to the present source may have a higher transmission.

Before advancing with changes of design of the LEBT, it is necessary to measure the emittance of the beam from the present source, and for this a pepper-pot emittance measurement system is being purchased and integrated into Linac3. Measurements of an argon beam may be possible in 2014, but no lead beam is scheduled until the second half of 2015.

A 10 Hz repetition rate of the linac would help to reduce the filling time of the Low Energy Ion Ring (LEIR). The ion source runs already at 10 Hz and most of the linac elements are designed for 10 Hz. Only some of the power converters in the ITF and the transfer line need an upgrade. All foreseen consolidations of the transfer lines take the 10 Hz operations into account.

At the end of the linac the beam is stripped to Pb^{54+}. This charge state is independent of the charge state in the linac. That's why it may be possible to increase the beam current out of the linac by transporting several charge states (two or three) in the linac before stripping. From the source several charge states around the main one (Pb^{29+}) are available. By cancelling the dispersion of the low energy spectrometer, one could have more than one charge state available for acceleration. Some calculations and very preliminary tests were done to confirm that the RF cavities could accelerate off-charge-state ions. But to

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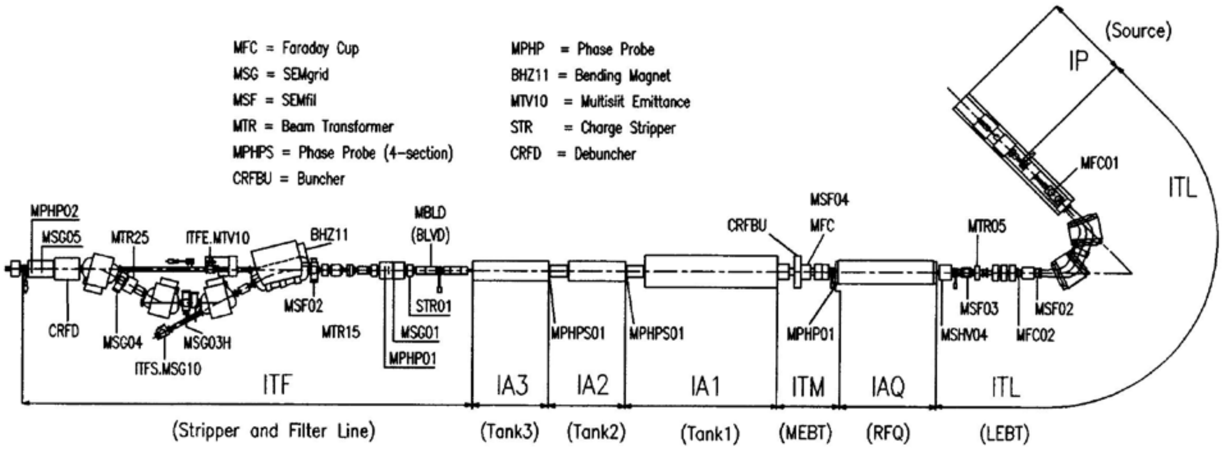

Figure 2: Layout of Linac3.

have sufficient input for a decision a test with the linac and LEIR in an operational state is needed (to verify the intensity and the energy spread), and either a new low energy spectrometer configuration is needed, or the source should be moved to allow a straight line to the RFQ input, while still including diagnostics to allow the tuning of the ion source.

HOW ABOUT A NEW SOURCE?

A new source will probably not solve the present intensity issues, as these issues are more linked to the transport and emittance issues of the beam instead of the intensity delivered from the source.

It could be shown that present 3rd generation ECRIS (with superconducting magnets and frequencies up to 28 GHz) needed more than 10 years to reach the peak performance. Besides, they have often a big emittance and unstable beams [3].

Present electron beam ion sources (EBIS) do not deliver enough current. But for HIE-ISOLDE a study is ongoing to develop a source based on the RHIC EBIS which could deliver the required number of ions per pulse. In addition an EBIS has the advantage to be able to switch in principle pulse to pulse the ion species, for which it requires one or more low charge state ion sources to inject ions into the EBIS for charge-breeding.

In general one has to keep in mind that new developments do not guarantee the success (e.g. the superconducting magnets for the MS-ECRIS never reached the specifications due to technological issues). And superconducting ECRIS sources have significant integration issues, meaning that failures of a single part can require substantial and long repairs. For such a source it would be mandatory to run with two sources in continuous operation mode in order to keep a high availability for LHC.

THE OVEN

Two ovens are available during operation for the evaporation of the solid lead into the plasma. There are around 1.5 g of lead in each oven. The consumption is roughly 2 mg/h, but not all the lead in the sample can be used. The 1st oven is good for around two weeks, the 2nd one only for another week, because it sees some plasma during the first two weeks. But there is a flexibility of some additional days after the three weeks.

Figure 1: Tip of an oven after two weeks of operation.

At the end of the life time usually the tip of the oven is blocked (see Figure 2).

An oven refill takes around 8 h from beam to beam, with the source requiring regular tuning for the next 24 hours. This is down time for the whole lead accelerator chain.

To improve the oven operation several attempts to change the procedures were made. Several filling methods were tested. But only the use of a fresh lead sample in an unused crucible gave some improvements concerning the source stability. All other methods (e.g. molten lead cast into the crucible) even shortened the life time.

In the near future an oven test stand is foreseen to study the oven (temperature distribution, relation between oven power and the evaporation of lead). The result of these studies may help to improve the oven and source tuning to get long term a more stable beam. In addition a redesign of the oven is not excluded, but would require a redesign of the whole source injection side (due to the present constraints).

MANPOWER CONSIDERATIONS

At the moment three experts are able to tune and to operate the Linac3 source, which needs a daily tuning. They also serve as linac supervisors. Four weeks of LHC running can be covered through careful planning, but longer times will need more trained staff (to operate the ion source one needs several years of practical experience!). And one has to keep in mind the higher operation workload as several source parameters with tight limits have to be monitored carefully and request a follow-up.

BIOLEIR

Studies are underway to improve the range of ions available from Linac3, to serve as test beams for a dedicated extraction line from LEIR for irradiation studies. The study looks at allowing fast switching between the ion type required by LHC, and lighter ions for BioLEIR, by using a second source and RFQ. The installation of this equipment into Linac3 will increase the complexity of operation and maintenance of the whole of Linac3, and even if priority is for the ion production for LHC, the integration and operation of the whole system must be assessed carefully.

CONCLUSIONS

A number of ideas to further improve the performance of source and linac are available. A dedicated lead operation period in 2015 is now needed to make tests and verify simulations to proceed with them.

The preparation for an oven test stand should start soon.

In addition a dedicated source test stand is needed (a similar request was refused in Chamonix 2006). Such a test stand can be used to test source modifications offline and to train additional source specialists. Based on a very approximate estimate one can assume that such a test stand would be roughly 5 MCHF. In addition on has to take into account 10 man years for the installation and commissioning of the test stand. To make a proper cost estimate a dedicated study with clear objectives is needed.

REFERENCES

[1] D. Manglunki, M.E. Angoletta, P. Baudrenghien, G. Bellodi, A. Blas, T. Bohl, et al., Ions for LHC: performance of the injector chain, CERN-ATS-2011-050 (2011).

[2] L. Dumas, C.E. Hill, D. Hitz, D. Küchler, C. Mastrostefano, M. O'Neil, et al., Operation of the GTS-LHC Source for the Hadron Injector at CERN, LHC Project Report 985 (2007).

[3] T. Nakagawa, Review of Highly Charged Heavy Ion Beam Production, 15th Intern. Conf. on Ion Sources, Chiba, Japan (2013), to be published in RSI.

Published by CERN in the Proceedings of RLIUP: Review of LHC and Injector Upgrade Plans, Centre de Convention, Archamps, France, 29–31 October 2013, edited by B. Goddard and F. Zimmermann, CERN–2014–006 (CERN, Geneva, 2014)

HEAVY ION OPERATION FROM RUN 2 TO HL-LHC

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Abstract

The nuclear collision programme of the LHC will continue with Pb-Pb and p-Pb collisions in Run 2 and beyond. Extrapolating from the performance at lower energies in Run 1, it is already clear that Run 2 will substantially exceed design performance. Beyond that, future high-luminosity heavy ion operation of LHC depends on a somewhat different set of (more modest) upgrades to the collider and its injectors from p-p. The high-luminosity phase will start sooner, in Run 3, when necessary upgrades to detectors should be completed. It follows that the upgrades for heavy-ion operation need high priority in LS2.

INTRODUCTION

The LHC started colliding beams of lead nuclei, $^{208}\mathrm{Pb}^{82+}$, in 2010 [2], achieving a significant luminosity within a few days of commissioning. The second one-month run in 2011 was even more successful [3] with a luminosity corresponding to twice the design value [4] (taking account of the natural scaling with energy-squared), as summarised in Table 1.

In 2012, a completely new mode of operation with hybrid proton-lead beams [5] was commissioned in a single pilot fill [6, 7], leading to an immediate harvest of unexpected physics results, and a substantial integrated luminosity was delivered in the LHC's third heavy-ion running period in early 2013 [7]. Allowing again for the natural energy-scaling, the peak luminosity reached 3 times the (unofficial)[1] design value [5, 1], within the first week of the 2013 run.

Unfortunately, because of time-pressure during the short runs and a variety of unlucky circumstances on other occasions, there has been little dedicated machine development (MD) time for the heavy-ion programme. Nevertheless, our understanding of the performance limits is now much better than it was before the start of operation. Broadly speaking the nature of the predicted limitations have been confirmed but they set in at higher levels than was expected on the basis of past, conservative, estimates of the energy deposition that might cause superconducting magnets to quench.

FUTURE RUNS AND SPECIES

Within colliding nuclei, with charges Z_1, Z_2 and mass numbers A_1, A_2, in rings with magnetic field set for protons of momentum p_p[2], the colliding nucleon pairs will

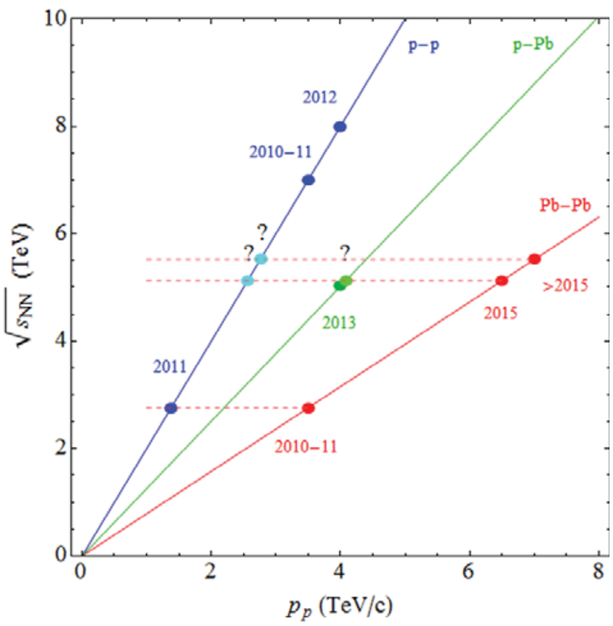

Figure 1: Survey of collision energies (1), and species in past and (some) future LHC runs as a function of the equivalent proton momentum p_p, for p-p, p-Pb and Pb-Pb collisions.

have an average centre-of-mass energy

$$\sqrt{s_{\mathrm{NN}}} \approx 2c\,p_p\sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \approx 2c\,p_p \begin{cases} 1 & \text{p-p} \\ 0.628 & \text{p-Pb} \\ 0.394 & \text{Pb-Pb} \end{cases} \qquad (1)$$

and a central rapidity shift

$$y_{\mathrm{NN}} \approx \frac{1}{2}\log\left(\frac{Z_1 A_2}{A_1 Z_2}\right) \approx \begin{cases} 0 & \text{p-p} \\ 0.465 & \text{p-Pb} \\ 0 & \text{Pb-Pb} \end{cases} . \qquad (2)$$

Figure 1 shows $\sqrt{s_{\mathrm{NN}}}$ according to (1) for past and expected future runs of the LHC. In a typical year the p-p operation will be followed by a month of heavy-ion operation, mainly Pb-Pb interspersed with p-Pb roughly every 3rd year [8].

Generally it will be more efficient to minimise commissioning and optics set-up time by running Pb-Pb or p-Pb at the same equivalent proton momentum, p_p, ie, the same magnetic field, as the preceding p-p run. However the need for comparison data at equivalent $\sqrt{s_{\mathrm{NN}}}$ may require lower energy p-Pb runs or special calibration p-p runs from time to time. Reference data taken in such runs should ideally track the integrated Pb-Pb luminosity [8].

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* Also at RWTH Aachen University, D-52056 Aachen
[1] There is no mention of the p-Pb collision mode in [4]
[2] Conditions imposed by the two-in-one magnet design of the LHC.

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Table 1: Design baseline and peak performance achieved with nuclear collisions, both Pb-Pb and p-Pb, in LHC Run 1. In the case of p-Pb, the projections of the physics case paper [1] are used as a reference.

	Pb-Pb				p-Pb	
	Baseline	Injection 2011	Collision 2011	Injection 2013	physics case paper	2013
Beam Energy [Z GeV]	7000	450	3500	450	7000	4000
No. Ions per bunch [10^8]	0.7	1.24 $\pm$ 0.30	1.20 $\pm$ 0.25	1.67 $\pm$ 0.29	0.7	**1.40 $\pm$ 0.27**
Transv. normalised emittance [μm. rad]	1.5	---	1.7 $\pm$ 0.2	**1.3 $\pm$ 0.2**	1.5	---
RMS bunch length [cm]	7.94	8.1 $\pm$ 1.4	9.8 $\pm$ 0.7	8.9 $\pm$ 0.2	7.94	9.8 $\pm$ 0.1
Peak Luminosity [10^{27} cm^{-2}s^{-1}]	1	---	**0.5**	---	115	110

Collisions of lighter species, such as the $^{40}\mathrm{Ar}^{18+}$ and $^{129}\mathrm{Xe}^{54+}$ that the source will soon produce for fixed-target physics [9], are not considered for the LHC at present. Better estimates of the potential performance can be given once there is some experience with these ions in the injector chain.

RUN 2 PROJECTIONS FOR Pb-Pb

Bunch parameter spreads

As also discussed in [9, 10, 11, 12], there is a considerable spread in Pb bunch parameters, particularly bunch populations, N_b, but also emittances, ε_n, and bunch lengths, σ_z, after injection in the LHC. An example is shown in Figures 2 and 3.

These are due in large part to intra-beam scattering (IBS) as bunch trains are built-up first in the SPS from batches injected from the PS. IBS causes some emittance growth but also losses, mainly longitudinally from the RF bucket. In addition there are effects of RF noise because of the special RF acceleration scheme, involving jumps of the phase, used for heavy ions in the SPS. When these SPS batches are subsequently injected in the LHC, a similar pattern, on a larger scale, is imposed on the entire LHC bunch train as the SPS batches spend different times at the LHC injection energy. Injecting shorter trains in the SPS would allow its cycle length to be reduced so that the earliest injected bunches would suffer less. However the final LHC bunch train would contain more kicker gaps, reducing the total number of bunches and it would take longer to fill the LHC. This leads to the sawtooth pattern seen in Figure 2 when several trains are assembled in the LHC.

These features will be present, but modified quantitatively in future runs. Our estimates of future performance are based on a developing model [12] to provide realistic quantitative predictions for the Pb-Pb luminosity. It works by first fitting data from the 2011 Pb-Pb run [12] to describe the intensity and emittance decay with time spent at injection in both the SPS and LHC. It then predicts the optimum number of PS injections per SPS cycle and can be used to compare different schemes for preparing batches in the PS. A further important ingredient is the minimum spacing of PS batches in the SPS which depends on the proposed upgrade of the injection kicker for ion beams in the SPS.

The initial bunch-by-bunch luminosity in ATLAS, Figure 4, at the start of ”Stable Beams” shows a more pronounced version of the pattern of the bunch intensities in Figure 2. The luminosity at ALICE would show a different pattern as the bunch-pair intensities are less correlated.

Optical and operational conditions

In heavy-ion, as opposed to proton, operation, a low value of β^*, is required at three, rather than two, experiments. The triplet quadrupoles around the ALICE experiment are not being upgraded as are those of ATLAS and CMS and no optical solution for $\beta^* < 0.5\,\mathrm{m}$ is presently available. We therefore envisage heavy-ion operation with $\beta^* = 0.5\,\mathrm{m}$ in IP1, IP2 and IP5 using a conventional LHC optics, ie, without the achromatic telescopic squeeze (ATS) [13]. The ATS optics for p-p operation is being designed to maintain this functionality for Pb-Pb or p-Pb physics. As in 2010 and 2011, the beams will remain separated at LHCb in an unsqueezed optics for Pb-Pb operation.

Generally, this will still allow us to take over most of the ramp and squeeze from the preceding p-p run to expedite commissioning. As usual it will be necessary to implement an additional squeeze and crossing angle set-up for ALICE [4, 14].

We assume the usual run length of about one month each year and present expectations are that 2015 and 2016 will be devoted to Pb-Pb with a p-Pb run (including LHCb) in 2017 and, most likely, Pb-Pb again in 2018, before LS2.

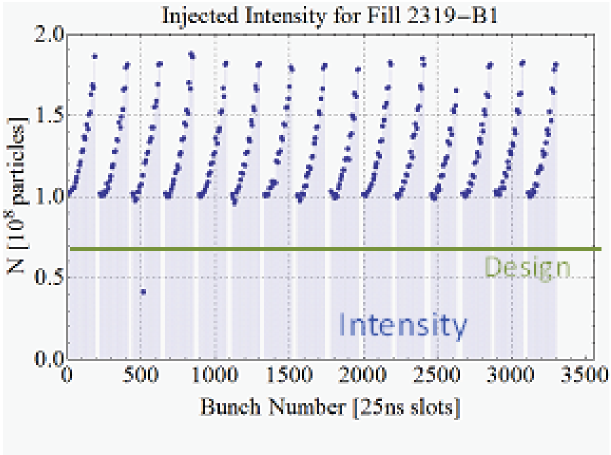

Figure 2: Injected intensity, bunch-by-bunch, along the complete LHC bunch train, composed of several SPS trains, in a typical LHC Pb-Pb fill in 2011.

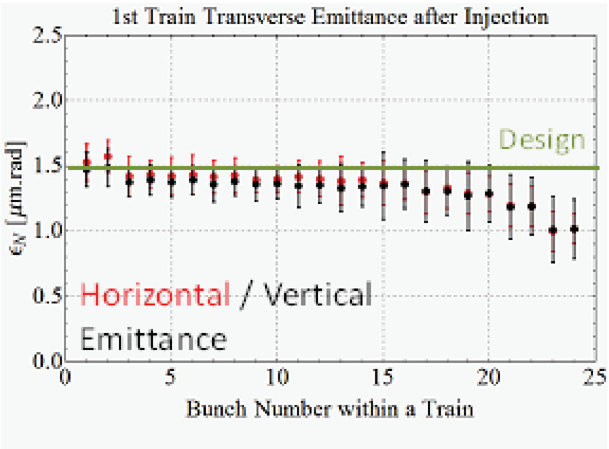

Figure 3: Injected emittance, bunch-by-bunch, from the wire-scanner, along a single SPS train in the LHC, averaged over the first injection in several LHC Pb-Pb fill in 2011.

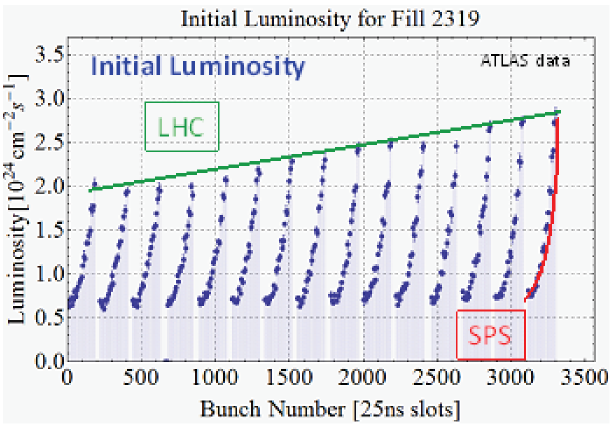

Figure 4: Initial bunch-pair luminosity at ATLAS, over a full revolution period, in a typical LHC Pb-Pb fill in 2011. The red and green curves indicate the dependences used in the predictive luminosity model, to be explained later.

Predictive luminosity model

In the following, the time evolution of colliding bunches during Stable Beams is simulated with the Collider Time Evolution (CTE) program [15, 16, 12]) which includes effects of:

1. Emittance growth and debunching from IBS (much stronger for heavy ions than for protons [4, 17, 15, 16]) including the non-gaussian longitudinal distribution.

2. Radiation damping (twice as strong for heavy ions as for protons [4, 17]),

3. Luminosity burn-off (much stronger for heavy ions than for protons because of the large electromagnetic cross-sections [18, 17, 15]).

The spectrum of initial bunch intensities and emittances implies a spectrum of luminosity lifetimes and bunch-pair luminosities which must be summed to yield realistic integrated luminosity estimates.

The initial distribution over the bunch train is given by a phenomenological model based on ATLAS luminosity data from 2011, as shown in Figure 4. The evolution of three typical bunch-pairs, from the head, middle and tail of an SPS train, representing the range of possibilities, according to CTE, is shown in Figure 5. Since the variations are smooth, we use interpolations between such cases to reduce the number of simulations runs necessary.

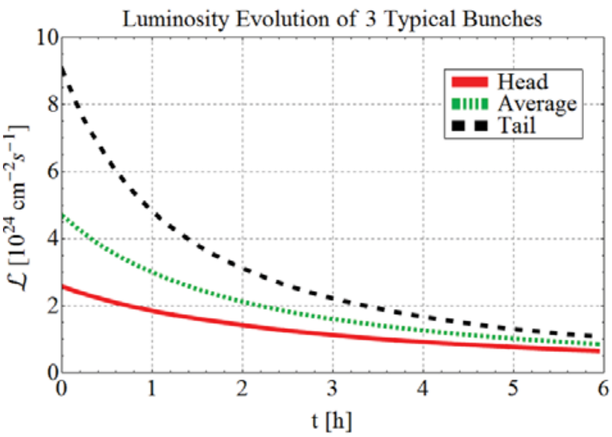

Figure 5: Evolution of the luminosity of three typical bunches, from the head, middle and tail of an SPS batch colliding in the LHC, simulated with the CTE program.

Modelling of the effects in the SPS are based on the distribution within the last train injected into the LHC (red curve in Figure 4) because this train is subject to little degradation as it spends the least time on the LHC injection plateau. Thus we obtain the cleanest picture of the impact on the luminosity from the variable time spent by PS batches at the SPS injection energy.

Table 2: Measured bunch intensities and scaling to future performance. Intensity scaling factor for best transmission means: 29% from LEIR to LHC injection, 96% from LHC injection to Stable Beams, 27% from LEIR to LHC Stable Beams. The F_{N_b} factors in the last row are taken for the cases labelled "2013 performance" and "+40%" in the following.

	2011	2013	+40% out of LEIR
LEIR pulse intensity [ions]	9×10^8	11×10^8	15.4×10^8
Number of bunches per batch	2	2	4
Intensity per future LHC bunch [ions]	4.5×10^8	5.5×10^8	3.9×10^8
Injected intensity per bunch into LHC [ions]	1.24×10^8 (27%)	1.6×10^8 (29%)	1.1×10^8 (29%)
Intensity in Stable Beams [ions]	1.2×10^8 (96%)	1.4×10^8 (87%)	1.0×10^8 (96%)
Transmission LEIR → LHC SB	26%	25%	27%
Intensity scaling factor for best transmission	1	1.28	0.88

To model the effects of the LHC injection (some bunches may spend over 30 min there), ramp and set-up for physics, we group bunches of equivalent PS batches from all trains, which saw the same SPS injection plateau length (green curve in Figure 4),

Both effects are well described by a fit to a similar functional form, resulting in an expression for the *square-root of the individual bunch-pair luminosity*:

$$\sqrt{L_{bb}} = F_{N_b} F_{\text{norm}} \left(a e^{-b t_{SPS}} + c\right) \times \left(A e^{-B t_{LHC}} + C\right) \quad (3)$$

where t_{SPS} is the time the bunch spent at injection in the SPS, related to the index of the bunch within the bunch train assembled in the SPS and t_{LHC} is a similar quantity related to the index of the SPS train to which it belongs within the full train assembled in the LHC. These correspond to the dependences shown in red and green in Figure 4. The other parameters within the parentheses come from the fits to 2011 data; F_{norm} is a normalisation factor and F_{N_b} is used to rescale the overall intensity according to expectations for future improvements as outlined in Table 2.

The model only takes variations due to the SPS and LHC into account; the ion source, LEIR and PS are assumed to have cycles similar to 2011.

The slides of this talk and future publications provide further details of this predictive luminosity model, including the benchmarking to reproduce the performance in 2011.

Operating energy in Run 2

Our Run 2 performance projections are for

$$E_b = 6.5Z\,\text{TeV} \Rightarrow \sqrt{s_{\text{NN}}} = 5.1\,\text{TeV}$$

Some interest has been expressed in reducing the energy to obtain the same s_{NN} as in the 2013 p-Pb run, ie,

$$\sqrt{s_{\text{NN}}} = 5\,\text{TeV} \Rightarrow E_b = 6.3Z\,\text{TeV}$$

Reducing the maximum field in the LHC magnetic cycle after p-p operation is estimated to cost an additional 1–2 days commissioning time. In any case, there will be the usual modified squeeze to implement.

Run 2—2011 Scheme, scaled N_b

Table 3: Injection scheme as in 2011 for Run 2 parameters.

2011 Filling Scheme	@ E = 6.5Z TeV β^*= 0.5m F_{Nb} = 1.28
Spacing PS [ns]	200
Spacing SPS [ns]	200
No. bunches/PS batch	2
No. PS batches/train	12
No. LHC trains	15
No. bunches/beam	358

With this model, a baseline configuration for Run 2 in 2015 could be to use the 2011 filling scheme, according to Table 3, but rescale the intensities to those achieved in the p-Pb run in 2013 [9] . Given that there were new, specific, sources of losses in the ramp and squeeze in the p-Pb run, it is reasonable to assume that the transmission of bunch intensities from injection to Stable Beams would be similar to 2011. On this basis we get the performance indicated in Figure 6 which sums to a maximum peak luminosity in ATLAS or CMS of

$$\hat{L} \simeq 2.8 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}. \quad (4)$$

Run 2—100 ns Batch Compression

For Run 2, an alternative also discussed in [9] is to use batch compression to reduce the spacing between pairs of

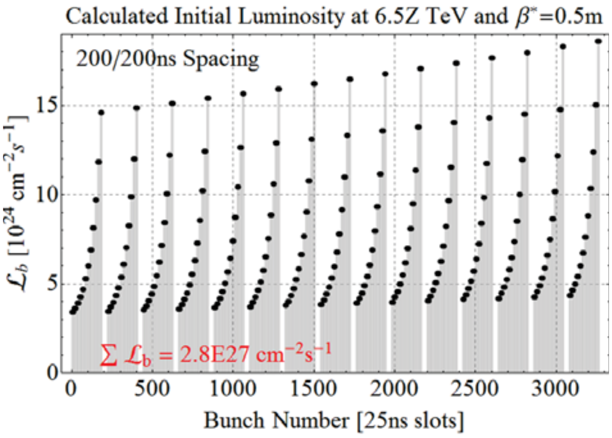

Figure 6: Bunch-pair luminosities in Run 2, with the 2011 filling scheme, 2013 bunch intensity performance and a transmission of intensity from injection to Stable Beams similar to 2011.

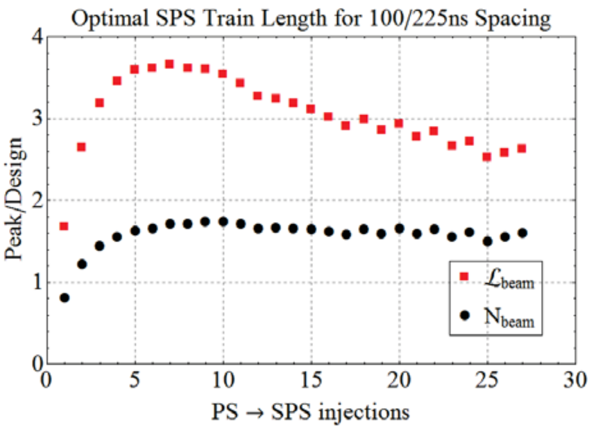

Figure 7: Optimisation of the number of PS batches injected to form a train in the SPS in the Run 2 100/225 ns injection scheme.

bunches in the PS to 100 ns. Several such batches can be injected with a spacing of 225 ns (set by the present SPS injection kicker) to form a train in the SPS.

The model takes into account that: not more than 40% of the SPS circumference should be filled; there should be 900 ns LHC kicker gaps and a 3.3 μs abort gap in the LHC train although final details of the filling scheme are not yet implemented.

Longer SPS trains will allow a larger total number of bunches in the LHC but will be subject to worse degradation on the SPS injection plateau. Figure 7 shows that the optimum number of PS injections for either total stored beam current or peak luminosity in the LHC are similar. Choices which should therefore provide the maximum integrated luminosity are summarised in Table 4.

Table 4: Optimum filling scheme for peak or integrated luminosity with the 100 ns batch compression scheme in Run 2.

Batch Compression	**@ E = 6.5Z TeV** **β^*= 0.5m** **F_{Nb} = 1.28**
Spacing PS [ns]	100
Spacing SPS [ns]	225
No. bunches/PS batch	2
No. PS batches/train	7 / 9
No. LHC trains	29 / 24
No. bunches/beam	406 / 432

Summing over bunch pairs, as before, the peak luminosity turns out to be

$$\hat{L} \simeq 3.7 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}. \quad (5)$$

The optimisaion gives a 30% improvement over the $3.3 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$ that would be obtained with a 2011-like scheme.

Levelling in Run 2

Before the upgrade of the ALICE detector in LS2, its Pb-Pb luminosity must be levelled at the original design value $\hat{L} = 1. \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$. On the other hand, ATLAS and CMS can accept the higher luminosity that will be available according to the analysis above.

Since the luminosity decay is dominated by burn-off, operation is largely a conversion of stored beam particles to phyics events. The higher luminosity experiments consume the beam more rapidly, reducing the luminosity very quickly and reducing the time that ALICE can run at the levelled value. The question arises whether ATLAS and CMS should be levelled also?

Figure 8 compares 3 possibilities:

1. Levelling only in ALICE to $1 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$ (red curves),
2. Levelling all experiments to $1 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$ (green curves),
3. Levelling ALICE to $1 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$, ATLAS and CMS to $2 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$ (black dashed curves).

The parameters used correspond to *average bunches* in Run 2. Note that some of the initial very high luminosity is likely to be lost anyway during collision set-up time (typical 10–15 min).

From these examples, we conclude that some level of levelling for all experiments is desirable. This provides a foretaste of future high luminosity p-p operation. If we consider that a typical fill will last about 6 hours, the intermediate levelling scenario (3) looks very equitable for all the experiments. In such a fill, ALICE could expect about 20 $\mu\mathrm{b}^{-1}$, only slightly less than in scenario (2), while

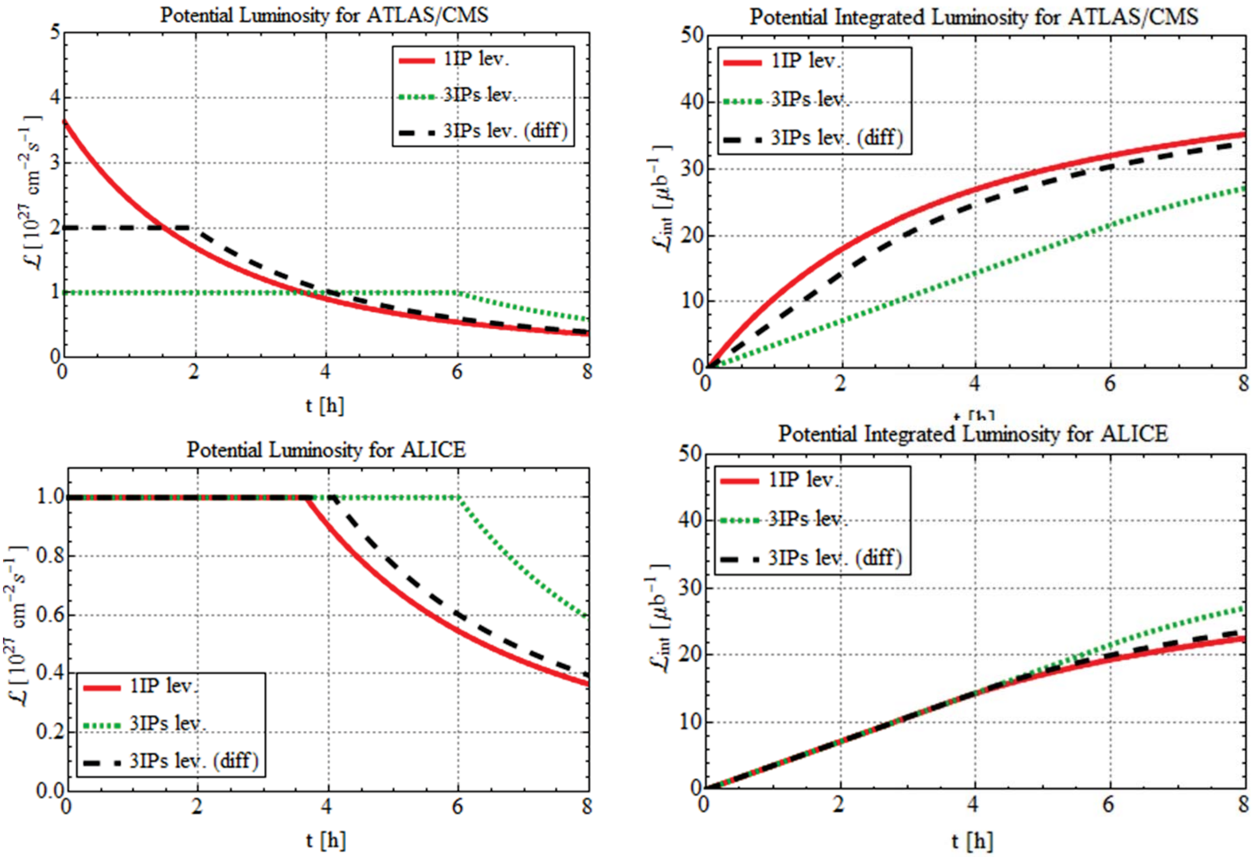

Figure 8: Analytical calculations to compare 3 levelling scenarios for Run 2, as described in the text. The plots in the top row show the instantaneous and integrated luminosity for the ATLAS and CMS experiments. The bottom row shows the same information for ALICE.

ATLAS and CMS could expect 30 μb^{-1}, only slightly less than in scenario (1).

Experience in the 2013 p-Pb run was similar because of initial minimum-bias operation of ALICE. There, the solution was to make two catch-up fills with beam separated in ATLAS and CMS. Clearly this remains an option available to the LHC physics coordination during Pb-Pb runs in Run 2. The optimum length of a fill also depends on real turn-around times.

Levelling can be done by the now-routine separation method (or, possibly, by variation of β^* during physics.)

RUN 3 AND BEYOND, Pb-Pb

In Run 3, the main strategy for increasing the luminosity will be to increase the total number of Pb nuclei stored in the LHC.

As also discussed in [9], this can be done by reducing bunch spacing within PS batches and/or decreasing the SPS kicker rise time to reduce the batch spacing in the SPS. These methods increase the number of bunches. There are also prospects to increase the bunch intensity out of LEIR by 40% and perform bunch splitting in the PS and to use slip-stacking in the SPS. Table 5 summarises the main possibilities remaining after recent discussions.

Table 5: The main candidate injection schemes for Pb-Pb in Run 3.

PS Spacing [ns]	SPS Spacing [ns]	No. Bunches/PS Batch	Present with batch
50 or 100	225	**2 (unsplit)** or 4 (split)	compression (100ns)
50 or **100**	**100**	**2** or 4	1. **Baseline** 2. **Batch compression** (50ns) with split bunches
50 or 100	75	2 or 4	
50 or 100	50	2 or **4**	1. **Slip stacking** with split bunches

Run 3—100/100 ns Baseline Scheme

The baseline scheme currently agreed with the LIU project, has the injection scheme parameters shown in Table 6 with the SPS injection kicker upgrade to a rise time of 100 ns. The choice of the number of PS batches per SPS train is based on optimisation shown in Figure 9.

Applying the luminosity model, with the assumption of 2013 transmission from injection to Stable Beams, gives

Table 6: Injection scheme parameters in the Run 3 100/100 ns baseline injection scheme.

100/100ns Scheme PS Bunch Splitting	E = 7Z TeV, β^* = 0.5 m, F_{Nb} = 1.28
Spacing PS [ns]	100
Spacing SPS [ns]	100
No. bunches/PS batch	2
No. PS batches/train	8
No. LHC trains	36
No. bunches/beam	576

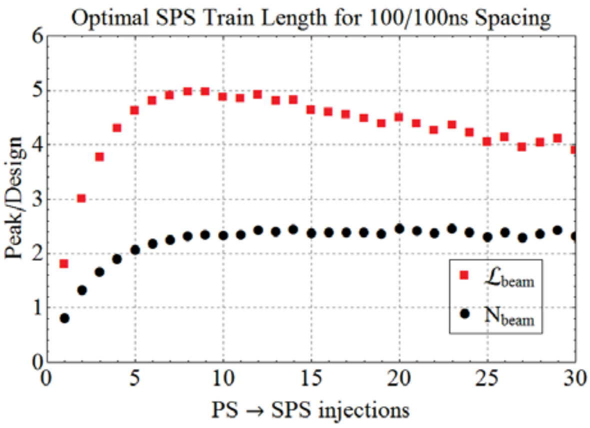

Figure 9: Optimisation of the number of PS batches injected to form a train in the SPS in the Run 3 100/100 ns baseline injection scheme.

the peak luminosity: $\hat{L} = 4 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ while the higher transmission that one can reasonably expect, as in 2011, yields

$$\hat{L} = 5 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}. \tag{6}$$

In the latter case, the bunch pair luminosity spectrum is as shown in Figure 10.

Run 3—other filling schemes

In this section we compare range of possible injection schemes, some no longer under consideration, to illustrate the potential for further improvement beyond the present "baseline" scheme presented in the previous subsection. Peak and integrated luminosities for various injections schemes are shown in Figures 11 and 12. Note that the upgrade to the SPS injection kicker, recently agreed upon [9], will provide a rise time of 100 ns so the shorter rise times are unlikely to be accessible and are shown here only for completeness.

We note that the peak luminosity will be higher for the 100 ns spacing in the PS with unsplit bunches. On the other hand, the higher brightness bunches decay faster so the effect on integrated luminosity is less. The luminosity decay curves for typical bunch pairs are shown in Figure 13. With these assumptions, it turns out that a somewhat higher integrated luminosity is obtained for the 50 ns PS spacing with

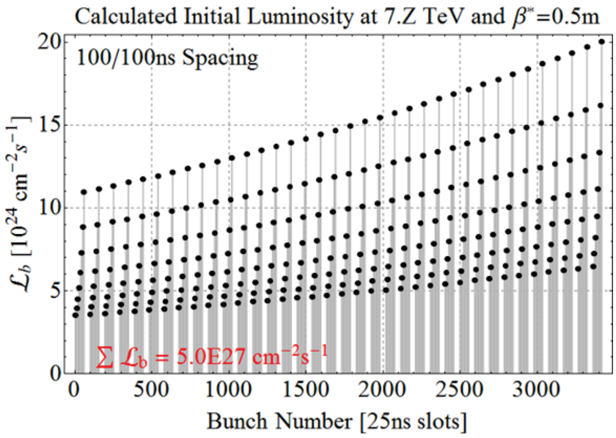

Figure 10: Initial bunch pair luminosities at ATLAS or CMS in the Run 3 100/100 ns baseline injection scheme.

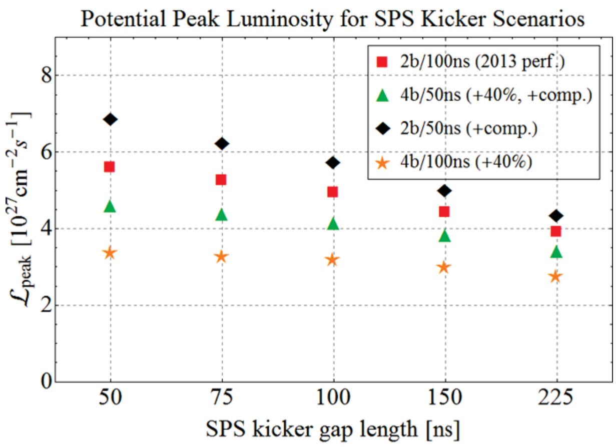

Figure 11: Peak luminosity versus SPS kicker rise time for various forms of PS batch, with and without the assumption of a 40% increase in single-bunch intensity.

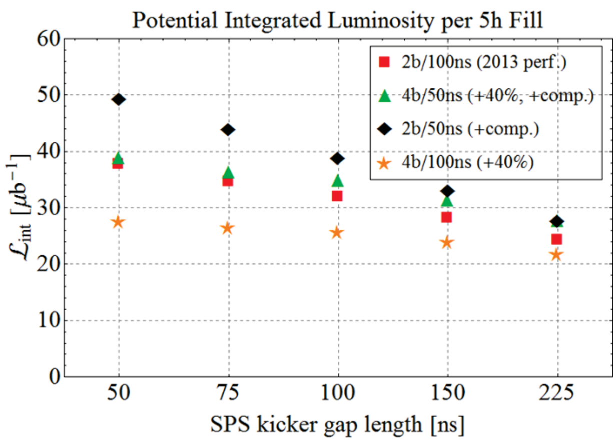

Figure 12: Integrated luminosity versus SPS kicker rise time for various forms of PS batch, with and without the assumption of a 40% increase in single-bunch intensity. Note that the red and green points for 100 ns have switched places between these two figures.

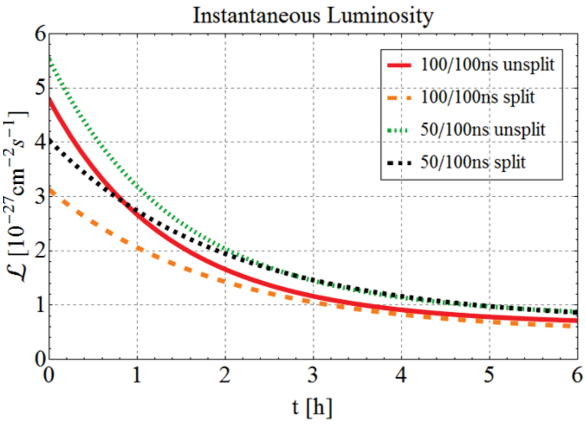

Figure 13: Luminosity decay in Run 3 for injection schemes with and without bunch-splitting in the PS.

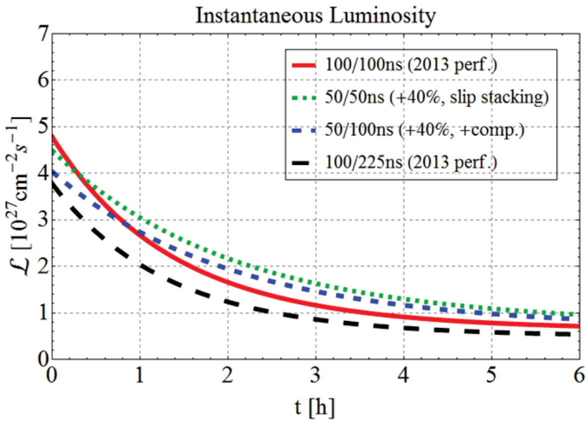

Figure 14: Luminosity decay for Pb-Pb in Run 3 estimated for the main upgrade injection schemes.

Table 7: Summary of performance of possible injection schemes in Run 3, including what is presently available.

Injection scheme	L_{int} after 3h [μb^{-1}]	L_{int} after 5h [μb^{-1}]	L_{int} in run with 30×5h	
100/225ns	19	25	0.8 nb^{-1}	Present
100/100ns	25	32	1.0 nb^{-1}	Baseline
50/50ns	29	39	1.2 nb^{-1}	Slip Stacking
50/100ns	26	35	1.1 nb^{-1}	Batch compression

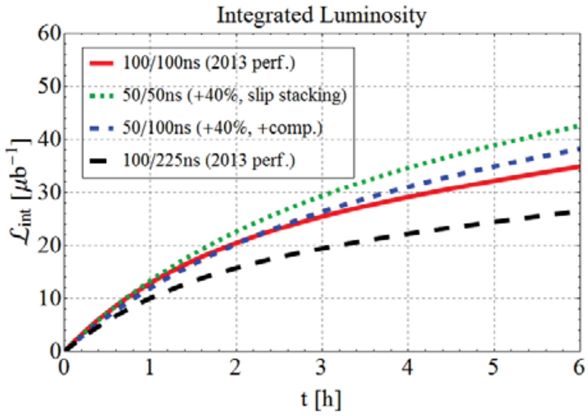

Figure 15: Integrated luminosity for Pb-Pb in Run 3 estimated for the main upgrade injection schemes.

split bunches, which gives $k_b \simeq 1000$ to compare with the $k_b \simeq 600$ without bunch-splitting. However, at present, it appears that the 50 ns spacing is unlikely to be available for the reasons given in [9].

Luminosity Evolution, Main Upgrade Scenarios

As discussed in [9], there are reasonable prospects for a 40% increase in bunch intensity and for a slip-stacking scheme which could allow a 50 ns bunch spacing in the trains assembled in the SPS.

Taking into account different initial bunch luminosities and bunch luminosity decay times that one can expect in these schemes, the evolution of the instantaneous and integrated luminosities are shown in Figures 14 and 15. A summary of the expected integrated luminosity in individual fills and over a typical one-month run is given in Table 7.

Pb-Pb LUMINOSITY SUMMARY

The projections discussed in the preceding sections are summarised in Table 8. These predictions are somewhat conservative in that they do not include any improvements beyond the injection schemes, including intensity scaling, and the natural reduction of $\beta^* = 0.5\,\mathrm{m}$ and beam size that are to be expected from the increase of energy to $7Z\,\mathrm{TeV}$.

The predictive luminosity model should be re-fitted to the real injector chain performance in the run-up to a given Pb-Pb run to re-optimise the length of the SPS trains. Some further remarks on the uncertainties in these estimates are in order:

- Any reductions of beam losses on the SPS flat bottom that can be achieved will have a big impact on the total luminosity.
- If peak luminosity limits (eg, the BFPP losses in ATLAS and CMS) are encountered, the initial luminosity may have to be levelled.
- Integrated luminosity estimates for a 24 day run are always very sensitive to a few days down-time of any essential system. So far we have been fairly lucky.
- No time has been deducted for possible p-p reference data runs.
- A 200 MHz RF system in LHC is in principle very beneficial for heavy ions (reduced IBS, better injection capture, ...) although theses benefits would need to be weighed against the disruption of replacing the base harmonic RF system.

Table 8: Summary of performance of possible injection schemes in Run 2, including what is presently available, and in Run 3.

Scenario	L_{peak} [Hz/mb]	L_{int} after 3h [μb^{-1}]	L_{int} after 5h [μb^{-1}]	L_{int} in run with 30×5h	L_{int} In run, "Hübner Factor"	
200/200ns	2	15	21	0.64 nb^{-1}	0.64nb^{-1}	2011 @ 7Z TeV
100/225ns	3.7	19	25	0.8 nb^{-1}	1.2 nb^{-1}	Run 2
100/100ns	5.0	25	32	1.0 nb^{-1}	1.6 nb^{-1}	**Baseline**
50/50ns	4.6	29	39	1.2 nb^{-1}	1.5 nb^{-1}	Slip Stacking
50/100ns	4.1	26	35	1.1 nb^{-1}	1.3 nb^{-1}	Batch Compression

- Greater operational efficiency than in 2011 would help, obviously.

RUN 2 PROJECTIONS FOR p-Pb

Although it had to work in a mode that was almost unprecedented at previous colliders, the LHC performed remarkably well as a p-Pb collider for a single fill in 2012 [6] and then for a one month run in 2013 [7, 19, 20, 21]. Before considering future proton-nucleus operation it is worth recalling a few of the special features of this run which, it is fair to say, was of unprecedented complexity in the history of hadron colliders.

Reminder of 2013 p-Pb run

Operating experience at all previous colliders is often said to have taught us that gradual optimisation of constant operating conditions is the path to high luminosity. In this run, the LHC experiments[3] asked us, on the contrary, to change operating conditions every few days. The most significant of these was the reversal of beam directions, from p-Pb to Pb-p, about half-way through the run which meant reversing not only the RF frequencies of the two rings during injection and ramp but also the off-momentum chromatic corrections applied to the optics during the squeeze after the re-locking of the RF frequencies. Figures 16 and 17 provide an overview of the luminosity production during these two phases. In addition, there were fairly complex luminosity levelling requirements at different times and reversals of the ALICE and LHCb spectrometer fields. Nevertheless we fulfilled all requests, thanks to the quality of the LHC hardware, software and operation, meticulous planning and some judicious risk-taking (with performance).

So, in our opinion, with the LHC, there is no *a priori* reason to fear complicated physics requests and we can indeed, with due care, flout the conventional wisdom of incremental improvement to constant operating conditions.

[3] ALICE, in particular

Bunch intensity in p-Pb operation

The p-Pb operation in 2012 and 2013 was constrained by the behaviour of the beam position monitors (BPMs).

On the one hand, fills were almost always dumped somewhat prematurely by some Pb bunch going below an intensity threshold. To avoid this in future, the monitors of the IR6 interlock BPMSs are being replaced by matched terminated striplines so that the high attenuation (used to reduce reflections in p beams in 2013 run) will not be needed. This will require tests with beams but low intensity Pb-bunches should no longer trigger the beam dump.

On the other hand, the maximum proton bunch intensity achieved in 2013 was $N_b \simeq 1.8 \times 10^{10}\,\mathrm{p/bunch}$. A test with $3 \times 10^{10}\,\mathrm{p/bunch}$ showed misreadings of a few BPMs whose source is still under investigation. If manageable (perhaps by the change of a few cards, or recalibration), we could go up to $5 \times 10^{10}\,\mathrm{p/bunch}$, the limit of the high sensitivity range of the BPMs [22]. Again tests with beams are most probably required to clarify the observation. In this case it is not obvious that the situation can be improved.

The total integrated luminosity per fill, summed over all experiments,

$$\sum_{\mathrm{experiments}} \int_{\mathrm{fill}} L_{AA}\, dt \leq \frac{\sum_c N_{\mathrm{Pb}}}{\sigma_t} \qquad (7)$$

is bounded by the total intensity of the colliding Pb bunches and the total cross-section σ_t, and is independent of the proton intensity[4]. Higher proton bunch intensities will not increase the integrated luminosity per fill but will simply allow it to be delivered in a shorter time. This may not be useful in the 2017 run where the peak luminosity in ALICE should be levelled.

Given the turn-around time to refill the LHC beams, it follows that *the priority for improvements in BPM behaviour should be to avoid dumps due to low intensities of individual Pb bunches.* This will allow the left-hand member of the inequality (7) to approach equality with the right.

[4] To an excellent approximation

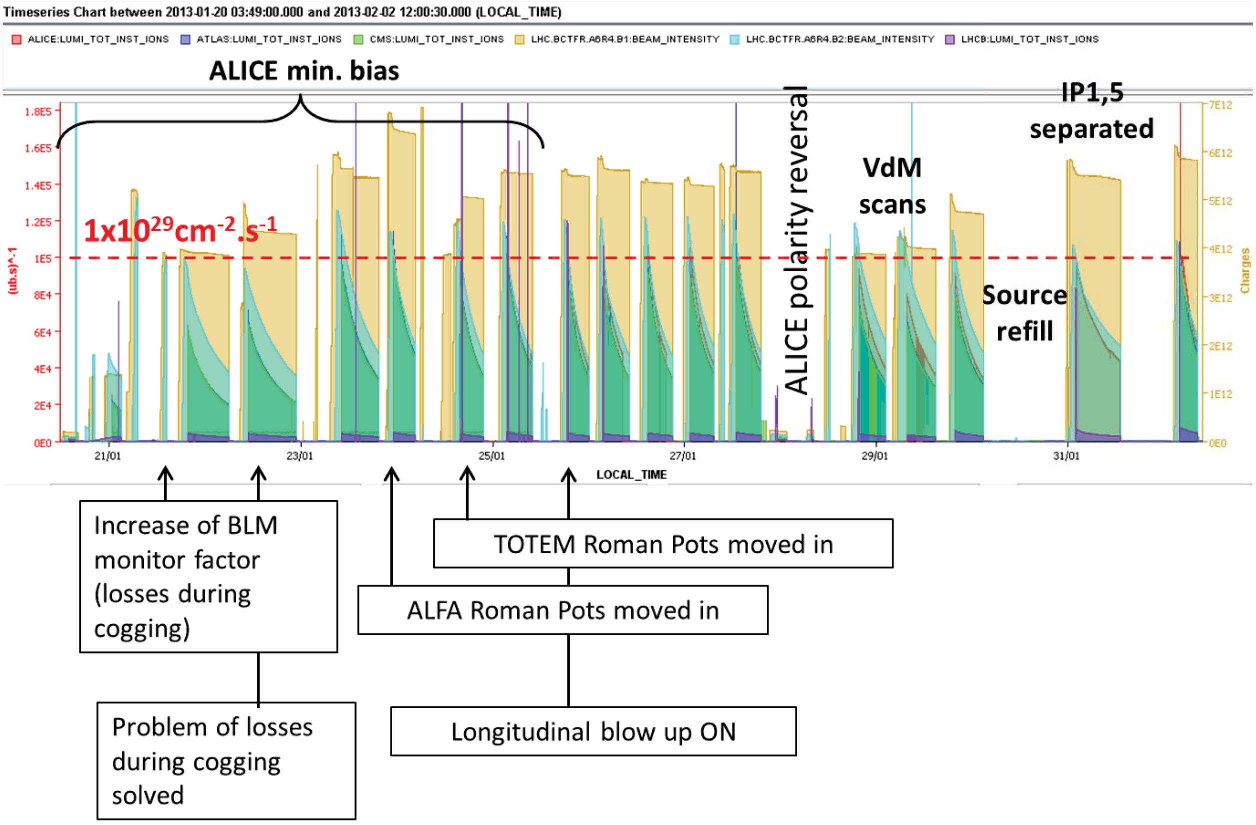

Figure 16: Overview of beam intensity and p-Pb luminosity production in 2013.

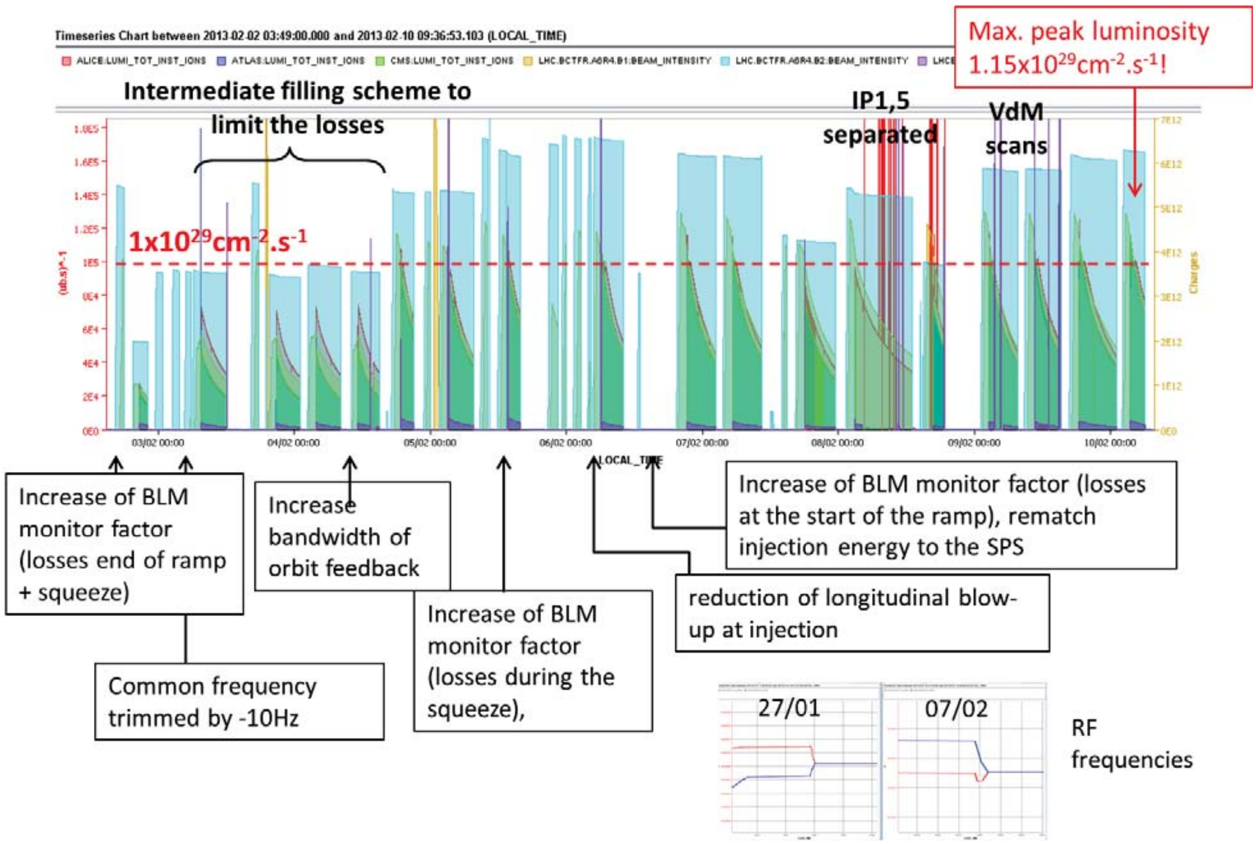

Figure 17: Overview of beam intensity and Pb-p luminosity production in 2013.

In the 2013 run, the difference was about a factor of 2 in most fills.

Performance for p-Pb in Run 2 and beyond

Table 9: Potential p-Pb parameters in Run 2.

E (Z GeV/c)	4	7
γ_p	4264	7463
N_p (10^{10} p/bunch)	1.8–5?	1.8–5?
N_{Pb} (10^8 Pb/bunch)	1.6	1.6
k_b	430	430
β^* (m)	0.5	0.5
$\varepsilon_{n,p}$ (μm.rad)	3.5	3.5
$\varepsilon_{n,Pb}$ (μm.rad)	1.5	1.5
f (kHz)	11.245	11.245
$L_{\rm peak}$ (10^{29} cm^{-2}.s^{-1})	2.5–7?	4.3–12
$L_{\rm int}$ (nb^{-1})	60 (up to 110?)	110 (up to 220?)

Tentative parameters for the next p-Pb run (probably in 2017) are given in Table 9 with some indication of the effect of raising the proton intensity. In any case, this may be constrained by stability of the Pb beam (moving long range encounters) and 5×10^{10} p/bunch is the maximum reachable proton intensity in any case because of the BPM limits. The number of bunches per beam is taken from the baseline scenario for a Pb-Pb run in 2015-2016. The integrated luminosity estimates assume the same integrated to peak luminosity ratio as in 2013. In any case, as in 2013, ALICE will level at $1\times10^{28}\,{\rm cm^{-2}s^{-1}}$ (for some minimum-bias operation) and then at $1 \times 10^{29}\,{\rm cm^{-2}s^{-1}}$ in Run 2.

Considering the choice between the two possible energies given in Table 9, it should be remembered that a run at the same proton energy as the preceding p-p physics will be more efficient in several ways (less setup time, smaller momentum shifts, ...) than a run at reduced energy. Setting up a run at reduced energy would further complicate these hybrid colllision runs with their many changes of configuration and higher risk. Detailed plans for this run will also attempt to increase the luminosity delivered to LHCb.

Further increases of p-Pb luminosity in Run 3 and beyond will depend mainly on being able to inject higher total Pb intensity with more bunches but other limits (eg BFPP losses from the Pb beam) may come into play.

PEAK LUMINOSITY LIMITS

As has been discussed extensively elsewhere, see for example [18, 23, 24, 25, 26, 17, 27, 28, 29, 30], the intense electromagnetic fields accompanying the colliding nuclei can cause a number of interactions which make small changes to their mass, m or charge, Q. Each of these makes a secondary beam emerging from the IP with a fractional rigidity change

$$\delta = \frac{1+\Delta m/m}{1+\Delta Q/Q} - 1 \tag{8}$$

In the case of the Pb-Pb collisions in the LHC, these include, with the highest cross-section, the first-order bound-free pair production (BFPP1):

$$^{208}{\rm Pb}^{82+} + {}^{208}{\rm Pb}^{82+} \to {}^{208}{\rm Pb}^{82+} + {}^{208}{\rm Pb}^{81+} + {\rm e}^+ \tag{9}$$

with

$$\sigma = 281\,{\rm b}, \delta = 0.01235. \tag{10}$$

The double bound-free pair production process (BFPP2):

$$^{208}{\rm Pb}^{82+} + {}^{208}{\rm Pb}^{82+} \to {}^{208}{\rm Pb}^{82+} + {}^{208}{\rm Pb}^{80+} + 2{\rm e}^+ \tag{11}$$

may also be detectable despite its much lower cross-section [31]

$$\sigma \approx 6\,{\rm mb}, \delta = 0.02500. \tag{12}$$

More significant processes are electromagnetic dissociation with emission of a single neutron (EMD1):

$$^{208}{\rm Pb}^{82+} + {}^{208}{\rm Pb}^{82+} \to {}^{208}{\rm Pb}^{82+} + {}^{207}{\rm Pb}^{82+} + {\rm n} \tag{13}$$

with

$$\sigma = 96\,{\rm b}, \delta = -0.00485 \tag{14}$$

or two neutrons (EMD2):

$$^{208}{\rm Pb}^{82+} + {}^{208}{\rm Pb}^{82+} \to {}^{208}{\rm Pb}^{82+} + {}^{206}{\rm Pb}^{82+} + 2{\rm n} \tag{15}$$

with

$$\sigma = 29\,{\rm b}, \delta = -0.00970. \tag{16}$$

The cross-sections for some of these processes are much larger than those of the hadronic interactions, $\sigma = 8$b, that occur when the nuclei overlap; these contain much less power in their debris[5].

For the LHC, the consequences of BFPP1, in particular have been discussed since [24, 25] and in most detail in [32]: the secondary beams hit the beam pipe in the dispersion suppressor, depositing enough power to potentially quench a superconducting dipole magnet, as illustrated for ALICE in Figure 18. Note that the BFPP1 beam is smaller than main beam because its source is the luminous region, not the Beam 1 distribution.

The losses corresponding to these effects were clearly detected in the 2010 and 2011 Pb-Pb operation. Figure 19 shows beam-loss monitor signals clearly peaking at the predicted location of the BFPP1 loss.

Further evidence of the direct correlation of these signals with luminosity while the luminosity decayed during a regular physics fill and during the van der Meer scans, when the luminosity was deliberately varied, are shown in Figures 20 and 21.

[5] For completeness, we should mention the double BFPP process where both nuclei gain an electron and the analogous double EMD process. For present purposes, without coincidence measurements, they are practically indistinguishable from BFPP1 and EMD1

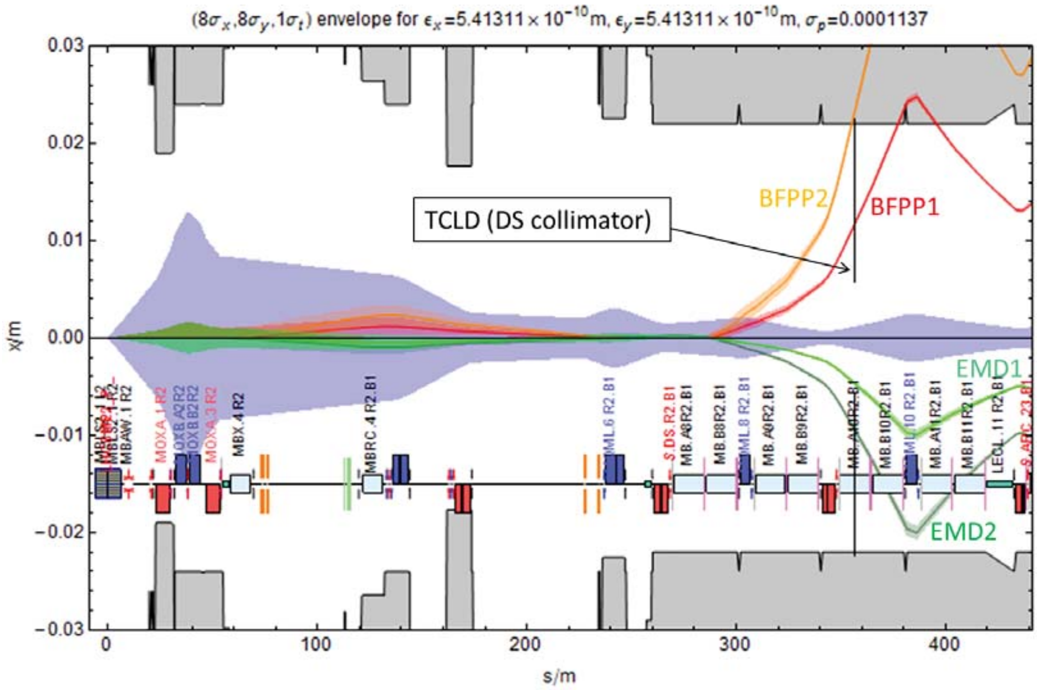

Figure 18: Horizontal projection of the secondary beams on the right side of IR2, emerging from the transformation of Beam 1 nuclei at the ALICE interaction point ($s = 0$). Beam 2 is similarly transformed on the left of the IP. Note that the EMD1 beam does not hit the beam pipe (it has a smaller $|\delta|$ but propagates through the arc to IR3 where it will be intercepted by the momentum collimation system).

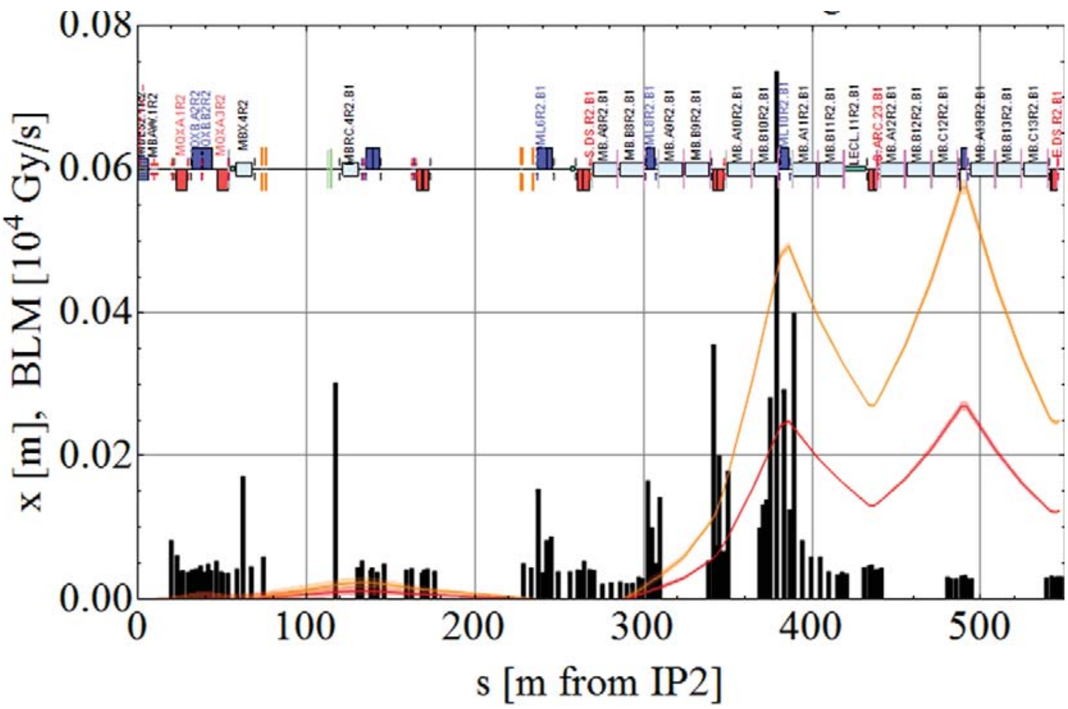

Figure 19: Beam-loss monitors in the dispersion suppressor right of IR2 during Pb-Pb collisions in 2011. The maximum losses occur precisely at the location expected from the calculations of BFPP1 shown in Figure 18.

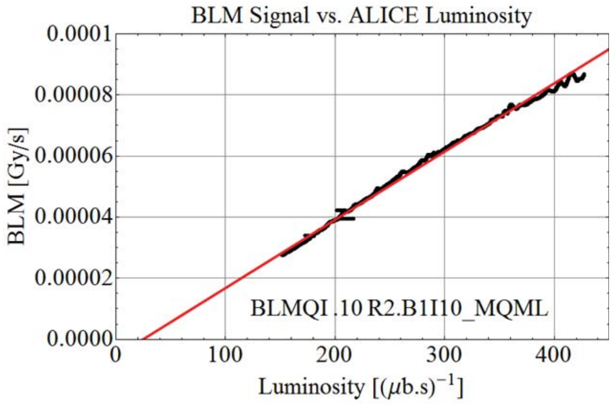

Figure 20: Correlation of highest BLM in IR2 signal with ALICE luminosity during a regular Pb-Pb physics fill in 2011.

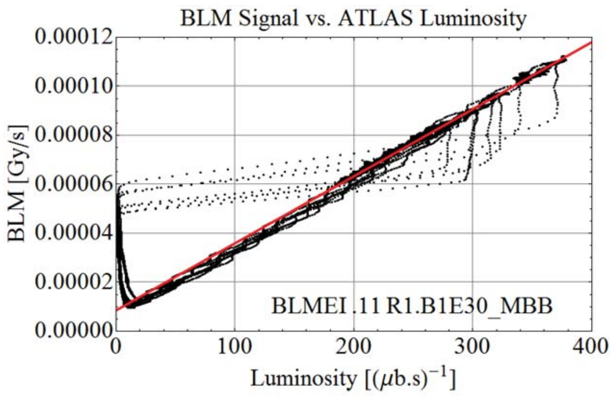

Figure 21: Correlation of highest BLM signal in IR1 with ATLAS luminosity during Pb-Pb van der Meer scans in 2011.

Luminosity goals

The ALICE experiment has set the Pb-Pb luminosity goal of $10\,\mathrm{nb}^{-1}$ for the period following its upgrade in LS2, some 10 times the initial LHC goal. For comparison with p-p running, this is equivalent to $0.43\,\mathrm{fb}^{-1}$ nucleon-nucleon luminosity. Moreover, approximately one annual run out of every three is expected to be devoted to p-Pb operation. To achieve the Pb-Pb goal, the annual integrated luminosity (1 month run) will need to be of order $1.5\,\mathrm{nb}^{-1}$. Accordingly, the detector upgrade will allow peak luminosities up to

$$\hat{L} \simeq 6 \times 10^7\,\mathrm{cm}^{-2}\mathrm{s}^{-1} = 6 \times (\text{original design}). \quad (17)$$

While this value is somewhat beyond those given on the basis of the rather conservative predictions above, it is by no means out of reach if we consider some of the possibilities for improvement that we alluded to above. With this luminosity, the two most powerful secondary beams emerging on each side of the IP will carry powers of

$$P_{\mathrm{BFPP1}} \simeq 155\,\mathrm{W} \quad (18)$$
$$P_{\mathrm{EMD1}} \simeq 53\,\mathrm{W}. \quad (19)$$

We should of course consider that, with three experiments taking data, the peak luminosity will not last long because of the rapid burn-off. If need be, levelling strategies could be used to reduce peak luminosity but we must in any case aim for high total intensity in the beams.

It should also be remembered that the BFPP1 losses during p-Pb runs at high luminosity may become comparable to Pb-Pb (on one side of the IP). The cross-sections are smaller but the luminosity is correspondingly higher.

Quench limit

Estimates of the power density in the superconducting cable due to BFPP1 were given in [32] (see the FLUKA shower simulation in Figure 7) and have been recently confirmed by further FLUKA studies reported in [33]. According to these calculations, the maximum power density in the dipole coil at $E_b = 7Z$ TeV for a luminosity L is

$$P = \frac{L}{10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}} \times 15.5\,\mathrm{mW/cm}^3 \quad (20)$$

whereas the latest quench limit estimates require

$$P < \begin{cases} 200\,\mathrm{mW/cm}^3 & \text{at } E_b = 4Z \text{ TeV} \\ 40\,\mathrm{mW/cm}^3 & \text{at } E_b = 7Z \text{ TeV} \end{cases} \quad (21)$$

Although these are considerably more optimistic than estimated in the past, it is clear that the levelled luminosities expected for ATLAS and CMS in Run 2 will already approach the limit and that the luminosity requested by the ALICE upgrade will be well beyond it and we can expect to quench the MB magnet and possibly also the adjacent MQ quadrupole.

Mitigation of the peak energy deposition by the bump method is expected to help but cannot yet be counted upon at this level. This is the basis for the proposal to implement the solution described in the following and recommended at the 2013 Collimation Review.

DS collimator solution

The BFPP1 and main beam are not sufficiently separated in the warm area so the TCLs are not useful as a mean to intercept the BFPP1 beam. The solution now planned for implementation in LS2 is also indicated in Figure 18. This is to install a collimator (TCLD) in the dispersion suppressor region before the impact point, where the BFPP1 beam is sufficiently well separated from the main beam. The favoured location for this collimator is indicated. It is also clear that, by varying the gap between the jaws of the TCLD, one can choose to intercept the EMD1 beam in addition to BFPP1 and EMD2. However it is not easy to select the very weak BFPP2 beam with a collimator located primarily to intercept BFPP1.

This solution was first discussed at [25] but rejected at the time since it would involve replacing or moving superconducting magnets in the cold section. The solution now adopted will replace one dipole with a geometrically equivalent assembly consisting to two shorter, higher-field magnets (now under development) with a collimator between them, as shown in Figure 22. Further information about the hardware is given in [33].

Resources expected in LS2 are sufficient only for an installation in IR2. Of course, the same problem of BFPP losses exists in the dispersion suppressors around ATLAS and CMS although the details of the loss locations somewhat different because of optical differences. Potential locations for TCLD collimators are shown in Figure 23.

In 2011, the highest BLM signals from BFPP in 2011 actually occurred on the right of IP5. We have some scope for mitigation using the orbit bump method tested in 2011 which will be made operational for Run 2 anyway. A final assessment of the need for these collimators should be possible at the end of the Pb-Pb run in 2015.

In the event that the high-field magnets are not ready, a possible alternative[6] might be to use a permanent orbit bump to pull the BFPP1 beam away from the beam pipe wall so that it would hit a collimator installed in the connection cryostat (where there are no magnets). This idea has still to be evaluated in detail.

ALICE Crossing Angle

When the beams are colliding, the vertical half-crossing angle at the ALICE experiment is [14]

$$\theta_{y_c} = \frac{\pm 490\,\mu\text{rad}}{E_b/(7Z\,\text{TeV})} + \theta_{y\text{ext}} \tag{22}$$

where the first term is the angle created by the orbit bump (entirely inside the innermost quadrupoles) required to compensate the detector's muon spectrometer magnet (whose field can vary in polarity but not magnitude) and the second term is the contribution of an "external" bump created by orbit correction dipoles further out.

In order to provide an unimpeded path for "spectator" neutrons emerging from the collisions to the Zero-Degree Calorimeter (ZDC) [34, 35], the condition

$$|\theta_{y_c}| < 60\,\mu\text{rad} \tag{23}$$

has been imposed in heavy-ion operation up till now. With bunch spacings, $S_b/c = 100\,\text{ns}$, as foreseen in the original LHC design [4], this provides adequate separation at the parasitic beam-beam encounters around the IP.

Some developments in the injectors (see [9] are aimed at increasing the number of bunches by achieving $S_b/c = 50\,\text{ns}$—half of the original design—for at least some of the spacings between bunches in the LHC. Figure 24 shows that, for this value, it is no longer possible to satisfy the usual separation requirements in ALICE together with (23) at the closest parasitic encounters to the IP. However, experience [14] suggests that, given the relatively low charge of the Pb bunches (compared to p bunches), it may be possible to operate with more relaxed conditions, say, $r_{12}/\max(\sigma_x.\sigma_y) > 3$ which should reduce the parasitic luminosity to acceptable levels [35]. Thus the efforts to

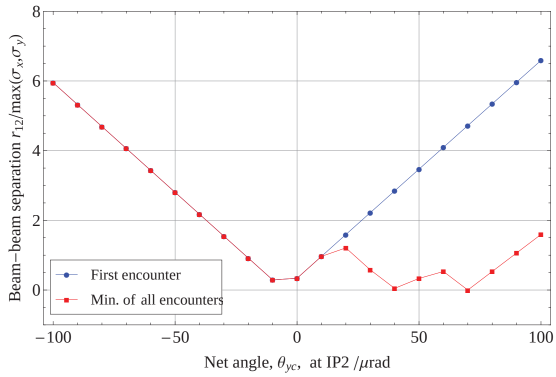

Figure 24: Beam-beam separation in IR2 as a function of the net half-crossing angle at the IP, θ_{yc}, for $E_b = 7Z$ TeV with $\beta^* = 0.5\,\text{m}$, the design Pb normalised emittance of $\varepsilon_n = 1.5\,\mu\text{m}$ and a regular bunch spacing of 50 ns and with the ALICE spectrometer polarity such as to contribute a positive crossing angle at the interaction point. At $\theta_{yc} = +70\,\mu\text{rad}$, the external angle is zero and parasitic head-on collisions occur. Separations are shown in units of the larger of the horizontal and vertical beam sizes, both at the first parasitic encounter (on either side of the IP) and at the minimum over all encounters excluding the IP itself.

achieve shorter bunch spacing remain well-motivated; it is unlikely, although not strictly excluded, that the data quality of the ZDC may be somewhat compromised by a need for a larger crossing angle. These considerations may lead to an upgrade of the TCLIA collimator to provide additional aperture clearance.

The ATLAS and CMS experiments do not have a muon spectrometer and separation requirements for Pb beams are less demanding than those established for protons.

Collimation Inefficiency

As discussed extensively in the past [36, 37, 38, 39, 40] the nuclear interactions [30] of heavy ions with the collimators reduce the collimation to a single-stage system with a higher collimation inefficiency. This translates into a limit on total intensity of Pb beams. Such limits have been encountered already in some unfavourable operational situations (eg, with Pb beam sizes larger than p, putting beams into collision with off-momentum p-Pb orbits). Again some mitigation has been achieved with a bump strategy in IR7 [7]. At present, this is not expected to be a principal limit in Run 2 or Run 3 but new work to improve the tracking simulations is starting and it is important to keep an eye on this problem.

STOCHASTIC COOLING OF Pb BEAMS

Inspired by spectacular luminosity enhancement [41] by 3D stochastic cooling of bunched Au and U beams at

[6] Thanks to M. Giovannozzi and L. Bottura for a useful discussion in which this idea emerged.

[7] This should work even better for protons and may be worth trying in 2015.

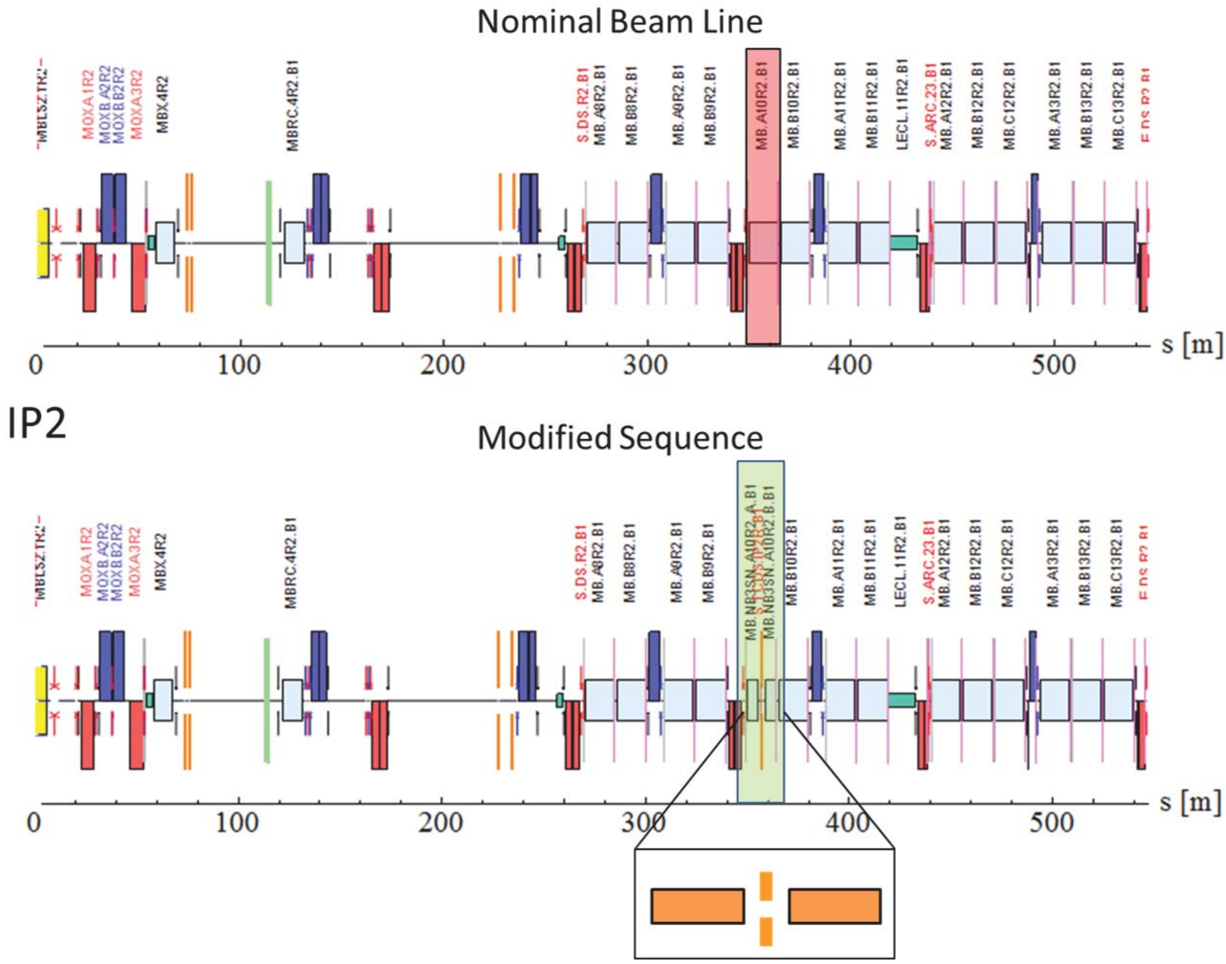

Figure 22: DS collimator installation in IR2. Magnet MB.A10R2 to be replaced by two 11T dipoles each with L = 5.3m surrounding a collimator jaw with L = 1m.

RHIC, we have established an informal collaboration with Brookhaven National Laboratory (the latest step was a visit from Mike Blaskiewicz in early summer) and undertaken a first study of the potential of a similar installation to cool heavy ion beams in the LHC. Simulation results were presented at the recent COOL13 workshop [42]. Figure 25 shows the potential for luminosity enhancement for typical bunch pairs in similar conditions to [42] except that three experiments are taking data so the cooling has to counter a much stronger luminosity burn-off. Nevertheless a substantial gain in integrated luminosity is evident.

In the HL-LHC, the benefits of the cooling lie in the reduction of colliding beam sizes at later stages of the fill. This maintains a high luminosity even when the bunch populations have been substantially eroded by the earlier luminosity burn-off. This is a much more efficient way to operate a collider since more of the particles stored in the beam are converted into collisions. A much smaller fraction are dumped at the end of the fill.

Studies are beginning to see whether the promise of a stochastic cooling system, at an apparently modest cost, can be realised in the LHC. Space for the system (roughly 20 m per beam for the kickers) must be found. They will be connected to the broadband pickups by fibre optics lines in the tunnel, avoiding chordal microwave links on the surface. As in RHIC, the kickers will have to come very close to the beam at physics energy so they must open at injection where a larger aperture is needed. In the open position, the design must have a low enough high-order mode impedance to avoid overheating in the presence of the high-intensity proton beams.

At present we are considering a possible demonstration of longitudinal cooling in 2015-16. The aim would be to use the existing Schottky pickup and an "off-the-shelf" 5 GHz amplifier. One of the unused shaker chambers in IR4 could be replaced with a suitable kicker (when ready) in a technical stop before the Pb-Pb run (to avoid the question of compatibility with proton beams). If successful, we would hope to strengthen our collaboration with BNL, to benefit from their experience and define fast-track implementation of a full system.

The 200 MHz RF system proposed for p-p could also be

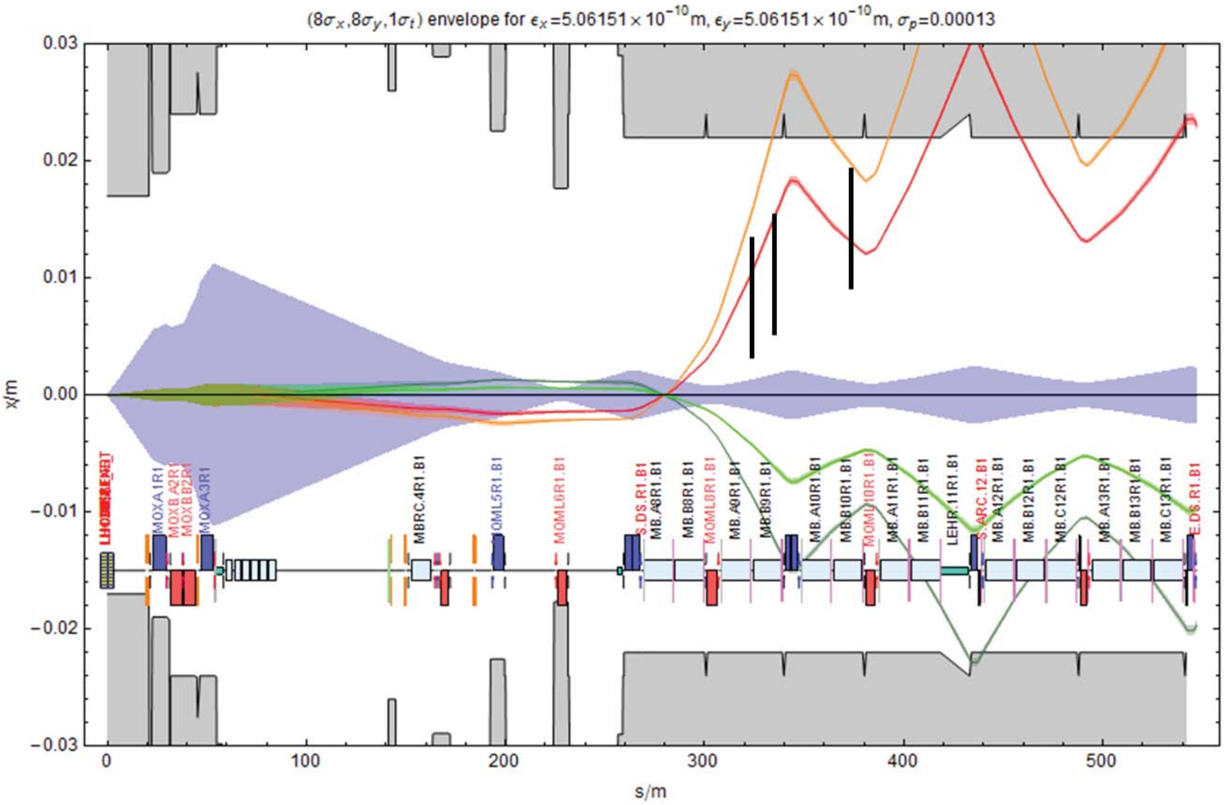

Figure 23: Secondary beams from the ATLAS collision point and possible DS Collimator locations, shown as black lines, on the right of IP1. The situation around CMS is similar.

expected to improve cooling.

CONCLUSIONS

In Run 2, Pb-Pb and p-Pb luminosities should already exceed the LHC design and the prospects of reaching the LHC design goal of $1\,\mathrm{nb}^{-1}$ in Pb-Pb are very good. A levelling strategy to meet the requirements of ALICE has been proposed.

With the current baseline upgrades foreseen from the injectors, the peak luminosity will increase further in Run 3 and beyond. Further gains from injectors should nevertheless be pursued as a priority to achieve the HL-LHC goal of $10\,\mathrm{nb}^{-1}$. These could include injection schemes for more, and brighter, bunches (50 ns spacing), means to reduce the intensity decay of bunches in the SPS.

The potential p-Pb performance depends critically on resolution of BPM problems, above all to avoid beam dumps due to single low-intensity Pb bunches.

Dispersion suppressor collimators are foreseen to be installed around ALICE in LS2; operating experience in 2015 will clarify the gain to be expected from them.

Following the success at RHIC, we also recommend initiating a fast track to stochastic cooling implementation. First simulations have shown very promising results but some key problems remain to be solved.

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REFERENCES

[1] C.A. Salgado, J. Alvarez-Muniz, F. Arleo, N. Armesto, M. Botje et al. Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements. *J. Phys.*, G39: 015010, 2012.

[2] J.M. Jowett, G. Arduini, R.W. Assmann, P. Baudrenghien, C. Carli et al. First Run of the LHC as a Heavy-ion Collider. *Proceedings of the 2011 International Particle Accelerator Conference, San Sebastian, Spain*, pp. 1837–1839, 2011.

[3] J.M. Jowett, R. Alemany-Fernandez, R. Assmann, P. Baudrenghien, G. Bellodi, S. Hancock, M. Lamont, D. Manglunki, S. Redaelli, M. Sapinski, M. Schaumann, M. Solfaroli, R. Versteegen, J. Wenninger, and D. Wollmann. Heavy Ions in 2012 and the Programme up to 2022. *Proceedings of the Chamonix 2012 Workshop on LHC Performance, 2012.*

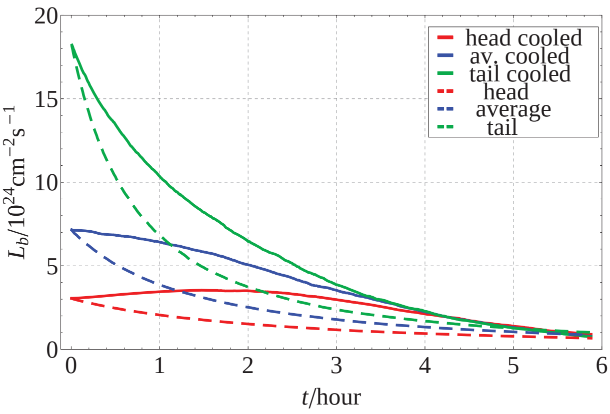

Figure 25: Evolution of bunch-pair luminosity with three experiments in collisions for three typical bunches in a train, with (solid curves) and without (dashed curves) the effect of stochastic cooling in all three planes. Bunch parameters are similar to the examples shown in the paper [42], except that luminosity burn-off is stronger with three experiments taking collisions. The bunch parameters are different from those shown in Figure 5.

[4] O. S. Bruning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock (editors). LHC Design Report V.1: the LHC main ring. *CERN-2004-003-V1*, 2004.

[5] J. M. Jowett and C. Carli. The LHC as a proton-nucleus collider. *Proceedings of the 2006 European Particle Accelerator Conference, Edinburgh, UK*, pp. 550–552, 2006.

[6] R. Alemany, M. Angoletta, P. Baudrenghien, R. Bruce, S. Hancock, D. Jacquet, J.M. Jowett, V. Kain, M. Kuhn, M. Lamont, D. Manglunki, S. Redaelli, B. Salvachua, M. Sapinski, M. Schaumann, M. Solfaroli, J. Uythoven, R. Versteegen, and J. Wenninger. First proton-nucleus collisions in the LHC: the p-Pb pilot physics. (CERN-ATS-Note-2012-094 MD), Nov. 2012.

[7] J.M. Jowett, R. Alemany-Fernandez, P. Baudrenghien, D. Jacquet, M. Lamont, D. Manglunki, S. Redaelli, M. Sapinski, M. Schaumann, M. Solfaroli Camillocci, R. Tomas, J. Uythoven, D. Valuch, R. Versteegen, and J. Wenninger. Proton-Nucleus Collisions in the LHC. *Proceedings of the 2013 International Particle Accelerator Conference, Shanghai, China*, (CERN-ACC-2013-0057): 49–51, May 2013.

[8] E. Meschi. Heavy Ion Plans: Experiments Perspective, these proceedings.

[9] D. Manglunki. Performance of the injectors with ions after LS1, these proceedings.

[10] D. Manglunki, M. Angoletta, H. Bartosik, G. Bellodi, A. Blas, M. Bodendorfer, T. Bohl, C. Carli, E. Carlier, S. Cettour-Cave, K. Cornelis, H. Damerau, A. Findlay, S. Gilardoni, S. Hancock, J. Jowett, D. Kuchler, M. O'Neil, Y. Papaphilippou, S. Pasinelli, R. Scrivens, G. Tranquille, B. Vandorpe, U. Wehrle and J. Wenninger. The First LHC p-Pb Run: Performance of the Heavy Ion Production Complex. *Proceedings of the 2013 International Particle Accelerator Conference, Shanghai, China*, (CERN-ACC-2013-0035): 2648–2650, May 2013.

[11] D. Manglunki et al. Ions for LHC: status of the injector chain. In *Proceedings of the 2007 Asian Particle Accelerator Conference, Indore, India*, pp. 226–228, 2007.

[12] M. Schaumann and J.M. Jowett. Bunch-by-Bunch Analysis of the LHC Heavy-Ion Luminosity. *Proceedings of the 2013 International Particle Accelerator Conference, Shanghai, China*, (CERN-ACC-2013-0136): 1391–1393, May 2013.

[13] S. Fartoukh. Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade. *Phys. Rev. ST Accel. Beams*, 16: 111002, Nov. 2013.

[14] R. Alemany-Fernandez, G.H. Hemelsoet, J.M. Jowett, M. Lamont, D. Manglunki, S. Redaelli, M. Schaumann, R. Versteegen, and J. Wenninger. ALICE spectrometer polarity reversal. CERN-ATS-Note-2012-039 MD, 2012.

[15] R. Bruce, J. M. Jowett, M. Blaskiewicz, and W. Fischer. Time evolution of the luminosity of colliding heavy-ion beams in BNL Relativistic Heavy Ion Collider and CERN Large Hadron Collider. *Phys. Rev. ST Accel. Beams*, 13: 091001, Sep. 2010.

[16] R. Bruce, J.M. Jowett and T. Mertens. Luminosity and Beam Parameter Evolution for Lead Ion Beams in the LHC. *Proceedings of the 2011 International Particle Accelerator Conference, San Sebastian, Spain*, pp. 1840–1842, 2011.

[17] J.M. Jowett, Hans-Heinrich Braun, M.I. Gresham, E. Mahner, A.N. Nicholson et al. Limits to the performance of the LHC with ion beams. *Proceedings of the 2004 European Particle Accelerator Conference, Lucerne, Switzerland*, pp. 578–580, 2004.

[18] A.J. Baltz, M.J. Rhoades-Brown and J. Weneser. Heavy ion partial beam lifetimes due to Coulomb induced processes. *Phys. Rev.*, E54: 4233–4239, 1996.

[19] R. Versteegen, R. Bruce, J.M. Jowett, M.J. McAteer, E.H. McLean, A.S. Langner, Y.I. Levinsen, T. Persson, S. Redaelli, B. Salvachua, P.K. Skowronski, M. Solfaroli Camillocci, R. Tomas, G. Valentino, J. Wenninger, and S.M. White. Operating the LHC Off-Momentum for p-Pb Collisions. *Proceedings of the 2013 International Particle Accelerator Conference, Shanghai, China*, (CERN-ACC- 2013-0180): 1439–1441, May 2013.

[20] R. Alemany, P. Baudrenghien, D. Jacquet, J.M. Jowett, M. Lamont, D. Manglunki, S. Redaelli, M. Sapinski, M. Schaumann, D. Valuch, R. Versteegen, and J. Wenninger. p-Pb Feasibility Test and Modifications of LHC Sequence and Interlocking. (CERN-ATS-Note-2012-052 MD), July 2012.

[21] R. Versteegen, J.M. Jowett, A. Langner, Y. Levinsen, M. McAteer, E. McLean, T. Persson, P. Skowronski, M. Solfaroli, R. Tomas, J. Wenninger and S. White. Optics commissioning for the first p-Pb run in the LHC. CERN-ACC-NOTE-2013- 0025, 2013.

[22] E. Calvo Giraldo, J.L. Gonzalez, L.K. Jensen, O.R. Jones, T. Lefevre, J.J. Savioz, R. Steinhagen and J. Wenninger. The LHC Beam Position System: Performance during 2010 and Outlook for 2011. *Proceedings of the 2011 10th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators, Hamburg, Germany*, C11-05-16.4 (CERN-BE-2011-010): 292, May 2011.

[23] P. Grafstrom *et al.* Measurement of electromagnetic cross sections in heavy ion interactions and its consequences for luminosity lifetime in ion colliders. *Proceedings of the 1999 Particle Accelerator Conference, New York, New York*, p. 1671, 1999.

[24] S.R. Klein. Localized beam pipe heating due to e-capture and nuclear excitation in heavy ion colliders. *Nucl. Instrum. Meth.*, A459: 51–57, 2001.

[25] J.M. Jowett. Ions in the LHC ring. *Proceedings of the LHC Performance Workshop, Chamonix XII, 2003.*

[26] J.M. Jowett, J.B. Jeanneret and K. Schindl. Heavy Ion Beams in the LHC. *Proceedings of the 2003 Particle Accelerator Conference, Portland, Oregon*, (TPPB029): 1682, 2003.

[27] A.J. Baltz, G. Baur, D. d'Enterria, L. Frankfurt, F. Gelis et al. The Physics of Ultraperipheral Collisions at the LHC. *Phys. Rept.*, 458: 1 –171, 2008.

[28] R. Bruce et al. Beam losses from ultraperipheral nuclear collisions between $^{208}Pb^{82+}$ ions in the large hadron collider and their alleviation. *Phys. Rev. ST Accel. Beams*, 12: 071002, Jul. 2009.

[29] C. Oppedisano. Measurement of the electromagnetic dissociation cross section of Pb nuclei at $\sqrt{sNN}$ = 2.76 TeV. *J. Phys.*, G38: 124174, 2011.

[30] H. Braun, H. A. Fasso, A. Ferrari, M. Jowett, J. R. Sala, P. and I. Smirnov. Hadronic and electromagnetic fragmentation of ultrarelativistic heavy ions at LHC. *Phys. Rev. ST Accel. Beams*, 17: 021006, Feb. 2014.

[31] R. Schicker. LHC Collimation Upgrade Specification Meeting, https://indico.cern.ch/event/229138/, Jan. 2013.

[32] R. Bruce, S. Gilardoni, J.M. Jowett, and D. Bocian. Beam losses from ultra-peripheral nuclear collisions between $^{208}Pb^{82+}$ ions in the Large Hadron Collider and their alleviation. *Phys. Rev. ST Accel. Beams*, 12: 071002, 2009.

[33] P. Fessia. LHC PICs: what are we talking about, these proceedings.

[34] R.B Appleby, J.M. Jowett and J. Uythoven. Moving the Recombination Chambers to Replace the Tertiary Collimators in IR2. (CERN-ATS-Note-2011-014 MD), Feb. 2011.

[35] K. Aamodt et al. (The ALICE Collaboration). The ALICE experiment at the CERN LHC. *Journal of Instrumentation*, 3(08): S08002, 2008.

[36] H.-H. Braun, R.W. Assmann, A. Ferrari, J.-B. Jeanneret, J.M. Jowett, and I.A. Pshenichnov. Collimation of heavy ion beams in LHC. *Proceedings of the 2004 European Particle Accelerator Conference, Lucerne, Switzerland*, p. 551, 2004.

[37] R. Bruce, G. Bellodi, H. Braun, S. Gilardoni, and J.M. Jowett. Monitoring heavy-ion beam losses in the LHC. *Proceedings of the 2006 European Particle Accelerator Conference, Edinburgh, UK,* pP. 544–556, 2006.

[38] R. Bruce, R.W. Assmann, G. Bellodi, C. Bracco, H.H. Braun, S. Gilardoni, E.B. Holzer, J.M. Jowett, S. Redaelli, and T. Weiler. Measurements of heavy ion beam losses from collimation. *Phys. Rev. ST Accel. Beams*, 12: 011001, Jan. 2009.

[39] R.W. Assmann, G. Bellodi, R. Bruce, M. Cauchi, J.M. Jowett et al. First Ion Collimation Commissioning Results at the LHC. *Proceedings of the 2008 European Particle Accelerator Conference, Genoa, Italy*, pages 1813–1815, 2011.

[40] S. Redaelli, R.W. Assmann, G. Bellodi, K. Brodzinski, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, B. Dehning, E.B. Holzer, J.M. Jowett, L. Lari, E. Nebot del Busto, M. Pojer, A. Priebe, A. Rossi, R. Schmidt, M. Sapinski, M. Schaumann, M. Solfaroli Camollocci, G. Valentino, R. Versteegen, J. Wenninger, D. Wollmann and Z. Zerlauth. Quench tests at the Large Hadron Collider with collimation losses at 3.5 Z TeV. *Proceedings of the HB2012 Workshop, Beijing, China*,(MOP245): 157, 2012.

[41] M. Blaskiewicz, J.M. Brennan, and K. Mernick. Three-Dimensional Stochastic Cooling in the Relativistic Heavy Ion Collider. *Phys. Rev. Lett.*, 105: 094801, 2010.

[42] M. Schaumann, J.M. Jowett and M. Blaskiewicz. Potential of stochastic cooling of heavy ions in the LHC. *Proceedings of the COOL2013 Workshop, Murren, Switzerland,* (CERN-ATS-2013-043): 76–78, Jun. 2013.

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EXPERIMENTS: SESSION 1 SUMMARY

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Abstract

The European Strategy for Particle Physics (ESPP) has recently recommended the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors. Given this, the physics motivation for the upgrades is outlined. The limitations of the present detectors given the proposed medium term upgrades are recalled. The proposed HL-LHC performance parameters together with these detector limitations motivate the need for major upgrades. The required detector upgrades as foreseen at present are briefly sketched. Despite the upgrades the HL-LHC parameter space remains challenging and possible mitigation measures are discussed.

The requirements of ALICE and LHCb in the HL-LHC era are presented. Finally an attempt is made to sketch the long-term LHC schedule given the known constraints in the lead-up to the HL-LHC upgrades.

INTRODUCTION

The first session of the RLIUP workshop was devoted to the experiments and the long-term schedule. The main goals were to: motivate the HL-LHC physics goals; examine the limits of the present detectors and to motivate the need for major experiment upgrades; to examine the challenges facing the proposed upgrades; and to attempt to sketch out a long-term post LS1 schedule taking into account the disparate requirements of machine and experiments.

The following presentations were given in the session.

- **Highlights from ECFA** (Austin Ball): Selection of highlights and topics of discussion from the ECFA HL-LHC Experiments Workshop (1-3 Oct) [1] which seemed (to the speaker) to be relevant to the workshop.
- **Physics landscape** (Fabiola Gianotti): The “physics landscape” from 30 fb^{-1} to 300 fb^{-1} to 3000 fb^{-1} and thus the physics potential of the HL-LHC.
- **Detector Limits** (Beniamino di Girolamo) The need to upgrade certain key detector elements of ATLAS and CMS for any programme beyond 300 fb^{-1}.
- **Performance parameters - experiments perspective** (Didier Contardo) The role of the upgrade changes to experiments in mitigating the high rate, high pile-up conditions of HL-LHC needed to reach the 3000 fb^{-1} target in a reasonable time-scale. The prospects for pile-up mitigation by tuning the luminous region were considered.
- **Plans and physics outlook for non-high luminosity experiments until and after LS3** (Richard Jacobsson) Physics motivation and realisation of the LHCb upgrade, plus the forward physics and ALICE proton-proton programmes.
- **Post LS1 schedule** (Mike Lamont) An attempt to fit the disparate requirements for operation and upgrade into a workable schedule, taking into account some constraints from accelerator consolidation and upgrade options.

The following summaries naturally draw heavily on the above presentations.

REPORT FROM EFCA HL-LHC EXPERIMENTS WORKSHOP

The motivation of the workshop held 1-3 October 2013 in Aix-les-Bains was to address the implications of the ESPP document adopted by Council in May 2013.

A key passage from the document states:

“ *The discovery of the Higgs boson is the start of a major programme of work to measure this particles properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier.*

The LHC is in a unique position to pursue this programme.

Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.”

The strategy explicitly recommends a 3 ab^{-1} target. There is preliminary approval for the HL-LHC programme and it may assumed that the machine and experiments may proceed with serious consideration of the options. Further evaluation of: the physics reach; the technical feasibility for experiments; and machine time-line and cost estimates is needed for formal approval by Research Board, Council, Funding Agencies etc.

Given this, the stated objective of the workshop was to help define the upgraded HL-LHC detectors and physics program for many years to come. In particular:

- Develop a common approach to the HL-LHC program; identify synergies and possible common efforts;
- Provide a consistent presentation of physics goals, detector requirements and technology R&D needed, also accelerator interfaces, long shutdown constraints, and costing methods;

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- Identify areas for further joint HL-LHC workshops;
- Provide a summary report to ECFA.

The outline conclusion was that 3 to 4 years of R&D followed by 5 to 6 years of construction are needed to complete the largest upgrades. R&D needs proper resources immediately. Long shutdown durations and schedule need further definition and consensus, especially to define clear profiles of resource needs versus time.

More specific conclusions included:

- Experience and expertise from building and operating current experiment systems (including power, cooling, gas, beam-pipes, survey, magnets and cryogenics, planning, coordination etc.) must be retained and transmitted to those developing new systems.
- Modelling of radiation levels and radiation damage is clearly important, and in some cases more results are needed to identify where upgrades are required. Many systems would benefit from more common facilities for irradiations and beam tests as well as greater coordination for use of those already available. Tools for dealing with the very challenging environments at and after LS3 should be developed in common with the machine and realistic timescales presented for interventions that take full account of the overriding ALARA principle.
- In some areas common standards and a common CERN interface with industries developing key technologies of importance to several experiments would be beneficial to minimize development and procurement costs. Forums exist for interaction between the machine and the experiments, but always helpful to update a larger forum, to be sure key parameters are widely understood across experiments.

PHYSICS LANDSCAPE

Three main results from LHC Run 1 were noted.

- We have consolidated the Standard Model with a wealth of measurements at 7-8 TeV, including the rare, and very sensitive to New Physics, $B_s \to \mu\mu$ decay. It works beautifully!
- We have completed the Standard Model with Higgs boson discovery after almost 100 years of theoretical and experimental efforts! It is a Higgs boson.
- We have NO evidence of New Physics.

Note that the last point implies that, if New Physics exists at the TeV scale and is discovered at $\sqrt{s}$ =14 TeV in 2015 onwards, its spectrum is quite heavy and it will require a lot of luminosity (for example 3000 fb^{-1} at the HL-LHC) and high energy to study it in detail. This has implications for future machines, for example, the New Physics - if it's there - is most likely not accessible at a 0.5 TeV linear collider.

On one hand, the LHC results imply that the SM technically works up to scales much higher than the TeV scale, and limits on new physics seriously challenge the simplest attempts (e.g. minimal SUSY) to fix its weaknesses. On the other hand there is strong evidence that the SM must be modified with the introduction of new particles and/or interactions at some energy scale to address fundamental outstanding questions, including the following.

- Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem)?
- What is the nature of the matter-antimatter asymmetry in the Universe?
- Why is Gravity so weak? Are there additional (microscopic) dimensions responsible for its "dilution"?
- What is the nature of Dark Matter and Dark Energy?

In addition the Higgs sector (and the Electroweak Symmetry Breaking mechanism) is the experimentally less well-known component of the Standard Model. A lot of work is still needed, for example, to understand if it is the minimal mechanism predicted by the Standard Model or something more complex (e.g. more Higgs bosons).

The HL-LHC can do a lot to address these (and other) questions given that answers to some of the above questions may be expected at the TeV scale. The strong physics case for the HL-LHC with 3000 fb^{-1} comes from the imperative necessity of exploring this scale as much as we can with the highest energy facility we have today (note: no other planned machine, except a 100 TeV proton-proton collider, has a similar direct discovery potential). It is likely, and perhaps more importantly, that the HL-LHC will also tell us what are the right questions to ask and how to continue.

DETECTOR LIMITS

The following potential limits to detector operations and possible mitigations were enumerated and explored.

- Limits from radiation damage and ageing (detectors)
- Limits from pile-up
- Limits from ageing (infrastructure)
- Limits, corrective measures, upgrades

Radiation damage and ageing The silicon detectors will hit one or both of these limits at around 400 to 500 fb^{-1}. The outer layers will follow with the rough scaling described in the presentation, here a missing layer has catastrophic effects: the detector needs to be upgraded. The calorimetry is also affected at the same threshold of around 500 fb^{-1}.

Limits from pile-up The current detectors have been designed for a pile-up of 25 events. We surprisingly managed in 2012 to live with up to around 37 pile-up events. In the medium term (Run 2 and Run 3) we aim to equip ourselves to be able to survive up to around 50 pile-up events (not all detectors) and it is clear we wont be able to stand 140 pile-up events without a substantial upgrade.

Following the approach of the machine the expected upgrades may be divided into: essential upgrades; and "Nice to have" upgrades. There are also are the "performance improving consolidations (PICs)" and essential consolidation for the experiments.

ATLAS and CMS PICs Most PICs are concentrated before LS3 (and some even before LS2).

- ATLAS Pixel and Strips: must act on the back-end electronics to avoid link saturations and processing performance bottlenecks.
- ATLAS Pixel: performed PIC on services to restore the detector to 99% and to cure link saturations.
- CMS Pixel: performed PIC to eliminate some bottlenecks.
- ATLAS is installing a 4^{th} layer (IBL) to fight against the ageing of the actual innermost layer.
- CMS will install a new Pixel detector to fight against the ageing and the pile-up increase.

We are forced to act on our Pixel and Strip detectors. We will have higher instantaneous luminosity than design, up to a factor 2.5 to 3 and quickly. By the time we will be at the LS3 threshold the inner detectors start to reach the 400 to 500 fb^{-1} limit and they will be dead soon after LS3. It takes a long time to change them and a one year stop is not enough: ATLAS has 100 M channels, 92 M are from the Pixel detector - imagine the services.

Infrastructure improvements and ageing effects Many examples were given at Aix-les-Bains workshop, only a few were reported here. For example, the back-end electronics is today based on VME standards. It will get old, obsolete, and difficult to maintain. New trends in telecommunications and higher speeds requires pushing towards different standards (xTCA) and/or commodity PCs. More speed means more power needed which in turn means more cooling will be needed. The current infrastructure already needs upgrades.

Limits, corrective measures, upgrades Here we have touched just the most important detector limits. For some of them corrective actions can be made: replacement of cabling, electronics, pipes; additional links to overcome saturations. For some other we really need upgrades. The detector layers will simply become non-operational with catastrophic effects on the physics already between 400 and 700 fb^{-1}.

The radiation damage effects would deserve a lot more information (different effects at different radii, etc.), but a ball park number is sufficient. The ageing of both detectors and infrastructure plays a role on top of the radiation and activation effects. The bottom line is that to go beyond 500 to 700 fb^{-1} upgrades of detectors and infrastructure are needed.

PERFORMANCE PARAMETERS: EXPERIMENTS' PERSPECTIVE

The challenge for the detectors of high luminosity operation and the impact of increasing pile-up were summarized. The main aims of the ATLAS and CMS upgrades were summarized.

LS1

Complete original detectors and consolidate operations for nominal LHC beam conditions:

- 13 to 14 TeV, 1×10^{34} Hz/cm^2, average pile-up ($\langle PU\rangle$) of 25

Prepare for start of upgrades for higher $\langle PU\rangle$.

LS1 through LS2

Prepare the detectors to maintain physics performance for:

- 1.6×10^{34} Hz/cm^2, $\langle PU\rangle$ of 40, ≤ 200 fb^{-1} by LS2
- 2.5×10^{34} Hz/cm^2, $\langle PU\rangle$ of 70, ≤ 500 fb^{-1} by LS3

LS2 through LS3

Prepare for up to:

- 5×10^{34} Hz/cm^2 with levelling, $\langle PU\rangle$ of 140, a total of around 3000 fb^{-1} in 10 years or so of operation.

One should: recognize the possible need to replace subsystems that no longer function due to radiation damage or ageing; and the challenge of maintaining physics performance at very high pile-up.

The planned Phase 1 and Phase 2 upgrades for both ATLAS and CMS were presented, including the ATLAS and CMS Trigger upgrades from Phase 1 to Phase 2 (this includes upgrades of calorimeter and muon detectors) and details of the pile-up effects visible throughout detector and readout chain. In summary both ATLAS and CMS are designing Run 4 detectors to cope with mean pile-up $\langle PU\rangle$ of 140 (25 ns, 5×10^{34} Hz/cm^2) with "tails" up to 200 events per crossing.

The experiments are very interested in methods (for example crab kissing) that allow tuning the extent of the luminous region in time and space, to reduce the pileup density in either z or t dimensions. Although a reduction in line density of 1.2 events/mm to 0.6 events/mm does not automatically open up a door to accepting twice the instantaneous luminosity (the mean pile-up also has bad effects - for example neutrals in the calorimeters). The potential to exploit fast timing to mitigate pile-up still requires substantial R&D (but there is a dedicated community pursuing this).

Performance parameters: conclusions

Phase 1 upgrades are needed to maintain performance beyond 1×10^{34} Hz/cm^2, $\langle$PU$\rangle$) of 25. With these upgrades ATLAS and CMS will be able to operate with good performance up to $\langle$PU$\rangle$ of 70 and integrated luminosity of up to 500 fb^{-1}.

For Phase 2 HL-LHC physics program ATLAS and CMS are preparing for operation up to 140 to 200 pile-up but with luminosity levelling available depending on performance at high pile-up. Present simulations assume 5×10^{34} Hz/cm^2, 140 pile-up with a Gaussian luminous region. A lot of work is ongoing to understand the limitations of Phase 1 detectors and and the benefits of Phase 2 upgrades, and there is an important eort to develop and tune data reconstruction and physics analyses.

It is essential that Accelerator and Experiments investigate all opportunities to mitigate pile-up eects to fully prot from the LHC High Luminosity potential.

PLANS AND PHYSICS OUTLOOK FOR NON-HIGH LUMINOSITY EXPERIMENTS UNTIL AND AFTER LS3

A concise run through of ALICE's and LHCb's physics motivation and upgrade plans was presented. Both ALICE and LHCb are going through major upgrades in LS2, which is assumed to be 18 months minimum. As regards the start of LS2, a delay of up to a year is advantageous. The scheduling of LS3 has little impact on ALICE and LHCb.

High luminosity programs of ALICE and LHCb are planned well into HL-LHC era. The principal targets being:

- ALICE 10 nb^{-1} of ions, and proton-lead runs etc.
- ALICE proton-proton Run 2: continuous running at 13 TeV
- ALICE proton-proton Runs 3 and 4: concentrated periods at nucleon-nucleon equivalent energy to collect at least 6 pb^{-1}. 1 to 2 months shadow data taking each year before the ion run.
- LHCb's target is 50 fb^{-1}. Operation assumes levelled luminosities for efficiency and physics stability, and 25 ns proton-proton operation.
- (ATLAS and CMS have a preference for intermediate energy proton-proton reference data in short annual runs of a few days.)
- (Forward Physics in special conditions is assumed to be complete by end Run 3.)

POST LS1 SCHEDULE

The constraints from experiments and machine were presented. Three main variations seemed possible.

Firstly a modified baseline would exclude the extended year end technical stop (EYETS), accept an extended LS2 of 18 months and keep the LS3 start in 2022. This is clearly disfavours CMS, and given upgrade development and funding considerations unrealistically forces the pace.

The second option which was called "Slipped baseline+6" sees:

- a 19 week EYETS in 2017;
- an extended Run 2 to mid-2018;
- a 3 year Run 3 with LS3 starting in 2023.

The third option which called "Slipped baseline+12" sees:

- a EYETS in 2017;
- an extended Run 2 to end-2018;
- a slightly shortened Run 3 with LS3 starting in 2023.

A modified "Slipped baseline+6" was presented by Frederick Bordry and approved by CERN management and LHC experiments spokespersons and technical coordinators on Monday 2$^{\text{nd}}$ December 2013.

CONCLUSIONS

- A strong physics case for the HL-LHC was presented.
- The detectors will have to work hard to maintain, and potentially improve, performance during Runs 2 and 3.
- The projected integrated luminosity in Runs 2 and 3 of around 300 fb^{-1} will bring main sub-detectors near to the end of their lifetime.
- Major upgrades are required to deal with the planned luminosity of the HL-LHC era. There are considerable challenges, the lead-time is long, and work must start now.
- Foreseen pile-up and pile-up density make considerable demands on vertexing capabilities and any methods to alleviate these demands must be pursued.
- ALICE and LHCb have planned upgrades which will allow them to operate well into the HL-LHC era.
- An updated baseline schedule has been established.

REFERENCES

[1] ECFA High Luminosity LHC Experiments Workshop, http://indico.cern.ch/conferenceDisplay.py?confId=252045, Aix-les-Bains, October 2013.

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SESSION2: POST-LS1 SCENARIOS WITHOUT AND WITH LINAC4

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Abstract

This document summarizes the talks and discussion that took place in the second session of the RLIUP Review. The main aims were to examine the performance of the injectors and LHC and what could be the integrated luminosity by 2035 if no major upgrade except the connection of LINAC4 and H^- injection is implemented and to take into account the lifetime of major accelerator components whose repair or replacement would require long shutdowns. The session comprised four presentations: "Expected performance in the injectors at 25 ns without and with LINAC4" by G. Rumolo; "Integrated performance of the LHC at 25 ns without and with LINAC4" by J. Wenninger; "Required maintenance and consolidation to run like that (injectors and LHC) until 2035?" by K. Foraz; and "What could stop us, when and how long?" by L. Bottura.

EXPECTED PERFORMANCE IN THE INJECTORS

Taking accepted beam loss and emittance blow-up budgets into account, it was shown that 25 ns beams delivered by the injectors (i.e., at the exit of the SPS) in 2012 were at or close to the brightness limit determined by space charge at injection in the PS, both for the standard production scheme and for the so-called batch compression, merging and splitting (BCMS) one. At the current PS injection energy of 1.4 GeV, this limit is closely aligned with the maximum brightness available from the PSB for these beams. A modest improvement could nevertheless be expected by increasing the longitudinal emittance in the PSB and using the second-harmonic rf in that machine to maintain the bunch length at extraction within the upper limit imposed by its recombination kickers.

A more substantial increase in brightness could be achieved using a new scheme with no splitting at low-energy in the PS – so-called pure batch compression. This would incur a filling penalty of around 13% in the total number of bunches in the LHC, but the shorter PS batches (trains of 32 bunches) would be beneficial from the standpoint of electron cloud.

All post-LS1 25ns schemes are limited to a maximum intensity per bunch of some 1.3×10^{11} by the rf power available in the SPS.

Linac4 offers the prospect of a factor of two increase in the brightness from the PSB. Consequently, space charge at injection in the PS becomes a clear limiting factor at 1.4 GeV. Even with the relaxed longitudinal emittance from the PSB, a 50% improvement is all that can be passed on directly and this only for the standard scheme. The BCMS scheme already operates at the space charge limit in the PS and has less margin to increase the longitudinal emittance injected into that machine.

It may be possible to recover more of the brightness gain by creating hollow bunches in the PSB or by employing high-dispersion or coupled optics at injection in the PS, but these approaches will require extensive MD time to develop. Also, a hollow distribution in longitudinal phase space will present a different tune footprint and will be difficult to triple split into bunches of equal intensity and longitudinal emittance.

The double brightness of Linac4 offers the additional possibility of delivering the present performance of LHC-type beams using single-batch transfer from the PSB. This could reduce the minimum waiting time of the LHC at 450 GeV by 17%, while the absence of a long injection plateau in the PS could permit the space charge ΔQ limit to be pushed beyond -0.31.

Discussion

R. Jacobsson asked what the 13% filling penalty of the pure batch compression scheme is with respect to. G. Rumolo replied that this is compared with the standard scheme.

S. Myers asked what increase in brightness could be expected from the pure batch compression scheme. G. Rumolo replied that a ~40% improvement is expected over what the BCMS beam will be able to deliver.

INTEGRATED PERFORMANCE OF THE LHC

This talk summarized the performance reach expected at the LHC by integrating the predictions of the previous one. It was re-iterated that only the standard scheme gains appreciably from Linac4, which left three cases to be analysed: the standard beam without Linac4 and the standard and BCMS beams with Linac4.

Electron cloud was considered to be the most serious potential limitation despite promising MDs in 2012 at 450 GeV in the SPS with doublet beams to enhance scrubbing. Although scrubbing is effective in the dipoles, where it is hoped to remove the effects of electron cloud completely, there is little evidence of improvement in the quadrupoles. This could be important for the inner triplets where the maximum heat load already translates into a luminosity limit of around 1.8×10^{34} $cm^{-2}s^{-1}$. Extrapolation of the UFO rate from 2012 data to 7 TeV suggests that roughly 100 beam dumps per year could be expected, although there is also evidence of fast conditioning with 25 ns beams. Serious deconditioning must be expected after LS1.

Assuming a stable beams efficiency of 35% (based on 37% achieved in 2012 and a 20 minute longer cycle to reach 6.5 TeV), an exponential fill length distribution with a mean of 6.5 hours (as observed in both 2011 and 2012) and a luminosity lifetime of 12 hours, then the standard and BCMS beams with Linac4 both have a very similar levelled (at a pile-up of 45) performance reach of close to

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50 fb^{-1} per year for β^* in the range 40-50 cm. Without levelling, this increases to ~55 fb^{-1} per year for both schemes at $\beta^* = 40$ cm, but with the penalty of increased pile-up. Pile-up is worse in the BCMS case because of the lower number of bunches stored. The (unlevelled) standard scheme without Linac4 would give only 38 fb^{-1} per year at $\beta^* = 50$ cm, which gives the BCMS beam a clear advantage until Linac4 comes online.

Discussion

L. Rossi claimed that the bunch population should always win as the most important factor. R. Garoby explained that this is a fallacy because the intensity per bunch throughout Run 2 will be limited by the injectors to a maximum of $\sim 1.3\times10^{11}$ for 25 ns beams.

L. Rossi then asked if any benefit of smaller transverse emittances would simply be negated by increased blow-up. M. Lamont said not necessarily and cited the example of the 50 ns BCMS beam in 2012 which suffered similar overall blow-up in the LHC to the standard 50 ns beam.

S. Myers asked whether the 50 ns beam was the only option given that there is no guaranteed solution to the problem of electron cloud. J. Wenninger replied that this would be covered in V. Kain's talk.

REQUIRED MAINTENANCE AND CONSOLIDATION

The aim of this talk was to establish a baseline scenario for shutdowns until 2035 within the somewhat artificial remit of no LIU upgrades (except for Linac4) and no HL-LHC. It constitutes a summary of extensive interviews with the relevant equipment groups.

CV and CRG maintenance determines the duration and frequency of all routine technical stops. These would have a duration of 5 days seen at the LHC and are required roughly every 10 weeks, with a further year-end technical stop of 10 weeks (including the Christmas holidays). The latter assumes operating with ions in the LHC at the end of each year in order to increase the cool-down time before access without high-intensity protons in the injectors.

Additionally, in a first scenario, there would be two long shutdowns each of 16 months duration for the LHC (LS2 from 2018 and LS4 from 2027), once again driven by the combined maintenance requirements of cooling, ventilation and cryogenics equipment, together with two long shutdowns each of 20 months duration for the LHC (LS3 from 2022 and LS5 from 2031) for the replacement of the inner triplets. Thus significantly long stops are required even with no upgrades. The 9 months to connect Linac4 would be in the shadow of LS2 in this scenario, which gives 57% for the scheduled availability of the LHC.

In an alternative scenario, the four long shutdowns are delayed by one year to permit Linac4 to be connected in 2017. This would mitigate the risk of the failure of Linac2 and spread the workload of LS2, but the scheduled availability of the LHC would be reduced to 54%.

Discussion

F. Bordry noted that a scenario with the connection of Linac4 in 2017 during an extended year-end technical stop (dubbed “LS1.5”) would imply a short run before LS2, which might not be desirable by the experiments.

R. Losito pointed out that, contrary to what was mentioned during the presentation, EN/STI does require technical stops during the run.

WHAT COULD STOP US?

The magnets of the LHC are subject to several failure modes: mechanical fatigue due to powering and thermal cycles; thermal and electrical stress due to singular events such as quenches; and radiation damage, particularly for those magnets in the triplet and collimator regions.

For the electromechanical issues, the mean time between failures of the superconducting magnets has been estimated at 400-500 years. This translates into 3 or 4 electrical non-conformities per year of operation and to at least 10-15 magnet exchanges per long shutdown, while one of the triplet magnets could be expected to fail within the next 10 years. The experimental magnets remain an open question.

Although there is a 50% uncertainty on the radiation dose that the triplets will accumulate by LS3, it may be sufficient to provoke a mechanically induced insulation failure. By that time the exchange of a triplet magnet could take ~1 year, including up to 6 months for cool-down. This limit to the radiation hardness of the triplets corresponds to an integrated luminosity of ~300 fb^{-1} and is consistent with previous analyses.

For the warm magnets of the collimation regions, actions have already been proposed and accepted to prevent insulation failure during Run 3.

Personal dose will be an important issue and all interventions must be carefully prepared. Access and work in the triplet and collimator areas will be subject to ALARA level III rules.

Discussion

S. Myers asked what is envisaged to avoid radiation damage to the new HL-LHC triplets. L. Rossi replied that sufficient shielding of the beam screen is foreseen to reduce radiation to the coils. The integrated radiation dose for a total integrated luminosity of 3000 fb^{-1} is expected to be smaller than that estimated for the coils of the present triplets after 300 fb^{-1}. L. Rossi added that this subject would be developed in the presentation of P. Fessia in Session 3.

O. Brüning asked whether the mean time between failures depends on the number of cycles (magnetic and thermal) to which the magnets are subjected. L. Bottura replied that this needs to be studied.

B. Di Girolamo asked if the experimental magnets might suffer from radiation damage. L. Rossi replied that this should be studied but he believes that the radiation dose accumulated by the experimental magnets should be smaller than that accumulated by the triplets by three orders of magnitude (in the range of 10 kGy).

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SESSION3: PICS AND UPGRADE SCENARIO 1

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Abstract

This document summarizes the talks and discussion which took place in the third session of the RLIUP Review.

The session was devoted to Performance Improving Consolidation (thereafter PICs) and Upgrade scenario 1. The PICs were defined as the “Replacement or upgrade of a system justified by consolidation but with the goal of improving performance”. The PICs scenario goals were further defined as accumulating 70 fb^{-1} integrated luminosity per year over a period a 10 years of operation, reaching 1000 fb^{-1} (starting with an initial integrated luminosity of 300 fb^{-1}).

An ‘Upgrade’ was defined as the ‘Replacement or addition of a system to improve the performance, which would otherwise not be necessary’. The Upgrade scenario 1 goals were defined as accumulating 170 fb^{-1} integrated luminosity per year over a period a 10 years of operation, reaching 2000 fb^{-1} (starting with an initial integrated luminosity of 300 fb^{-1}). This scenario assumed no crab cavity, no levelling, and a crossing angle adjusted for 12 sigma long range beam-beam separation.

The aim of the session was to analyse which beam parameters can reach these targets and what are the related actions on the equipment.

In the first part of the session, the PICs were presented and discussed for both the LIU and the HL-LHC project. This part comprised three presentations: “Injectors: PICs: what are we talking about?” by K.Hanke; “LHC: PICs: what are we talking about?’ by P.Fessia and “LIU-HL-LHC: PICs: what do we gain in beam performances?” by G.Arduini. The second part of the session was devoted to the Upgrade scenario 1, with four presentations: ‘HL-LHC: How to achieve Upgrade Scenario 1 goals in the LHC?’ by O.Brüning; “Work effort in the LHC accelerator for upgrade scenario 1” by E.Todesco; “LIU: Which beams in the injectors fulfil HL-LHC US1 goals?” by S.Gilardoni and “Work effort in the LHC injector complex, including Linac4 connection, for upgrade scenarios” by J.-B.Lallement and B.Mikulec.

PICS IN THE INJECTORS: WHAT ARE WE TALKING ABOUT? – K. HANKE

K.Hanke emphasised that despite the fact that there is a clear PIC definition, some overlaps and grey zones persist with pure consolidation (defined as ‘Partial or complete replacement of a system to be performed in order to maintain the present level of performance/availability’) and Upgrade scenarios. A summary of all the PICs needed for the LIU project was given and the time driver activity for a minimum duration single block adds up to 12 months for the LIU-PSB, 3 months for the LIU-PS and 6 months for the LIU-SPS. It was stressed that all time estimates depend strongly on the available manpower and a consequent amount of work is indeed to be done in parallel for all machines. So the planning has to be weighted together with the consolidation and maintenance activities.

In terms of cost, 50 MCHF is needed for PICs in the LIU-PSB, 16 MCHF for the LIU-PS and 23 MCHF for the LIU-SPS.

It is important to note that the PICs are mandatory and must be fully implemented in the injectors in LS2 regardless of which upgrade scenario is chosen.

PICS IN THE LHC: WHAT ARE WE TALKING ABOUT – P.FESSIA

P.Fessia described the extensive LHC PIC activities which concern practically all the sectors of the machine and are spread between the 1st long technical stop after LS1 and LS3.

The interaction region interventions in IP 1 and 5 provide safe operation for 2025 to 2035 years and the required luminosity capacity.

The collimation interventions should reduce the whole machine impedance providing more robust collimators and ensure safe ion run in IP2.

The beam diagnostic interventions provide the necessary diagnostic capacity, with hardware compatible with the higher radiation dose.

The SC (superconducting) links provide a solution to radiation electronic issues for the Power converters, and (by removing also the DFBs from teh tunnel) are key for reducing collective dose and interventions time.

The Cryoplant at point 4 provides flexibility in the management of the RF interventions and eliminate the 1st machine bottleneck in term of cooling capacity. All cryogenics installation have to be performed with a long term view in the installation/integration perspective (foresee for future needs).

The high radiation dose calls for radiation management and possible reconfiguration to provide the best possible reliability and access conditions. Radiation tolerant electronic development (including R&D and testing) will affect several equipment groups (costs, resources).

PICS: WHAT DO WE GAIN IN BEAM PERFORMANCE? – G.ARDUINI

G.Arduini summarised the possible performance, depending of the beam parameter scenarios (cf. tables in G.Arduini’s presentation).

To be noted:

- The luminosity target can be reached with the standard 40cm/20cm optics;
- The BCMS (Batch Compression Merging and Splitting) gives a slightly higher performance

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but is more sensitive than the standard scheme to additive sources of emittance blow-up;
- The 50/25 optics provides margin in aperture and offers a reduction of the pile-up density below 0.7 events/mm;

The key questions and studies required in Run 2 have been sketched, e.g. understanding and control of the sources of blow-up; confirmation of the feasibility of β*-levelling as a possible solution for IP8; confirmation of the feasibility of scrubbing the dipoles down to SEY=1.3-1.4 possibly with dedicated beams; full understanding of the stability limits for single and two-beams.

WHICH BEAMS IN THE INJECTORS FULFIL THE UPGRADE SCENARIO 1 GOALS? – S. GILARDONI

S.Gilardoni investigated all the different possible options in order to reach the Upgrade Scenario 1 goals, with the emphasis that large bunch intensity in LHC is more important than low emittances.

His investigation led to the conclusion that the 200 MHz RF Upgrade in the SPS is mandatory to match the goals of LHC-Upgrade scenario 1, with unchanged longitudinal parameters at LHC injection. Therefore, for the LIU project, there is no difference in terms of hardware strategy between Upgrade scenario 1 and 2.

HL-LHC: HOW TO ACHIEVE UPGRADE SCENARIO 1 GOALS IN THE LHC? – O.BRÜNING

O. Brüning derived the possible performance reach scenarios, using the beam parameters presented by S.Gilardoni, assuming the LIU SPS 200 MHz full upgrade (1.9 10^{11}ppb within 2.26 μrad emittance (> 70% blow-up wrt SPS extraction), at LHC collision energy).

For example, the following case could reach the Upgrade Scenario 1 goals and is possible from the IBS point of view, requiring TAS and TAN upgrades, as well as matching section upgrades.

- N at collisions = 2508 colliding pairs in IR1 and IR5 (revised BCMS filling scheme)
- flat beams with beta* = 0.4m / 0.1m
- beam separation of 10 sigma -> crossing angle of 310 μrad
- IBS growth rates of ca. 22h horizontally and 25h longitudinally (scaled)
- Peak Luminosity = 8 10^{34} cm^{-2} s^{-1}
- Leveling time = 2.9 h; Luminosity decay time = 4 h; Turnaround time = 3 hours
- Total fill length (leveling + decay + turnaround) = 9.9h
- Integrated Luminosity per fill =1.06 fb^{-1}; Luminosity per year for perfect operation = 413fb^{-1}
- Required efficiency for achieving 170fb^{-1} per year = 41%

The following additional remarks were made:

- Beam-Beam Wire compensator is very important for Upgrade scenario 1. An optimum position at 10 sigma would require checking carefully the integration aspects with the Collimation System.
- The small emittance beams from LIU upgrade cannot really be utilized in the LHC due to IBS limitations.
- The Upgrade Scenario 1 goals are compatible with full SPS upgrade and HL-LHC PIC when operating with flat beams (40cm/20cm). Smaller β* (e.g. 40cm/10cm) can provide more performance (>20%) but requires some Matching Section upgrades.

WORK EFFORT IN THE LHC ACCELERATOR FOR UPGRADE SCENARIO 1 – E.TODESCO

E.Todesco described the LHC work effort to meet the upgrade scenario 1 goals.

The same peak luminosity as for the Upgrade scenario 2 will be reached (heat loads), and 2/3 of data (radiation damage) – many unknowns to be seen with 7 TeV operation

The new triplet/D1 as defined for PIC (larger aperture and W-shielding) allows swallowing larger heat loads (thanks to new cryoplant for the triplets), and radiation damage.

The Matching section becomes a bottleneck for β* (not lower than 30 cm), but can swallow heat load and radiation damage.

The scenario relies on the ability to increase beam intensity.

The main work effort lies in the collimators in IR7, IR1, IR5, in the superconductive link for matching sections in IR1 and IR5, and in the Beam-beam long range wire compensator. This equipment is essential, it is a new piece of hardware and a proof of principle for the LHC will be given in ~2017.

WORK EFFORT IN THE LHC INJECTOR COMPLEX, INCLUDING LINAC 4 CONNECTION, FOR THE UPGRADE SCENARIOS – J.-B.LALLEMENT, B.MIKULEC

J.-B.Lallement confirmed that 15 weeks are needed to deliver a Linac4 beam to the PSB (linac2/linac4 interface and LBE line activities, including beam commissioning). B.Mikulec investigated the overall Linac 4 connection to the PSB and about 9.3 months will be needed.

During LS2, the time line is driven by the PSB activities (a big amount of cabling work to be performed which inevitably will compete with cabling needed for other projects). The PSB first beam (LHCPROBE) will be sent to the PS after 17.5 months. The PS will be ready for beam from PSB already after 14.5 months. So clearly it is needed to gain 3 months in PSB planning. The SPS will be ready for beam from PS after 16.5 months. So the first injection of LHCPILOT into the LHC will take place after

~20.5 months and the minimum time for injection of LHC production beam into the LHC is estimated to ~22 months (due to scrubbing to be performed).

OVERALL SUMMARY OF SESSION 3 – M.MEDDAHI, L.ROSSI

- PICs
  - Need to be fully implemented in the LIU regardless of the chosen Upgrade Scenario;
  - PICs (new triplet+collimation upgrade+ Cryo…) are mandatory for future HL-LHC operation;
  - PICs provide at least 70 fb^{-1} / year and fulfil the 1000 fb^{-1} target sets for the PICs only scenario until 10 year operation to 2035.
- Upgrade scenario 1
  - Means Full Upgrade of the injectors (identical upgrade to scenario 2);
  - Allows reaching the set target of 2000 fb^{-1} (170 fb^{-1}/y) using 'smaller' emittance beams. However, in lack of Crab cavity, foreseen only in Upgrade scenario 2, the long range BB compensating wire is necessary in the LHC.
- Schedule
  - Coordinated effort to plan all the upgrade implementation is to be started, taking into account all needed resources for LIU, HL-LHC but also CONS and other requests;
  - Should cover a longer time span (few LS);
  - LS2: LIU implementation to be ready for post-LS3 operation;
  - LS2 should be at least 18 months (but for LIU is necessary to solve the cabling problem, by increasing resources and speed of laying)

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SUMMARY OF SESSION 4 - UPGRADE SCENARIO 2

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Abstract

The performance target for Upgrade Scenario 2 (US2) was defined for the purposes of the RLIUP meeting as accumulating 3000 fb^{-1} in the years to 2035. As shown earlier in the meeting, this sets the requirement for ~270 fb^{-1} per year of operation after LS3. The presentations in Session 4 were arranged to evaluate the performance of HL-LHC given the assumed baseline upgrade path, to present the optimum beam parameters in collision and from the injectors, to evaluate whether the injectors could reach the required parameters in view of the LIU upgrades, and to then investigate possible alternative (i.e. non-baseline) ideas or possibilities for improving the performance reach of HL-LHC and its injector chain. The session concluded with two talks, one on the challenges and outlook for improving the achieved physics availability of HL-LHC, and the second on the analysis of the possible issues with the baseline 25 ns bunch spacing and the estimate of the performance potential with the alternative option of 50 ns.

SESSION AGENDA

The presentations for Session 4 were aimed at evaluating the performance of, and work-effort for, HL-LHC with all baseline upgrades, and also whether any previously unconsidered or non-baseline ideas could really contribute to a performance improvement. In addition the challenges of reaching the demanding availability targets were highlighted, together with the performance evaluation for 50 ns bunch spacing. The session contained seven presentations, for which the presenters and titles were:

1. **R. de Maria** How to maximize the HL-LHC performance;
2. **H. Bartosik** Can we ever reach the HL-LHC requirements with the injectors;
3. **L. Rossi** How to implement all the HL-LHC upgrades;
4. **R. Tomas Garcia** HL-LHC: exploring alternative ideas;
5. **H. Damerau** LIU: exploring alternative ideas;
6. **M. Lamont** How to reach the required LHC availability;
7. **V. Kain** 50 ns back-up scenario.

In addition, the talk in Session 3 on Work Effort in the LHC Injector Complex, including Linac4 connection, for the Upgrade Scenarios by **B. Mikulec and J.-B. Lallement** included the full information on the work effort in the shutdowns for the injector complex for Upgrade Scenario 2, as these were essentially identical.

HOW TO MAXIMIZE THE HL-LHC PERFORMANCE

The talk presented the performance estimates for the full baseline upgrade, and highlighted the limitations on the total integrated luminosity. The required parameters for the injectors were defined. The performance reach against the key factors of machine availability (expressed as average fill length) and acceptable pile-up (expressed as levelling luminosity) were plotted, Fig. 1. The attainable peak virtual luminosity (for example through β^*, emittance or bunch intensity) play a role in defining the boundaries of the accessible region, and thus are secondary considerations compared to the machine availability for physics and the pile-up limit.

With the assumption of constant 6 h fill length and 140 pile-up limit, the HL-LHC could deliver about 230 fb^{-1} per year.

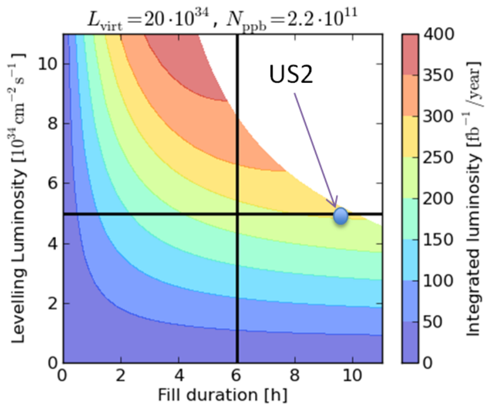

Figure 1: HL-LHC performance reach assuming that all fills optimistically last the same duration (delta function distribution). A fill duration of above 10 h would be needed to approach the HL-LHC target. The coloured region is accessible with 2.2 $\times$ 10^{11} p+ per bunch at 25 ns, with 2.0 $\times$ 10^{35} $cm^{-1}s^{-1}$ peak virtual luminosity.

Main conclusions

- The LIU-US2 standard production scheme approaches the bunch intensity target, assuming that operation at 25 ns with a bunch population of 1.9 – 2.2 $\times$ 10^{11} p+ is possible;
- The LIU-BCMS schemes offer lower emittance that increases peak luminosity but the reduction of colliding bunches and IBS lifetime reduce overall performance - there is no real interest in emittances below about 2.0 μm in collision;

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- The present pile-up limit of 140 events per crossing (with a maximum pile-up density of 1.3 mm^{-1}) and the assumed machine availability smear out the performance differences, in the strongly-levelled regime;
- Baseline hardware is well advanced and the layout is being validated before next iteration;
- Intensity limitations are being investigated and need to be overcome, in particular ecloud;
- Beam-beam effects and wire compensation are critical for flat beam schemes;
- The full leveling scheme via β^* is a challenge and remains to be detailed and studied – for this reason it is essential to deploy in IP8 for Run 2;
- The pile-up density can be mitigated with crab kissing, or longer/flattened bunches. Flat beams at the IP and the wire compensation are interesting to reducing the crabbing requirements;
- The HL-LHC baseline can meet the luminosity target if machine availability can be significantly improved. It could even exceed the target if, in addition, the pile-up limit can be significantly increased.

CAN WE EVER REACH THE HL-LHC REQUIREMENTS WITH THE INJECTORS?

The performance reach of the injector chain after all baseline LIU upgrades was evaluated, after a recall of the main limitations and upgrade items. Assuming that the LINAC4 connection and 160 MeV H- injection allows a doubling of the present brightness from the PSB, that 2 GeV injection into the PS removes the space charge limit there, and that electron cloud can be solved in SPS, the remaining limitations in the complex are the PSB brightness and the longitudinal beam stability in the SPS which is directly linked to the RF power available. The SPS will be able to deliver about 2.0×10^{11} p+ per bunch in a transverse emittance of 1.88 μm, at injection into the LHC, Fig. 2. This is enough to 'saturate' the LHC performance for the assumed pile-up limit and availability/fill length.

The decision-making process for whether to coat the SPS with aorphous carbon (aC) was also outlined; two sets of scrubbing tests are planned, in late 2014 and early 2015, to decide experimentally whether scrubbing after a long shutdown is a viable path back to operational performance.

Main conclusions

- With the full program of baseline upgrades the injector complex can just about match the parameters needed by HL-LHC, for the presently assumed pile-up limit and machine physics efficiency;
- The main necessary upgrades are LINAC4 connection and 160 MeV PSB injection, 2 GeV PS injection and RF system upgrade, SPS 200/800 MHz power increase and ecloud mitigation. Many, many other systems across the complex also need major upgrades;
- With all baseline upgrades there is little or no margin to further increase the number of protons per bunch transferred from SPS, should improvements in LHC allow an increase in the optimal intensity.

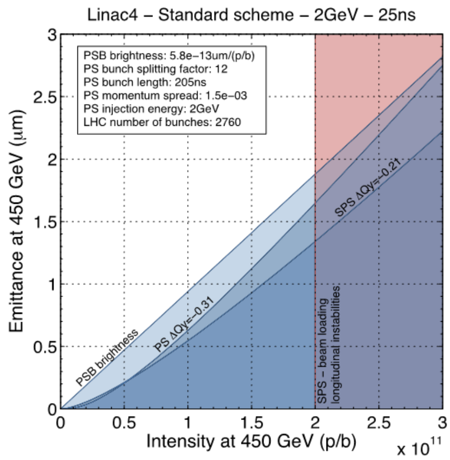

Figure 2: Accessible beam parameters with standard 25 ns production scheme at injection into LHC, from the injectors after all baseline upgrades.

HOW TO IMPLEMENT ALL THE HL-LHC UPGRADES

The vast amount of work required for HL-LHC was recalled in detail, encompassing a significant fraction of the ring. New triplets and deep changes in IP1 and 5 are the core of the work, but many other systems are affected. The total material budget is estimated at 810 MCHF.

Some work is already being prepared for LS2, including DS collimators in P2 and perhaps in P7, horizontal SC links in P7, an additional cryoplant in P4 and some reduced impedance collimators. The LS2 work is expected to fit inside 18 months with adequate margin. The main uncertainty is the availability of two sets of 11 T/DS collimator units for P7.

The major part of the work is planned for LS3, and is expected to fit inside 26 months. Detailed shutdown planning is needed to handle the massive co-activity and possible contstraints from radiation dose to personnel, which becomes more of an issue as the integrated luminosity increases.

In addition to the agreed baseline, other potentially beneficial systems are actively under study. These include extra SC RF systems (800 or 200 MHz), hollow electron lens, long range beam beam wire compensator and crystal collimation. It is expected that these options will be evaluated as part of the design study which should be finished in 2015 with a Technical Design Report. Any extra systems should push HL-LHC to reach and even exceed the luminosity target, since there is interest in establishing some margin in the performance reach, given the uncertainties which are still attached to some of the limitations in the LHC and the injectors.

The upgrades should also improve the robustness of the hardware in the face of increasing radiation dose - the SC link, QPS upgrades and new triplets will all contribute in this direction, and the objective is that the hardware will be more robust for the 3000 fb^{-1} than it is for the present 300 fb^{-1}.

Main conclusions

- Some work will take place inside the 18 month LS2, with the bulk of the HL-LHC work happening inside a 26 month LS2;
- Detailed resource loaded LS2 and LS3 shutdown planning is needed, together with all other co-activity, to validate the schedule assumptions;
- Widespread performance upgrade should also make the machine robust to the expected radiation dose;
- Margin in the performance reach is highly desirable, hence alternative ideas are to be actively pursued.

HL-LHC: EXPLORING ALTERNATIVE IDEAS

Many ideas for improving the HL-LHC performance have been discussed and evaluated, of which the most promising were presented in some detail. In view of the possible problems with electron cloud, the performance reach with an alternative "8b+4e" structure from the injectors (instead of the regular 12b produced per PSB bunch) was evaluated. The same number of protons are redistributed into a sub-train of only 8b, separated by gaps of 125 ns, which should be compatible with the available peak RF power at 200 MHz in the SPS because the duration of 12x25 ns is shorter than the filling time of the Travelling Wave cavities. This is expected to give much less electron cloud in the LHC, compared to the regular 25 ns beam, with a threshold δ_{max} of about 1.6 for the acceptable heat load in the arcs, while giving better luminosity at the pile-up limit than a full 50 ns beam. This scheme should therefore be maintained as an intermediate possibility between 50 and 25 ns, for instance during a slow scrubbing/physics production operation.

Another very promising option is to add a new 200 MHz SC main RF system in LHC. This would allow transfer of longer bunches from SPS, which opens the way to 25 ns bunch intensities of around 2.5×10^{11} p+ per bunch. The longer bunches also give less electron cloud, reduce the pile-up density and give less higher-order-mode heating. This option is interesting even without the addition of the crab cavities; together these two systems give a slight performance improvement compared to crab cavities alone, or 200 Hz system alone. First studies of the system indicate that the required ~3 MV could be feasible within the present technical constraints.

Also explored was pile-up density levelling, which would still allow an integrated yearly luminosity of around 250 fb^{-1} per year. The four options explored were β^* levelling with 10 cm long bunches, 800 MHz system plus β^* levelling, crab kissing and 800 MHz plus crab kissing.The peak pile-up density can be levelled by β^* alone to 1.0 mm^{-1} without any new hardware and with little (~%) loss in performance. A new 8 MV 800 MHz system would allow a reduction to about 0.9 mm^{-1}. With a new 200 MHz system the pile-up density could also be levelled to 1.0 mm^{-1} for a similar integrated luminosity, while using the crab cavities for "kissing", plus the 800 MHz the pile-up density can be levelled to 0.7 mm^{-1}.

Other more exotic proposals for beam cooling were also presented, including coherent electron cooling and optical stochastic cooling. These were not considered to presently offer significant performance potential.

Main conclusions

- The 8b+4e scheme should be followed up as a promising alternative, intermediate between 50 and 25 ns, in case of prolonged difficulties with 25 ns beams;
- A new 200 MHz SC main RF system for LHC looks very promising in several regards (2.5×10^{11} p+ per bunch from SPS, better for electron cloud and beam heating, similar for pile-up density levelling). This option has started to be studied in detail and should be a high priority;
- Pile-up density levelling to ~1.0 mm^{-1} or even below will be possible using whichever combination of hardware is installed, and will cost maximum ~7% in integrated luminosity;
- No other highly promising ideas were indentified (which means that the baseline is well adapted).

LIU: EXPLORING ALTERNATIVE IDEAS

For the injector chain, a wide range of ideas for alternative performance improvements was considered. A review of possible additional batch compression, merging and splitting (BCMS) schemes showed that the 48b version tested in 2012 would matched perfectly the parameters to the PS space charge tune shift limit (at 2 GeV after the PSB extraction energy upgrade), and also that the resulting brightness reach would in fact be beyond that requested by HL-LHC, due to the very small attainable emittance. The case of no low-energy bunch splitting at all in the PS was considered as the logical extreme of the possible potential BCMS scheme. The bunches would only then be split at high energy by a factor 4, to give batches of 32b, which would result in about 13% fewer colliding bunches in LHC. This would push the SPS to its assumed space charge limit, but again is of limited use to HL-LHC limited by pile-up and operating in the strong levelling regime. Also concerning bunch patterns, the 8b+4e scheme potential was also explored more in detail, with important tests to make in the injectors and possibly LHC during Run 2, as a function of the results of 25 ns operation.

Ideas to mitigate space charge were considered. The production of flat bunches in the PSB using a double harmonic RF system or hollow bunch distribution were shown to give a potential reduction in space charge tune shift of ~25%, and longer bunches were also evaluated. Overall a possible increase in the PS brightness of about 15% might be achievable, but this would be technically challenging and in any case obviated by the eventual upgrade of the PSB extraction to 2 GeV. Ideas for space charge mitigation by resonance compensation and optics modifications were also considered - these need more study and will be pursued.

For the SPS transfer to LHC, it was shown that more additional 200 MHz RF power beyond the presently foreseen doubling suffers from the law of diminishing returns, with not much additional benefit. The benefits of a 200 MHz capture system in the LHC were again clearly shown - with the important qualification that this will only help overall in tandem with the 200 MHz power upgrade in the SPS.

The benefit of a possible increase of the SPS injection energy to 28 GeV would be to reduce space charge tune shift by ~15%. Operating the SPS with a split-tune optics of Q_h=20 and Q_v=26 would give ~5% gain in space charge tune shift, and would also help facilitate injection at 28 GeV. There is less opportunity than in the PS to deploy an irregular optics with significant vertical dispersion, and this would require important cabling changes and the installation of dedicated skew quadrupoles. Overall the SPS appears less flexible than the PS with less margin for this type of improvement.

Main conclusions

- There is no magic alternative to the baseline LIU upgrade core, of LINAC4 plus 2 GeV PSB extraction plus SPS 200 MHz power upgrade;
- A large number of schemes exist to increase the bunch intensity and brightness from the injectors, where the SPS may be pushed to its space charge limit;
- An LHC 200 MHz RF system produces a significant gain in the bunch population which can be transferred from SPS, but there is not much motivation to look at increasing the SPS 200 MHz system RF power beyond the proposed upgrade;
- Interesting alternatives can be studied during Run 2, like long/flat/hollow bunches in PSB and PS, different BCMS schemes in PS and split tune in SPS;
- Important to keep the flexibility in the injectors to be able to produce the different beam types, to follow LHC performance evolution.

HOW TO REACH THE REQUIRED LHC AVAILABILITY

The challenges and specific issues of obtaining and maintaining a high physics efficiency were explored. A lot of effort and progress is already evident for large distributed systems with major down-time potential, like cryogenics and the electrical network, spread across operations, R2E, the equipment groups and HL-LHC project. A reduction in the rate of faults requires more rigorous preventive maintenance, which also depends on sustained and well-planned consolidation of installations. Redundancy can help for key systems, and design with reliability in mind is clearly important. The newly-formed Availability Working Group is covering part of this analysis, but the issues are spread across many projects in the whole complex, and deserve a more comprehensive approach in terms of identification of areas to improve, prioritisation of resources and approbation of actions between projects.

The overhead for recovery after faults is being addressed by better fault tracking and measures to reduce the number of tunnel interventions, with remote resets and surface controls, and the speed of fault interventions is being improved with measures like remote radiation surveys.

For improving still further the operation efficiency, all procedures for the HL-LHC should be robustly established and maintained, with optimisation of important items like BLM thresholds made regularly. Cycle efficiency can be improved with actions like combined ramp and squeeze, and more efficient and optimised set up, including beam preparation in the injectors, is also important. There are also specific system upgrades which should be examined in this context, for example deploying 2-quadrant power supplies on critical circuits to reduce ramp-down time.

The key topic of R2E was also described in some detail, drawing attention to the fact that the requirement for HL-LHC in terms of "false" beam dumps per accumulated fb^{-1} of data is more than a factor 100 below that achieved in 2011.

Main conclusions

- Fault fixing is only part of the problem: there are also large overheads when a fill is slot (in ramp, squeeze or physics);
- The number one cause of lost fills was not fault related, but due to beam losses with the tight collimator settings. The gain in efficiency from choosing somewhat relaxed operational parameters might outweigh the slight loss in peak performance;
- The faults on the systems, especially the huge distributed ones like QPS and cryogenics, must continue to be addressed, with the R2E mitiagations critical;
- Further big improvements are not realistic - instead the performance needs to be edged up by working "on the % level" on many fronts;
- A large effort in the HL-LHC era will be needed just to reach the 2012 efficiency levels. We cannot count at this stage on doing much better;
- Coordination of the overall efforts to improve HL-LHC efficiency is needed; presently this effort is distributed widely.

50 ns BACKUP SOLUTION

The target and achievable parameters for 25 and 50 ns operation were compared. For 50 ns, the injector chain falls short of the required bunch population of ~3.7×10^{11} p+ due to the intensity limits in the PS from longitudinal instabilities. A realistic bunch population limit of 3.0×10^{11} p+ was used in the performance comparison.

The possible show-stoppers for 25 ns operation were presented and evaluated. These include machine protection absorbers, beam induced heating, UFOs, beam-beam and e-cloud. The expected limits for each of these effects were presented. The protection absorbers will require new materials and possibly new optics and layouts, but should be solvable. Beam-induced heating depends on whether a broad- or narrow-band impedance is being considered - for both 25 and 50 ns beams, the factor of increase in power deposited is about the same, with 50 ns slightly worse for broad-band impedances. For UFOs the 25 ns beam provoked an order of magnitude increase in the rate, but this appeared to condition down quickly. For beam-beam the head-on tune shift will be worse with 50 ns beam, and the crossing angle of 590 μrad should be enough for the long-range for both 50 and 25 ns.

Given the present state of knowledge, the main threat for 25 ns seems to be from e-cloud. The 2012 scrubbing tests showed that the scrubbing at 450 GeV does not behave as expected. The e-cloud is still present in the triplets, despite 2 years of high-intensity 50 ns operation, and the cryogenic heat load at 4 TeV increased by a factor of 4, coming only from e-cloud in the dipoles. No scrubbing was seen at 4 TeV.

This could limit the total number of bunches in the LHC to around half of the nominal 2808. Possible mitigations include the use of the special doublet scrubbing beam developed initially for LIU-SPS and tested in 2012, increasing the cryogenic power of the arcs for the dipoles, and coating or electrodes in the new HL-LHC triplets.

The possible performance reach with 50 ns spacing was evaluated to estimate what this beam could bring as a backup. The fill length was modelled using the observed exponential fit, which gives results close to those observed in 2012 (and about 15% lower than modelling using a fixed average fill length of 6 hours). taking 160 days of physics operation and luminosity levelled to a pile-up limit of 140, the expected performance with 2012 efficiency is bout 120 fb^{-1} per year with or without crab cavities. For comparison the same model with 25 ns gives 220 and 170 fb^{-1} per year with and without crabs, respectively.

It was noted that a physics efficiency of beyond 50% is unrealistic - already to reach the 36% achieved in 2012 will be a major accomplishment.

Extending the run length obviously benefits the total prorata, for both 25 and 50 ns spacing. Because of the strong levelling and relatively short (compared to the levelling time) fill lengths expected, there are no injector upgrades identified which could make a significant improvement to the 50 ns LHC performance. It was also pointed out that the very high single bunch intensity of 3×10^{11} p+ might also pose stability problems in LHC, as the maximum accelerated and collided in 2012 was 1.8×10^{11} p+.

Main conclusions

- 25 ns spacing is the clear preference but some uncertainties remain, the main one of which is e-cloud. 2015 operation will be key in determining whether LHC can run efficiently with this bunch spacing;
- The alternative of 50 ns bunch spacing is attractive from an e-cloud point of view, but cannot compete in terms of delivered performance, with the pile-up limit of 140 restricting the luminosity. The expected performance is about half that of 25 ns, under the current assumptions;
- No additional improvements have been identified which would allow 50 ns to compete with 25 ns. Efficiency and the crab cavities (for 25 ns) are more important than stretching the beam parameters from the injectors;
- Intermediate schemes (e.g. 8b-4e) should be tested during Run 2, as they provide a bridge between 25 and 50 ns in terms of performance and also in terms of limitations.

OVERALL CONCLUSIONS AND DISCUSSION

The analysis of the performance reach with the full baseline upgrade scenario showed that, under the agreed assumptions of maximum pile-up of 140 events per crossing and a physics efficiency of 36%, the HL-LHC integrated luminosity per year would be about 230 fb^{-1} for a uniform fill length of 6 hours. This number will be reduced for a realistic distribution of fill lengths, such that the yearly total is expected to be around 220 fb^{-1}.

This yearly total is rather insensitive to the injected bunch population, provided that this is above about 1.9×10^{11} p+. Increasing the number of protons available from the injector chain only contributes to improving the integrated luminosity if either the efficiency or the pile-up limit can be improved.

The foreseen injector upgrades therefore match well to the expected performance limits in the HL-LHC. However, there appears to be little margin, either to improve performance should HL-LHC be able to accept higher intensities, or for alternative schemes should unforeseen limitations arise. It is therefore very important to keep pushing in directions which could bring more margin for operation and improvement - in this regard, the proposal to investigate a 200 MHz RF system in the LHC appears to be very promising, to gain 25% in the intensity which can be injected into the LHC, and to help overcome several of the identified limitations in the LHC proper.

More detailed planning of the LS2 and LS3 shutdowns is needed for HL-LHC, to account for co-activities and to identify potential bottlenecks like cabling, where extra resources might be required well in advance to prepare or advance key activities. The work already done for the injectors needs to be integrated, and all other major projects need to be included in this exercise to avoid last-minute difficulties.

Improving the LHC physics efficiency and the pile-up limit are the keys to opening the door to higher overall performance, and both should be investigated with all possible means. Strengthening the coordination of the efficiency improvements for the HL-LHC era seems mandatory, and all methods to allow an increase in the acceptable pile-up for the experiments should be followed up, both on the experiments' and machine side (including schemes for reducing pile-up density which may allow some trade-off with pile-up).

The flexibility in the beam production schemes in the injectors is important to maintain and even enhance, to allow efficient luminosity ramp-up and the ability to react rapidly to unexpected situations, as well as giving access to the widest parameter space to match to HL-LHC's needs. THe investigations of alternative schemes and ideas should continue across the complex.

In case of severe problems with 25 ns it seems inevitable that the overall luminosity production will suffer, since there is no way to reach an equivalent performance with 50 ns. For similar machine efficiency and pile up limit the luminosity production with 50 ns is about 50% of that expected with 25 ns. No upgrades specific to 50 ns were identified. Intermediate filling schemes should be tested ready to be deployed if needed, to minimised the impact of a difficult commissioning with 25 ns. Experience with LHC Run 2 will be critical in this respect.

ACKNOWLEDGMENT

The speakers are congratulated for the excellent quality of their presentations, together with the impressive preparatory work. In addition the many people who have contributed to the results and analyses presented are gratefully thanked for their invaluable contributions.

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SUMMARY OF SESSION 5 ON ION OPERATION DURING HL-LHC

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Abstract

The session goal was to review the LHC upgrade plans related to the ion operation and to discuss the related machine updates for LHC RunII and RunIII and during the HL-LHC operation period.

INTRODUCTION

The session discussed machine upgrade plans particularly relevant for the ion operation during the HL-LHC operation period and had a look at options for extended ion runs during the LINAC4 connection to the PSB. In this context the session reviewed the current baseline ion operation schedule of one month of dedicated ion run per year and discussed alternative operation options for the ion beam operation. The session featured 5 talks covering the topics of:

1) The Experiments perspective by Emilio Meschi;
2) The performance projections of the LHC injector complex with ion beams by Django Manglunki;
3) Options for running the LHC with ions during the LINAC4 connection by Jean-Babtist Lallement (most of this presentation was already addressed in the previous session);
4) Options for running the source and Linac3 with ion beams in the future by Detlef Kuchler;
5) Future heavy-ion performance projections of the LHC after LS1 by John Jowett.

EXPERIMENTS PERSPECTIVE

The experiments perspective talk first discussed the physics highlights of the LHC RunI operation (Quark-Gluon plasma measurement and Jet suppression in p-Pb collisions). The presentation highlighted the need for regular 'control experiments' (e.g. p-p data taking and p-Pb runs at intermediate beam energies [e.g. Pb-Pb @ 5 TeV and 5.5 TeV and p-Pb at 5 TeV and 8.2 TeV]) in addition to the core ion schedule and the implied configuration changes for the asymmetric p-Pb collision (requiring additional workload and schedule time for the machine operation) and a regular polarity reversal for the ALICE spectrometer magnet. The p-p data taking at ALICE during the LHC RunII operation requires 5 orders of magnitudes lower luminosities as compared to the General Purpose (GP) experiments ATLAS and CMS which might imply additional operational challenges as compared to the LHC RunI period. Furthermore, for background reduction, ALICE requires a vacuum of 10^{-9} mbar or better which might be challenging to achieve during RunII with the 25ns bunch spacing and its associated electron cloud activities.

The ALICE RunII wish list consists of:

- 2015: Operation with p-p collision for minimum bias measurements over a period of about 24 weeks with a luminosity between 10^{29} and 10^{30} cm^{-2} s^{-1} and Pb-Pb collisions for 4 weeks with a levelled target luminosity of 10^{27} cm^{-2} s^{-1}.
- 2016: Operation with p-p collisions for rare triggers over a period of about 24 weeks with a luminosity of 5-10 10^{30} cm^{-2} s^{-1} plus a 4-week dedicated data taking run with Pb-Pb collisions and a levelled luminosity of 10^{27} cm^{-2} s^{-1}.
- 2017: Operation with p-p collisions over a period of about 24 weeks with a luminosity of 5-10 10^{30} cm^{-2} s^{-1} plus a 4-week dedicated data taking with p-Pb with a levelled luminosity of 5-10 10^{27} cm^{-2} s^{-1}.

The ATLAS experiment would like to accumulate an integrated luminosity of 3 nb^{-1} by LS3 and all experiments would like to collect at least 1 nb^{-1} by LS2. ALICE will undergo a major detector upgrade during LS2 and aims at a total integrated luminosity of 10 nb^{-1} after LS2. ALICE will require a levelled luminosity for both Pb-Pb and p-Pb operation while ATLAS and CMS will not and LHCb would like to have the p-Pb operation ***not*** scheduled at the end of the LHC RunII period, which is currently the baseline scheduling for the ALICE experiment.

All experiments look at the operation with different ion species (e.g. Pb-Pb, p-Pb, Ar-Ar and p-Ar) after LS2 (there is even an expression of interest in the operation with N and O beams by LHCf but the physics case still needs to be approved by the LHCC) and all experiments prefer a regular annual running with ions beams and are ***not*** in favour of an extended ion run as part of an extended technical stop for the LINAC4 connection with reduced ion operation after the LINAC4 connection.

PERFORMANCE OF THE INJECTORS WITH IONS AFTER LS1

The presentation on the LHC injector complex operation with ion beams started with a summary of the injector performance with ions during the LHC Run1 period. During RunI, the injectors prepared 2 bunches with 200ns spacing in the PS, injected 24 ion bunches per SPS cycle and prepared a total of 360 bunches per beam for collisions in the LHC. An increase of the bunch intensity for operation after LS1 will not be trivial as the RunI intensities were already at the limit of IBS (in the SPS) and luminosity burn-off rates would probably demand leveling. Increasing the number of PS injections into the SPS is also not favored due to the required increase in the SPS injection plateau and the associated additional beam emittance blow-up.

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However, a 100ns batch compression in the SPS could already be envisaged for RunII (already planned for the PS but without the required SPS injection upgrade) leading to a maximum of 432 colliding bunches per beam in the LHC.

An upgrade of the SPS injection system could increase the number of colliding bunches in the LHC from 432 to 624 bunches. Higher bunch intensities in LEIR (which was already operating above design intensities during RunI) would require further studies before operation for the LHC.

The implementation of Slip stacking in the SPS could lead to even smaller bunch spacing, e.g. 50ns. In all cases it is necessary to operate LINAC3 at 10Hz (the LINAC3 source is already pulsing with 10Hz).

HOW TO RUN IONS IN THE FUTURE

Detlef Kuchler summarized the operational records and normal operational performance of the source and Linac3 operation during LHC RunI and highlighted the plans for upgrading Linac3 to 10Hz rep-rate. Further upgrade plans include the option for multi charge acceleration, the re-design of the oven, allowing for longer operation time between two oven refills (the optimum goal would be to achieve an oven fill length in excess of 4 weeks), and the development of a dedicated source test stand for a continuous performance improving developments.

The presentation further highlighted the wish for dedicated ion runs in 2015 for machine developments and tests.

FUTURE HEAVY-ION PERFORMANCE OF THE LHC

The presentation highlighted the need for detailed bunch-by-bunch modelling (IBS blow up at SPS and LHC injection plateaus) for the estimating the luminosity evolution and maximizing the performance in the LHC. John Jowett estimates that performance levels of $2.8\ 10^{27}$ $cm^{-2}\ s^{-1}$ and $3.7\ 10^{27}\ cm^{-2}\ s^{-1}$ are within reach for ATLAS and CMS with the 2011 bunch pattern and the new 100ns bunch spacing scheme respectively. The luminosity in the ALICE detector needs to be levelled at $10^{27}\ cm^{-2}\ s^{-1}$ before the ALICE detector upgrade is completed during LS2.

The luminosity decay in RunII will be dominated by burn-off due to the beam collisions at the Interaction Points.

The estimated performance for asymmetric p-Pb collisions is estimated to be between $2.5 – 7\ 10^{29}\ cm^{-2}\ s^{-1}$ and $4.3 – 12\ 10^{29}\ cm^{-2}\ s^{-1}$ for operation at 4 ZTeV/c and 7 ZTeV/c respectively.

Performance levels of $6\ 10^{27}\ cm^{-2}\ s^{-1}$ are within reach for Pb-Pb operation after LS2. This value would correspond to 6 times the original design performance. The performance after LS2 will be limited by losses in the cold sections of the LHC due to Bound Free Pair Production and Electromagnetic dissociation and the emittance blow up due to IBS. The first limitation can be mitigated by the installation of additional collimators in the cold section of the dispersion suppressors (formerly called ‘cryo collimators’) or, in the case of ATLAS and CMS (less easily for ALICE), by a technique of orbit bumps that was demonstrated in 2011 for CMS.

Discussion and Conclusions

The general discussion identified the following key observations:

- ALICE highlighted the need for regularly scheduled dedicated ion operation periods on an annual base during each LHC run period and expressed the wish for a clear commitment to a ‘standard running scenario’.
- The LS2 duration with LINAC4 connection as H-injector is estimated to take 20.5 month.
- The experiments have no interest in a long dedicated ion run during an extended technical stop for the LINAC4 connection to the PSB before LS2.
- While dispersion-suppressor collimators are foreseen for installation in IR2 during LS2, these additional collimators are not yet foreseen in the baseline LS3 upgrade plan for IR1 and IR5. Should it turn out that losses from bound free pair production limit the peak Pb-Pb luminosity during Run III, the luminosity during the initial part of a fill may have to be levelled at a lower value in the ATLAS and CMS experiments as compared to ALICE. However this appears increasingly unlikely given the recent optimistic estimates of quench levels and the successful demonstration of a mitigation technique in 2011. The impact on integrated luminosity should be modest.
- Levelling the RunII Pb-Pb luminosity differently in each experiment may have to become the default way of operation.

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REVIEW OF LHC AND INJECTOR UPGRADE PLANS - SUMMARY

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Abstract

From 29 to 31 October 2013 the Review of the LHC and Injector Upgrade Plans (RLIUP) took place in Archamps (Haute Savoie). This paper summarizes the RLIUP conclusions, which were presented at CERN on 8 November 2013.

HISTORY & MOTIVATION

The LHC schedule for the next ten years considered prior to the RLIUP workshop had been proposed at a time when much less information had been available and it had not been developed in any self-consistent (iterative) way.

The typical machine performance of a high-energy collider is such that in the early years of operation, spectacular performance increases can be attained by pushing the accelerator physics limitations (intensity, beta*, emittance …). After some years of operation, these possibilities become exhausted. Slower performance increases then come about through upgrades and through small (%) improvements on a multitude of fronts including machine availability etc. LHC is entering this new phase, i.e. upgrades and small improvements on many fronts. Both of these need careful planning.

MAXIMUM PERFORMANCE GOAL

The overriding performance goal for the 10-20 year schedule is to maximize the LHC performance in terms of useful integrated luminosity. The *peak luminosity* of the LHC is limited by pile up in the detectors and by the accelerator performance. The *useful integrated luminosity* (for the 4 detectors) is determined by the time available for physics (iterative with shutdowns) – implying a play-off between the upgrades and the time lost for physics (see Fig. 1 for an educating example) – and, especially, by the *timing of the upgrades* (the sooner the better).

During discussion with the CMAC (whose members participated in the RLIUP review) also the possibility of a future increase of the *beam energy* has been raised.

SHUTDOWNS – WHEN & HOW LONG?

The *factors for planning the timing* (start) of the shutdowns are:

- the technical lead-time needed (for the experiments and for the machine);
- the funding profiles (mostly for the experiments);
- the radiation damage effects for the experiments and for the machine, which limit the maximum integrated-luminosity values prior to certain upgrade steps and thereby define date limits; and
- the need for regular preventative maintenance (mostly of the machine, e.g. for cryogenics).

The *factors driving the duration* of the shutdowns are:

- *the amount of work* to be done (both on the machine and on the experiments);
- the manpower resources needed (and co-habitation);
- the environment (induced *radiation*) with related specific manpower limitations; and
- the efficiency of the work execution (access times etc.).

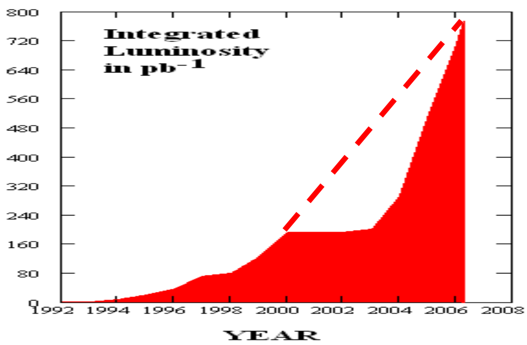

Figure 1: Integrated luminosity evolution of HERA before and after its luminosity upgrade together with an extrapolation (dashed line) how the luminosity would have developed without the upgrade.

STRUCTURE OF THE REVIEW

At RLIUP five different scenarios have been considered for a comparison of performance and cost. Each scenario encompasses all accelerators in the LHC chain.

For each scenario the tasks have been

- to identify the technical requirements (work needed and shutdowns) ; and
- to evaluate the peak and integrated yearly luminosities (time available for physics).

We note that in the preparation for the review, these scenarios were meant for *comparison*. Later, it became apparent that they could be better used for the evaluation of the *evolution of the performance with time* over the long time scale examined.

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REVIEW OBJECTIVES

The goal of the review was to assess the *critical* criteria for the evaluation of the long term performance of the LHC, including:

- radiation *limits for the detectors* (fb^{-1}) constraining the start of LS3;
- the radiation *limit for the inner triplets* etc. also defining a latest possible starting date for LS3;
- the *peak luminosity,* including related issues like pile up, operation with 25-ns bunch spacing, brightness from injectors, UFOs, beam heating, instabilities; and
- the machine availability.

INPUT ON RUNS AND SHUTDOWNS

The runs and shutdowns required by the different experiments and machine teams compiled by M. Lamont are summarized in Table 1. The overriding requirements are highlighted by the red boxes.

Table 1: Required runs and shutdowns per experiment or machine activity [1] (courtesy M. Lamont).

	Run 2	EYETS	LS2	Run 3	LS3
ALICE		Contingency	18 months Shift into 2018		
ATLAS	3 years	No	14 months Start 2018		27 (35) months Start 2022
CMS	EYETS plus N months	5 months	14 – 18 months Not before summer		30 – 35 months Start 2023
LHCb		Contingency	18 months End 2018		
Cryo	4 years max.	Selective maintenance			
Maintenance		Selective maintenance	16 mo.		20 months
LIU		9.5 months for L4 connect/or cable prep.	20.5 months beam to pilot		
LHC	3 years max contiguous	Opens way for year 4	18 mo.	3 years	2 years

ANSWERS TO IMPORTANT QUESTIONS

The RLIUP workshop provided the following answers to some important questions:

- the *radiation limit* for detectors [2] and machine [3] is 300–500 fb^{-1} (where the machine possibly is more critical);
- *LS2* needs ~18-24 months;
- *LS3* needs ~ 24-36 months; and
- *Run2* should last for 3 years.

LUMINOSITY

The overriding limitation to integrated luminosity is due to event pile-up (PU). The presently proposed upgrade to the detectors foresees an increase to 140 PU (average) with a possible extension to around 200.

Several new schemes have been proposed on the machine side in order to alleviate the PU problem by *reducing the "pile-up density"*. These schemes will be further investigated and tested as soon as possible.

Together machine and detectors should continue to explore new possibilities to allow *even higher PU* than the 140 (200) presently foreseen.

MACHINE AVAILABILITY & TURN AROUND

The limitation (from the pile up constraints) is one on the *peak luminosity*. Therefore, one should *optimise the time available for physics* by

- *minimising the down time* due to faults, through a more *in-depth analysis of down-time periods and "amplification factor"* and through a *prioritized* (by risk analysis) *mitigation* of the most critical faults by consolidation; and
- *faster turnaround* "physics to physics" through technical *upgrades* to the LHC equipment (e.g. modification of power converters to allow faster ramp down of magnets), and through more *streamlined operational procedures* (e.g. combined ramp and squeeze).

"TO DO" LIST

At RLIUP the following actions were determined:

Concerning *resources*, a global (i.e. comprising machine, detectors and services) **resources-loaded schedule** is needed as soon as possible. This schedule can then be used to identify and correct weaknesses in some areas of expertise (e.g. cabling…)

In view of the *ALARA* principle, radiation must be optimized by design (minimum access time needed for exchanges and use of the right materials "ActiWiz" [4]).

Electron-cloud effects could hinder operation with 25-ns bunch spacing [5]. Both short term mitigation (new scrubbing schemes, alternative intermediate filling schemes such as "8b+4e") and long term solutions must be sought. This issue is so critical that even very costly new technical schemes should not be excluded such as partial or full coating of chambers, clearing electrodes, etc.

IMPORTANT COMMENTS

The European Strategy stipulates that "*Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting **ten times***

more data than in the initial design, by around 2030” [6].

“The STRONG physics case for the HL-LHC with 3000 fb^{-1} comes from the imperative necessity of exploring this scale as much as we can with the highest-energy facility we have today (note: ***no other planned machine, except a 100 TeV pp collider, has a similar direct discovery potential***). …

We have NO evidence of new physics, which implies that, if New Physics exists at the TeV scale and is discovered at $\sqrt{s}$ ~ 14 TeV in 2015++, its spectrum is quite heavy; it will require a lot of luminosity (HL-LHC 3000 fb^{-1}) and energy to study it in detail, with important implications for future machines (e.g. most likely not accessible at a 0.5 TeV LC).

HL-LHC is a Higgs Factory*. It can measure the Higgs coupling with an accuracy of a few %.”* [7].

STRATEGY

LHC has been constructed, operated and will continue to be operated on a CONSTANT BUDGET. The HEP community owns a beautiful scientific facility, unique in the world. It has invested (and is investing) a huge amount of its resources in this unique facility both for construction and for operation.

The FULL operational costs integrated over the future operating years exceed the proposed upgrade costs. ***Hence this unique facility should be operated in the most efficient way possible.*** This means:

(1) both upgrades, *LIU and HL-LHC*, should *aim for the maximum useful integrated luminosity* possible;

(2) *LS3 should come as soon as possible* in order to maximize the integrated luminosity (every delay by one year of LS3 “costs” 200fb^{-1}); and

(3) LS2 should not delay LS3.

The ultimate goal of 3000 fb^{-1} by ~2035 is *challenging* but attainable.

SHUTDOWN SCENARIOS

Table 2 presents five plausible shutdown scenarios. In Scenario 1 (S1) LS2 (2018) lasts for 1.5 years, and LS3 (2022) for 2 years. S2 equals S1 delayed by 1 year; and S3 is the same as S2, but delayed by 1 year, [or as S1 delayed by 2 years]. In Scenario 4 (S4), LS2 (2018) lasts for 2 years, and LS3 for 3 years. S5 equals S4 delayed by 1 year. Figure 2 compares the predicted time evolution of the integrated luminosity for these various scenarios. For example, the accumulated luminosities at the time of LS3 are 280, 330, 380, 280, and 330 for Scenarios 1 to 5, respectively. It should be noted that the total luminosity numbers given for these five scenarios are meant to allow relative comparisons, but do not represent absolute luminosity forecasts.

TO BE DONE WITH SOME URGENCY

Actions soon to be done include:

- decision on the shutdown scenario (management of CERN and of the detectors);
- implementation of a *new plan*, entailing a *global resources-loaded schedule* for accelerators and experiments, taking into account *limitations imposed on personnel by radiation* and providing *improved access to the tunnel*; and
- submission and collection of *requests*, to identify and strengthen weak areas of expertise.

Table 2: Five shutdown scenarios. The numbers indicate the expected integrated luminosity per year. The bottom column shows the total integrated luminosity.

	LS2=1.5y, LS3=2y			LS2=2.0y, LS3=3y	
Year	S1	S2	S3	S4	S5
2015	35	35	35	35	35
2016	50	50	50	50	50
2017	50	50	50	50	50
2018		50	50		50
2019	25		50		
2020	60	25		25	
2021	60	60	25	60	25
2022		60	60	60	60
2023			60		60
2024	150				
2025	250	150			
2026	250	250	150	150	
2027		250	250	250	150
2028	200		250	250	250
2029	250	200			250
2030	250	250	200	200	
2031		250	250	250	200
2032	200		250	250	250
2033	250	200			250
2034	250	250	200	200	
2035	250	250	250	250	200
Total	2580	2380	2180	2080	1880

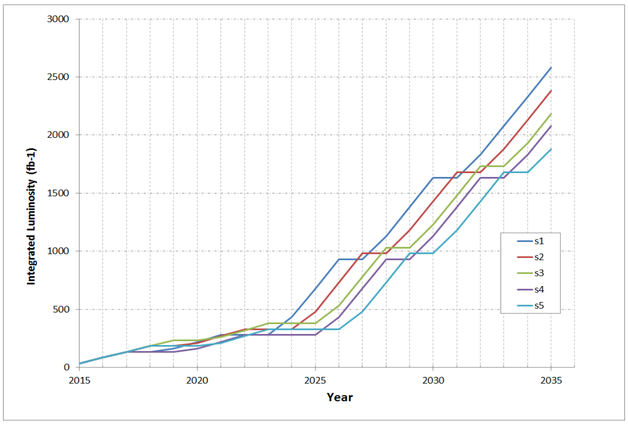

Figure 2: Predicted integrated luminosity evolution for the five shutdown scenarios of Table 2.

SUMMARY

The LHC/HL-LHC *performance* will be determined by pile-up and pile-up density (detectors and machine); by 25-ns: e-cloud, scrubbing, short term mitigation, long term solution; and by machine availability calling for a *minimisation of down time* and s*peeding up of the turn-around time.*

Shutdowns have to be planned well in advance, including a global *resources-loaded schedule*, the identification and rectification of *weaknesses in some expertise areas*, and a design for ALARA with minimum intervention time and use of the correct materials (ActiWiz).

An *increase of the maximum beam energy* in the medium term should be investigated, noting the planned use of 11T magnets for collimation.

REFERENCES

[1] M. Lamont, “Post LS1 Schedule,” Proc. 2013 RLIUP workshop (2013).
[2] B. Di Girolamo, “Detector Limits,” Proc. 2013 RLIUP workshop (2013).
[3] L. Bottura, “What could stop us, when and how long?,” Proc. 2013 RLIUP workshop (2013).
[4] H. Vincke, C. Theis, “ActiWiz – optimizing your nuclide inventory at proton accelerators with a computer code,” NBI Workshop 2012
[5] J. Wenninger, “Integrated performance of the LHC at 25 ns without and with LINAC4,” Proc. 2013 RLIUP workshop (2013).
[6] A. Ball, “Highlights from EFCA HL-LHC experiments workshop: 1-3 October 2013,” Proc. 2013 RLIUP workshop (2013).
[7] F. Gianotti, “The Physics Landscape,” Proc. 2013 RLIUP workshop (2013).

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