Parameters and operation plans for 2011

J. Wenninger, CERN, Geneva

Abstract

The assumed LHC beam parameters for 2011 are first summarized. The overview of the 2011 schedule is presented and includes hardware commissioning, beam recommissioning, re-validation, scrubbing, technical stops, MD, ions and special physics run requests. A proposal is made for the strategy in intensity stepping up and potential issues are described together with possible actions. Finally, the potential peak and integrated luminosity are given.

INTRODUCTION

Client request

The LHC experiments wishes for 2011 may be summarized as follows:

- For ATLAS and CMS the (integrated) luminosity should be as high as possible. The integrated luminosity should exceed $1\ \mathrm{fb}^{-1}$.
- For LHCb the luminosity should not exceed around $3\times10^{32}\mathrm{cm}^{-2}s^{-1}$, and the number of events per crossing μ should not exceed 2.5 (based on a visible cross-section of 72.5 mb).
- For ALICE the luminosity should not exceed around $4\times10^{30}\mathrm{cm}^{-2}s^{-1}$.
- TOTEM wants to operate during normal physics runs down to a distance of 15σ from the beam (as compared to 18σ in 2010). TOTEM would like a leading probe intensity bunch to be added to the standard filling scheme.

A number of special requests have also been expressed.

- Like in 2010, the experiments want to perform Van De Meer scans (i.e. extended luminosity scans). The exact conditions have not been defined yet. To simplify the scan procedure, the TCTs should be moved together with the beams.
- ALICE made a request for a special run at 1.38 TeV (the energy equivalent to the nucleon energy in Pb-Pb collisions). ALICE wants to collect around 50×10^{6} events. This corresponds to a few fills with low intensity bunches.
- TOTEM (and ALFA) want to take data with the 90 m β^{*} optics (which must first be commissioned). The beams should be composed of a few bunches with a charge of $6-7\times10^{10}$ p. They would like to operate with Roman Pots at a distance of $7-8$ and $5-6\sigma$ from the beam. This requires closing the primary collimators to $3-4\sigma$. The emittances should be 3 and 1μm.

Finally both ALICE and LHCb would like to flip their spectrometer polarities from time to time (most likely during technical stops). The LHCb spectrometer affects only the horizontal orbit, the correction of the non-closure (non-reproducibility) using external compensators is working well. For ALICE the solenoid is flipped at the same time. In principle the ALICE spectrometer should only affect the vertical orbit, but due to the large coupling from the solenoid, there is an important perturbation of the horizontal orbit. In 2010 the structure of the crossing angle non-closure correction knobs mixed the horizontal and vertical planes, which made the reversal of the ALICE spectrometer and solenoid tricky. In 2011 a simpler correction of the non-closure will be available in YASP, and the knobs will properly decouple the planes (at least for ALICE).

ENERGY

It is assumed here that the LHC will be operated at 4 TeV, even if the decision will only be taken at the Chamonix workshop in January 2011. The difference with respect to 3.5 TeV is moderate in terms of operational issues:

- The reach in β^{*} is slightly increased at 4 TeV.
- The physical emittance scales with the inverse of the energy, luminosities at 4 TeV are 14% higher.
- The quench threshold is some 20% lower at 4 TeV, see Fig.1. This has a small effect on the criticality of UFOs.

BEAMS

The following beam types are considered as possible candidates for 2011 and are available in the injectors [1]:

- The 150 ns beam is operational, and up to 368 bunches were used at 3.5 TeV in 2010. With this scheme up to around 450 bunches may be injected into the LHC. The emittances at the exit of the SPS may be as low as 1.5 μm for intensities in excess of 1.2×10^{11} p per bunch.

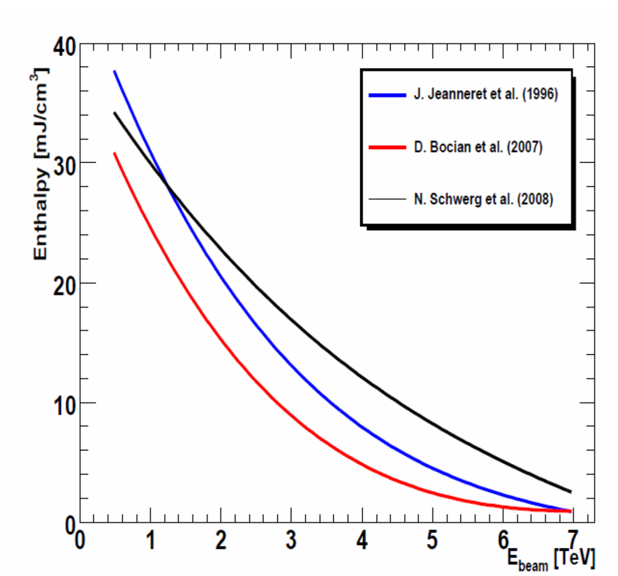

Figure 1: Estimated magnet enthalpy as a function of the energy for 3 different models (Courtesy M. Sapinski).

- The 75 ns beam is operational in the injectors, but some moderate scrubbing time is required to ensure adequate vacuum conditions with high intensity. Up to 950 bunches may be injected with this beam. At the exit of the SPS bunch intensities of 1.2×10^{11} protons with transverse emittance of 2μm have been achieved so far (single batch transfer PSB-PS).

- The 50 ns beam is likely to be only used for MD and beam scrubbing tests. Electron cloud effects have been observed in the arcs with this beam, and significant beam scrubbing time may be required before this beam may be in a state for use in regular operation [2].

With the good machine stability (and thanks also to the feedbacks), good lifetimes of the beams and excellent collimation performance, there is no limit on the total intensity for those beams.

The filling schemes will have to incorporate a leading probe bunch (intensity around 10^{10} protons) and a first injection with $12 - 24$ nominal bunches. Injections of up to 96 and 144 bunches should be achievable despite issues with the BLMs. Those constrains use up around 3μs of the LHC circumference.

Beam density

In terms of maximum beam density, the collimators are designed to stand the nominal beam at 7 TeV. For the TCDQ the exact limit is not yet known (work in progress), but the limit is expected to be lower than the nominal beam. It must be noted that for all the considered beams (50 ns or larger spacing) the beam load is a factor 2 and more less (in terms of number of bunches) than a nominal 25 ns beam.

The energy density ρ_E of the showers scale to first order as [3, 4]

$$\rho_E \propto \frac{N\,E}{\varepsilon_n/E} = \frac{N\,E^2}{\varepsilon_n} \qquad (1)$$

where N is the number of particles and ε_n the normalized emittance. This simple rule is similar to the scaling law for the Setup Beam Flag (SBF) intensity limit N_{SBF} as derived in :

$$N_{SBF}\,E^{1.7} \propto \mathrm{Constant} \qquad (2)$$

where the effects of the shower length and emittance scaling with energy where taken into account (assuming a constant value for ε_n).

Given the possible beam intensity and emittance performance from the injectors, there is no limit on intensity and emittance in 2011.

β^* REACH

The reach in β^* is defined by the (knowledge) of the aperture, the tolerances for collimator alignment and the reproducibility of the orbit. The orbit reproducibility has increased along the 2010 run. The ion period was better than the 150 ns periods which was itself better than the single bunch run in July/August. The improvements are due to a better control and correction of the BPM electronics temperature effects ($\approx 50\mu\mathrm{m/deg}$), as well to a better calibration procedure. The residual excursions that accumulate on the time scale of one month are around ± 0.2 mm peak-to-peak. Further improvements are anticipated in 2011 [5].

The reach in β^* has been presented elsewhere in this workshop [6]. With 'intermediate' collimators settings (as used in 2010) β^* of 2.5 m can be achieved without problems (thanks to the larger aperture in the triplets). With 'moderate' collimators settings (reduced margin TCT-triplet and TCT-TCDQ) β^* could be pushed down to 2 m or even 1.5 m. One must also take into account that below 2 m, the squeeze becomes more tricky, as the triplet errors start to play a non-negligible role. Aperture measurements should be performed in the early part of the 2011 run to define the final value of β^*. Squeeze settings should be prepared down to 1.1 m or so for CMS and ATLAS.

To gain aperture the separation of the beams should be reduced from ± 2 mm (injection and ramp) to ± 0.7 mm for the squeeze. This could be done in the first 2 minutes of the squeeze (or in the ramp). To keep things simple the crossing angles should be changed from injection ($\pm 170\mu$rad) to physics settings ($\pm 120 - 140\mu$rad) at the same time. The bumps changes will be implemented using the bump scaling feature of the orbit feedback. This will allow the squeeze to be performed in a single step.

ALICE

ALICE would profit from a β^* of 2 m for the vertex reconstruction. To reduce the separation during physics operation and gain aperture in IR2 (one critical point less) a β^* of 10 m could also be used. A squeeze to same β^* as the high luminosity IRs would reduce ion switch-over time, but this gain does not really justify to operate for the entire proton run with such a small β^*.

LHCb

LHCb has requested a β^* of 3.5 m as an optimum for integrated luminosity during intensity ramp-up and high luminosity operation at a recent LPC meeting. Overall a β^* of 4 to 5 m could represent a better optimum, which eventually also depends on the achievable (or expected) peak luminosity. To satisfy the LHCb requirements in terms of luminosity (see previous sections) a separation of up to $2\sigma^*$ may be required, unless β^* is squeezed dynamically during physics operation.

STARTUP 2011

The startup in 2011 will begin with a re-commissioning of the base machine:

- Inject the beams and obtain circulating beams. There is a good chance that a circulating beam may be obtained immediately with the settings of 2011 for the orbit, tune and chromaticity.
- Injection steering and rough optimization on TI2 and TI8.
- Establish asap a new base orbit for 2011. This orbit should be used on all phases, only the IRs bumps (separation and crossing) should change for different operating conditions. To establish this reference it is essential to have the best possible BPM calibration.
- The optics at injection must be checked and corrected if needed.
- The aperture should be measured at injection to confirm the reach in β^*.
- The collimators and absorbers must be setup completely around the new orbit at injection. The settings must be validated with beam tests (resonance crossing, debunched beam tests).
- Checkout ramp and squeeze with flat orbit and safe beam. Measure and correct the optics.
- Commission the ramp and squeeze with separation and crossing angles.
- Full collimator and absorber setup through the squeeze.
- Setup for collisions.

Numerous controls change are anticipated or have been requested, and some time must be anticipated for tests. Around 1-2 weeks are required for the machine protection system checkout.

RAMPING UP INTENSITY

The intensity ramp up strategy has not been discussed or decided at this moment in time. A reasonable guess based on the 2011 experience is:

- In a first phase the number of bunches is increased to 200 in steps of 50 bunches. This period will probably last around 10 days if all goes well. During this period the main sequence should be finalized. This ramp up could be done with 75 ns or 150 ns beams.
- A one week scrubbing run could possibly be inserted after this first phase.
- In a second phase the intensity would then be ramped up in steps op 100 (200) bunches up to around 900 bunches. A possible sequence could be: 200-300-400-500-600-700-900. Assuming a few fills at each step, this period would last around 3 weeks. The progress could be driven by e-cloud and vacuum, beam stability, UFOs, MPS issues, SEUs and OP considerations.

LUMINOSITY PERFORMANCE

The Hubner factor H relates the peak luminosity $\mathcal{L}_p$, the integrated luminosity $\mathcal{L}_{int}$ and scheduled time T_{op}

$$\mathcal{L}_{int} = \mathcal{L}_p \; H \; T_{op} \tag{3}$$

To set the scale: for $\mathcal{L}_p = 10^{32}\mathrm{cm}^{-2}s^{-1}$, $H = 0.2$ and T_{op} of 200 days, $\mathcal{L}_{int}$ is 172 pb^{-1}.

The Hubner factor may be estimated using the following simple model of the luminosity a typical fill. Assuming that each fill starts with a peak luminosity $\mathcal{L}_p$ and is dumped when the luminosity is halved, then the average luminosity is not far from $< \mathcal{L} > \simeq 3/4\mathcal{L}_p$. The integrated luminosity may therefore be expressed as:

$$\mathcal{L}_{int} = \mathcal{L}_p \; H \; T_{op} = < \mathcal{L} > \; \epsilon_{sb} \; T_{op} \simeq \frac{3}{4}\mathcal{L}_p \; \epsilon_{sb} \; T_{op} \tag{4}$$

where ϵ_{sb} is the ratio of time spent in stable beams with respect to the total run time T_{op}. From the above expression it is easy to deduce that

$$H \simeq \frac{3}{4}\epsilon_{sb} \tag{5}$$

for this simple model. To reach $H = 0.2$ the efficiency must be $\epsilon_{sb} \simeq 26\%$, a figure that has been achieved in 2010 in certain periods (for example during the ion period).

The tentative breakdown of the 2011 proton runs in terms of operational days taking into account MDs, technical stops, commissioning etc is given in Table 1: the total number of days at high luminosity T_{op} is 124 only days. For the following tables and figures $T_{op} = 125$ days will be assumed.

Table 2 presents luminosity estimates for 4 TeV based on 75 ns operation with 930 bunches for different values of

Item	Days
Run length	262
11 MDs (2 days)	-22
6 Technical stops (4+1 days)	-30
Special requests	-10
Commissioning	-28
Intensity ramp up	-40
Scrubbing	-8
Total	124

Table 1: Breakdown of the proton run in 2011 in terms of operational days.

β^* (m)	N_b (10^{10})	ε_n (μm)	E_{stored} (MJ)	$\mathcal{L}$ (cm$^{-2}s^{-1}$)	$\int\mathcal{L}$ (fb^{-1})
2.5	11	3.5	65.5	4.7×10^{32}	1.0
2.0	11	3.5	65.5	5.9×10^{32}	1.3
1.5	11	3.5	65.5	7.8×10^{32}	1.7
2.5	12	2.5	71.4	7.8×10^{32}	1.7
2.0	12	2.5	71.4	9.8×10^{32}	2.1
1.5	12	2.5	71.4	13.3×10^{32}	2.8

Table 2: Luminosity estimates for 75 ns operation, assuming 930 bunches. For 150 ns operation, the stored energy and luminosity figures should be halved. The integrated luminosity is based on 125 days of operation and H of 0.2

β^*, bunch population and emittance. For β^* of 2 m and below, it is possible to achieve peak luminosities in excess of $10^{33}\mathrm{cm}^{-2}s^{-1}$ provided the emittance is lower than nominal (but similar to what has been achieved for 150 ns in 2010) and the intensity slightly larger than nominal. The integrated luminosity is in the range of 1 to 3 fm^{-1} for 125 days of operation and H of 0.2.

Figures 2 and 3 indicate the bunch population and emittance required to reach $\mathcal{L}_p$ of 8×10^{32} and 10^{33} as a function of β^* assuming 950 bunches. The greyed area indicate the expected performance in terms of bunch population and emittance.

LUMINOSITY LEVELING

Luminosity leveling can be made with beam separation at the IR. This method was used very successfully and apparently without major impact on performance for IR2 in 2010. To reduce the peak luminosity $\mathcal{L}_p$ to the desired luminosity target $\mathcal{L}$, the required separation S is given in units of single beam size at the IP by:

$$S[\sigma] = 2\ln\left(\frac{\mathcal{L}_p}{\mathcal{L}}\right) \quad (6)$$

The separation is plotted as a function of the desired luminosity reduction in Fig. 4.

For ALICE the required beam separation is in the range of 3 to 4 σ^* depending on the final choice of β^*.

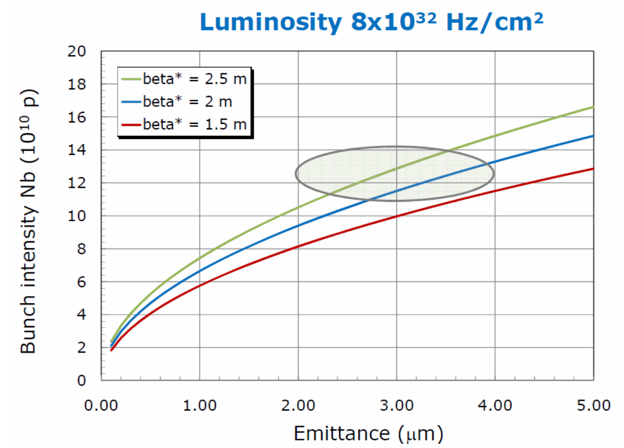

Figure 2: Required bunch intensity and emittance to reach a luminosity of $8\times10^{32}\mathrm{cm}^{-2}s^{-1}$ as a function of β^* (assuming 950 bunches). The shaded region is the typical reach of the injectors (details depend on the beams).

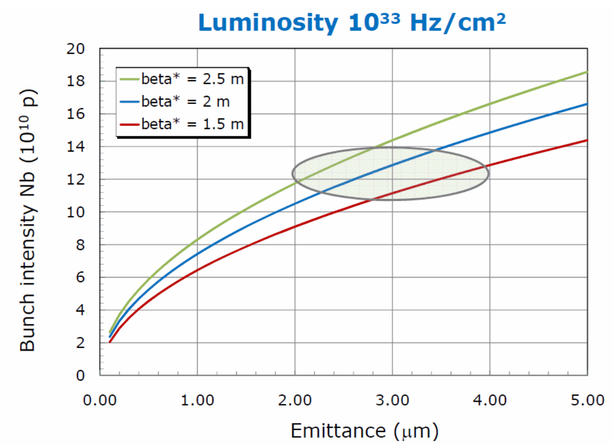

Figure 3: Required bunch intensity and emittance to reach a luminosity of $10^{33}\mathrm{cm}^{-2}s^{-1}$ as a function of β^* (assuming 950 bunches). The shaded region is the typical reach of the injectors (details depend on the beams).

For LHCb the beam separation and choice of β^* may be made like follows:

- Starting from the assumed peak luminosity in case of head-on collisions $\mathcal{L}_p$, the end-of-fill luminosity is assumed to be $\approx \mathcal{L}_p/2$.
- From the end-of-fill luminosity β^* is selected to match the LHCb peak luminosity. Some additional margin may be added (pick a somewhat lower β^*) to take into account that $\mathcal{L}_p$ could end up higher than expected!
- This ensures maximum luminosity up to the end of the fills, the luminosity being leveled with separation that can be reduced steadily as the luminosity decays in the fill.

Depending on the assumption on $\mathcal{L}_p$, the optimum β^* is in the range of 3 to 5 m. The required separation is in the range of 0.5 to 2 σ^*.

In case beam separation would eventually lead to beam-beam issues, the other choice for luminosity leveling is a continuous β^* reduction during a fill. In 2010 it was clearly demonstrated that the squeeze can be made very smooth thanks to feedbacks and reproducible optics, therefore this option could be envisaged. Technically one would have to define a number of squeeze points for LHCb, and 'jump' from one point to the next every now and then. In order not to loose to much time, those squeeze steps must be done in stable beams, else too much time would be wasted to move back and forth between stable beams and adjust. Such an operation would also require extra collimator setups and validations. Finally as a last word, it is worth mentioning that such a continuous β^* reduction is not an operation that is easy to commission with 900 bunches in the ring.

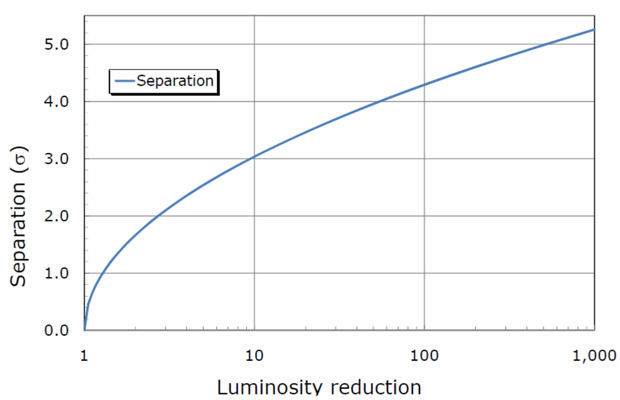

Figure 4: Separation of the beams at the IP (in terms of single beam size) as a function of the desired luminosity reduction.

IONS

The ion run foreseen at the end of 2011 will also profit from the β^* reduction used for the proton run. The current schedule foresees only 4 days of setup which could be tight in case the squeeze has to be commissioned for IR2. The reduction in β^* could boost the luminosity by a factor of roughly 2 with respect to 2010 (to $6 \times 10^{25}\mathrm{cm}^{-2}s^{-1}$). To increase the luminosity further the number of bunches must be increased beyond the maximum value of 139 used in 2011 with bunch spacing of 500 ns. This requires switching to the nominal ion scheme (100 ns bunch separation) and using crossing angles for collisions. It is important to note that in 2010 the bunch intensity was significantly higher than the design value, and that with the 100 ns nominal ion scheme the intensity per bunch will probably go down, reducing the gain from the increased number of bunches. Together with the β^* reduction, moving to the nominal ion scheme this could yield a total luminosity gain of up to a factor 10 (to $3 \times 10^{26}\mathrm{cm}^{-2}s^{-1}$) - but only if the bunch intensity remains high. It must also be noted that this increased luminosity will also make SEU effects more critical in the dispersion suppressors of IR1, IR2, IR3, IR5 and IR7.

CONCLUSIONS

The main conclusions concerning the performance in 2011 can be summarized as follows:

- The total number of days of high intensity operation is only around 50% of the total scheduled time for proton operation, around 125 days. In order not to waste more time operation must follow a good plan, diversion from the target of stable high intensity running will be very costly in terms of integrated luminosity.
- With 75 ns beams and β^* of 2 m or below it is possible to reach or even exceed peak luminosities of $10^{33}\mathcal{L}_{int}$. The integrated luminosity is in the range of 1 to 3 fm^{-1}.
- Operational efficiency is of prime importance and may favor certain beam parameters (for example lower emittances are better for injection) over others.
- Beam separation at the IR presents the simplest way of leveling luminosity for LHCb.

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