GLOBAL OVERVIEW OF BASELINE OPERATIONAL PARAMETERS

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Abstract

This paper gives a global overview of the machine and beam parameters most likely to be chosen for the LHC proton beam operation in 2015: beam energy, bunch spacing, optics and β^* reach, preferences for the mitigation of instabilities, etc. The peak instantaneous luminosity performance is sketched, both for a conservative scenario and for a pushed one.

INTRODUCTION

The first period of LHC operation ("LHC Run 1", end of 2009 to beginning of 2013) was characterized by extreme success, and culminated in the discovery of the Higgs boson. It is worth recalling that the few weeks of operation in 2009 and the whole 2010 were dedicated to the first exploitation of the machine, and the target of the year was set in terms of peak luminosity performance. The following years, 2011 and 2012, could then be dedicated to luminosity production, and the yearly targets were set in terms of integrated luminosity. Detailed values are reported in Table 1, and the positive balance between target values and achieved values helps stress the Run 1 success.

Table 1: Yearly targets and achieved results in Run 1.

Year	Target	Achieved
2010	$10^{32}\,\mathrm{cm^{-2}s^{-1}}$	$2.1\times10^{32}\,\mathrm{cm^{-2}s^{-1}}$
2011	$1\,\mathrm{fb^{-1}}$	$\approx 6\,\mathrm{fb^{-1}}$
2012	$20\,\mathrm{fb^{-1}}$	$23.3\,\mathrm{fb^{-1}}$

After the end of the first Long Shutdown (LS1, 2013-2014), Run 2 will start and it will be structured similarly to Run 1. The first year, after the major modifications carried out during the shutdown, will be dedicated to establishing proton operation at the higher energy and preparing for physics production. The following years, 2016–18, will be dedicated to physics production.

This paper summarizes the 2015 machine and beam baseline parameters as established for the preparation of this workshop, namely beam energy, bunch-to-bunch spacing, choice of the machine optics and β^* reach, options for the mitigation of instabilities, etc. The beam parameters and their evolution are also sketched, and folded into a projection of the peak luminosity performance.

BEAM ENERGY

The LHC was designed to run at a centre of mass energy of 14 TeV, i.e. 7 TeV per beam [1]. Due to issues with the quality of the main busbar splices, the beam energy was initially reduced to values for which the risk to have a 2008-like incident was evaluated to be negligible: 3.5 TeV/beam in 2010 and 2011, 4 TeV in 2012. During the LS1, a full campaign of splice verification and repair was performed, so to guarantee a splice quality allowing operation up to the design energy.

A campaign of training quenches will be performed during the hardware commissioning period preceding Run 2, in the second half of 2014. Estimates predict that ≈15 quenches will be necessary to reach 6 TeV/beam, ≈100 quenches for 6.5 TeV/beam and one order of magnitude more will be necessary to reach 7 TeV/beam [2]. The maximum possible beam energy will be known only at the end of the hardware commissioning campaign, foreseen for December 2014.

For 2015, it is decided to run at a maximum beam energy of 6.5 TeV (it is unlikely but possible that the hardware might limit the energy to lower values). This choice is partly determined by the LHC experiments' need to know the energy early on to perform the relative Monte Carlo simulations: a conservative but likely choice is preferred for 2015, while further increases towards the design value are foreseen for the following years.

BUNCH SPACING

The LHC experiments clearly state a preference for 25 ns spaced beams, as planned originally [1]. The alternative, 50 ns spaced beams, results in too high pile-up (μ, number of inelastic events per bunch crossing) for the same luminosity.

The maximum pile-up that the ATLAS and CMS experiments accept for 2015 at the start of a physics fill is $\mu \approx 50$ [3]. Note that if luminosity levelling is required, then the experiments would prefer levelling further down to the more comfortable levels of $\mu \approx$ 30–40.

From the machine point of view, 25 ns operation brings along new challenges and possible complications: the formation of electron cloud and the resulting need to scrub [4]; more long-range encounters, resulting in increased beam-beam related problems; the need for a larger crossing angle, also resulting in higher β^* values; higher total beam current and higher intensity per injection, concerns for beam intercepting devices and Machine Protection in general; increased statistics of Unidentified Falling Objects (UFOs), which additionally worsen with the higher energy [5].

OPTICS

The choice of which optics to use was recently discussed in several occasions [6, 7]. At present, the idea is to restart with an Achromatic Telescopic Squeeze (ATS)-compatible optics, which includes: new collision optics for all experiments (Interaction Region, IR), e.g. to overcome strength limitations of the 2012 optics, and compatible with the full ATS scheme and "flat beam" optics; an exact 90 degree phase advance between the dump kicker (MKD) and the dump protection absorber (TCDQ); increased separation at IR8 (see also [8]); new optics in IR4 to allow the increase of the β function at the transverse emittance instrumentation like wire scanners and synchrotron light telescope (which would otherwise be diffraction limited at the higher energy, due to the operational emittances that are more than a factor two smaller than in [1]).

It is fairly unlikely that innovative options are implemented for the 2015 restart (e.g. flat beams, or the combination of acceleration and squeeze, i.e. "combined ramp and squeeze"). At present there is no request from the LHCb experiment to perform the tilting gymnastics like in 2012 [3].

The full validation of this new optics will be performed in the coming months to prepare for a final choice at the Chamonix LHC Performance Workshop (22–26 Sept. 2014). The items that require follow-up are: the verification of the dynamic aperture, including beam-beam weak-strong simulations and octupoles; the verification of the presence of loss spikes due to a possible local collimation inefficiency; the impact of injection kickers misfires in IR8; the implications of the change of phase between the IR5 tertiary collimator and the dump kickers for ring 2 (the new phase advance is 90 degrees, resulting in the collimator to be directly exposed in case of asynchronous dump: most critical item in this list). The change of phase advance between the MKD and the TCDQ was already verified and approved.

β^* Reach

The configuration at injection is fairly similar to 2012: $\beta^* = 11\,\mathrm{m}$ in IR1/5, $\beta^* = 10\,\mathrm{m}$ in IP2/8, 170 μrad half crossing angles, and 2 mm separation (IR8: 3.5 mm).

Concerning the flat top, it is proposed to start with a fairly conservative scenario in the beginning of 2015, and push further the performance at a later stage (e.g. autumn 2015 or beginning of 2016). For commissioning efficiency, the cycle would be prepared and corrected up to the smallest β^*, while physics production would start at a conservative value and be pushed further after the main questions are resolved (e.g. beam stability and emittance control).

A possible start-up configuration includes [9]: 2012 collimator settings in mm in IR7, 11 σ beam-beam separation, up to 3.75 μm emittance, and results in: $\beta^* = 65\,\mathrm{cm}$ and 160 μrad half crossing angle. This configuration does not require luminosity levelling at IR1/5 and should not pose problems in terms of beam stability. It assumes a 2012-like aperture, which is to be verified at the start of commissioning.

The configuration could later be pushed to the following "ultimate" values [9]: 2012 collimator settings in σ, 10 σ beam-beam separation, up to 2.5 μm emittance, resulting in $\beta^* = 40\,\mathrm{cm}$ and 155 μrad half crossing angle. This configuration requires the beam to be stable and the emittances to be under control, and takes advantage of the full gain from the new tertiary collimators with integrated beam position monitors. This scenario might impose the need for luminosity levelling at IR1/5.

MITIGATION OF INSTABILITIES

At the injection plateau a chromaticity $\mathrm{Q}' = 2$ is used. Concerning the Landau octupoles, a starting value could be $\mathrm{K_3L} = 12\,\mathrm{m}^{-3}$ that was used during the 2012 scrubbing run (i.e. 26 A in the focusing octupoles), even though further studies are required to prove what the optimum is.

Concerning high energy, the recommendations from collective effects team [10–12] include the use of negative polarity for the focusing Landau octupoles, which is best for single beam stability, and high chromaticity ($\mathrm{Q}' = 15$). It is also advised to avoid the long-range regime in the squeeze where instabilities were observed in 2012, either by setting large crossing angles and use small emittances, or by performing the last part of the squeeze with colliding beams to profit from the Landau damping given by the head-on beam-beam encounters ("collide&squeeze", from $\beta^* = 3\,\mathrm{m}$).

In case of problems, alternative options are the use of collide&squeeze, the opposite octupole polarity or eventually to increase the β^* so to be able to retract the collimators and reduce the impedance. It is important to stress that possible problems or requirements will be probably confirmed only at the start of the intensity ramp-up period, with multi-bunch operation. Nevertheless, a maximum of beam-based experiments should be performed as early as possible, e.g. the measurement of the instability growth rates and octupole strength thresholds with chromaticity and ADT gain should be performed as early as possible to improve the understanding.

In this context it is worth recalling that the request for bunches non-colliding in IP1/5 is still standing [3], in order to allow the experiments to evaluate the beam-gas background.

Collisions and Squeeze

Collide&squeeze [13] was positively tested in three Machine Development sessions in 2012, proving the feasibility and reproducibility of the orbit at an interval of about three weeks. The full operational feasibility is yet to be demonstrated though, the main question being the orbit

Table 2: Beam parameters at injectors, production schemes. Values are at SPS extraction.

Scheme	standard	BCMS
production scheme	$(4+2)\times 3\times 2\times 2$	$(4+4)\times 3/2\times 2\times 2$
bunches/PS batch	72	48
max number of SPS injections	4	5 / 6
transverse emittance [μrad]	2.4	1.3
N_b [10^{11} p/b]	1.3	1.3
max number of bunches/ring	2748	2604 / 2508
max numebr of colliding pairs in 1/5	2736	2592 / 2496

control and reproducibility (to keep the beams colliding, within some deviation, e.g. $< 1\sigma$).

When performed in "Stable beams", collide&squeeze becomes "β^* Levelling", in which the possibility to change the β^* to modify the luminosity and thus the pile-up is emphasised (as opposed to the use of collisions as a stabilization means). Obviously, this implies a change of optics during "stable beams", with all the complications that derive from this (e.g. collimator movements and loss maps). A set-up overhead is foreseen with respect to the traditional commissioning to allow for finer beta-beating corrections, possibly at every squeeze stop point.

One of the two options might be needed before the end of Run 2 for helping beam stability or for levelling luminosity at ATLAS and CMS if the more pushed scenarios are successful, and β^* levelling is part of the Hi-Lumi LHC upgrade. Consequently, even if not part of the baseline choices at startup, it would be important to perform milestone tests and a basic preparation during commissioning to acquire some experience with these techniques and ease their implementation later. LHCb volunteers for the first tests of β^* levelling, and is supported by the other experiments.

BEAM PARAMETERS

Production

At present, two schemes are foreseen at the LHC injectors to produce 25 ns spaced beams [14, 15]. The main characteristics of the standard scheme [1] and of the newer Batch Compression, bunch Merging and Splitting scheme (BCMS, [16]) are recalled in Table 2.

Notably, the BCMS scheme provides smaller emittances but shorter trains injected into the SPS. The maximum number of injections from the PS into the SPS are presently being looked into: six injections seem feasible from the point of view of kick lengths, but might exceed the damage limits at the TDI [17].

Beam Parameter Evolution in the LHC Cycle

The transverse emittance evolution in the LHC cycle in 2012 is not fully understood. Some causes for the blow-up are known, e.g. Intra-Beam Scattering (IBS), 50 Hz noise, the end-of-squeeze instabilities, but additional, unknown ones were also present. In this context, it is important to stress the importance of the transverse emittance measurements, which should be operational as soon as possible in Run 2.

We assume a worst case scenario of 3.75 μm emittances at the start of physics, e.g. on selected bunches due to electron cloud. We also assume a best case scenario in which instabilities and transverse emittance blow up are under control, and electron cloud sufficiently scrubbed. In this best case, IBS is still present, and, when simulated for BCMS beams, results in a 20% emittance increase (<0.3 μm, for 1.3 μm, 1.3×10^{11} p/b, 1.25 ns [18]), mostly due to the injection plateau and energy ramp. For the performance estimates, we take additional margins and consider an overall 30% emittance increase, which can include, together with IBS, also some emittance increase from vertical coupling and other unknown sources. Consequently, 1.3 μm at injection result in 1.7 μm at the start of physics.

Concerning the intensity evolution and losses, we assume 5% losses, i.e. 95% transmission over the whole cycle, which is in agreement with the 2012 experience [19]. Consequently, 1.3×10^{11} p/b at injection results in 1.2×10^{11} p/b at the start of physics.

Concerning the longitudinal parameters, more is available in [20]. The bunch length is 1.2 ns at the injection plateau for 6 MV total voltage. Thanks to the controlled emittance blow-up, the bunch length at the flat top can be controlled, and is set to 1.25 ns, in 12 MV. While longer bunches help reduce machine equipment heating thanks to the narrower spectrum, are favourable for IBS growth rates in the transverse plane, and help reducing the vertex pile-up density, shorter bunches help reduce the losses in collisions (the reduction of off-momentum dynamic aperture is due to the beam-beam interactions). Consequently, in the absence of elements that require bunch lengthening, shorter bunches are favourable from the point of view of losses and integrated luminosity.

PROJECTED PERFORMANCE

The start-up and ultimate scenarios introduced earlier are used to estimate the instantaneous luminosity at the start of physics (Table 3). A range of emittances is used: on one side, the maximum acceptable for that set of settings, on the other side the BCMS 1.7 μm best case. The BCMS scheme, with five PS-to-SPS injections, is preferred thanks to the low emittances, and the proposed physics filling scheme is defined in [3]. It includes a total of 2508 bunches and 2496 colliding pairs in IP1/5. For comparison, a sixth PS-to-SPS injection would allow having 2592 colliding pairs in IP1/5. The nominal scheme, despite offering less profitable emittances, can provide up to 2736 colliding pairs in IP1/5. It should still be considered a viable alternative in case of problems with the BCMS scheme.

Table 3: Main beam and machine parameters and projected peak performance.

Parameter	**start-up**	**ultimate**
bunch spacing	25	25
β^* [m]	0.65	0.40
beam-beam separation [σ]	11	10
half crossing angle [μrad]	160	155
N_b [10^{11} p/b]	1.2	1.2
transverse emittance [μrad]	3.75 - 1.7	2.5 - 1.7
colliding pairs in IP1 and 5	2496	2496
total number of bunches/ring	2508	2508
L [10^{34} cm^{-2}s^{-1}]	0.7 - 1.3	1.4 - 1.9
pile-up μ	22 - 39	43 - 56
stored energy [MJ]	312	312

Even in the start-up scenario, in case the emittance blow-up is under control, the 10^{34} cm^{-2}s^{-1} design luminosity can be reached and even exceeded. In the case of the ultimate scenario and controlled emittances, the pile-up mildly exceeds the experiments' request and the peak luminosity exceeds the triplet cooling limit (1.75×10^{34} cm^{-2}s^{-1} [21]).

CONCLUSIONS

The baseline parameters for the 2015 LHC run are introduced: 6.5 TeV beam energy, 25 ns spaced bunches, produced by the means of the BCMS scheme, which allows reaching up to 1.2×10^{11} p/b and 1.7 μm at the start of collisions. The choice of the ATS compatible new optics is pending validation, and negative focusing octupole strength is suggested together with high chromaticity for the control of instabilities. Two possible scenarios are proposed: a more conservative one that includes $\beta^* = 65$ cm and 160 μrad half crossing angle, and an ultimate one characterized by $\beta^* = 40$ cm and 155 μrad half crossing angle. Both scenarios allow getting beyond design luminosity, if the transverse emittances are under control.

Only the effectiveness of electron-cloud scrubbing and the observation of multi-bunch effects (and UFOs) at the intensity ramp up will give final answers to the questions of emittance blow-up, beam stability, etc. A two stage approach to commissioning is strongly supported: at first, a conservative set of parameters is chosen, with a minimum set of unknowns and risks taken, and then, after a first period of physics, the performance can be pushed further based on the acquired knowledge. In view of this two-stage approach, it is important to still invest in key early measurements that would allow a faster implementation of new features in the second part.

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