BEAM PARAMETERS AND MACHINE PERFORMANCE TO BE REACHED IN 2010

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Abstract

A review of the beam parameters compatible with the energy foreseen for the 2010 physics run will be made. The target parameters and machine performance will be presented together with the rationale behind the selection made. A review of the status of the optics database for the forthcoming year of LHC operation will be carried out, too.

INTRODUCTION

As in the past, when a review of beam parameters for a 5 TeV physics run was made [1], the decision to run the LHC at 3.5 TeV triggered a number of studies to assess the available parameter space and the most effective way to vary the key quantities such as beam current, number of bunches, and optical parameters at the experimental interaction points (IPs). The main considerations are:

- Experiments desiderata (see Refs. [2-4] for a complete overview).
- Machine protection constraints, such as collimation settings, maximum intensity [5].
- Beam dynamics considerations, such as performance reach, available aperture, crossing angle, collision schedules [6, 7].
- Evolution of beam parameters based on operational considerations [8, 9].

This approach is aimed at finding a balance between robust operations (efficiency and machine protection) and satisfying the experiments (luminosity and event pileup). The number of bunches, bunch intensity and β^* are the key parameters varied throughout the period of commissioning to ensure safe and efficient operation.

The 2010 run will constitute a first stage, starting with a pilot run at 3.5 TeV/beam and partially squeezed beams, first with no crossing angle (43×43 and 156×156 bunches), then with crossing angle and a truncated short-spacing bunch train scheme with increasing intensity (e.g. a truncated scheme with 50 ns spacing and 144, 288, 720 ... bunches per beam).

COLLIMATION SYSTEM AND INTENSITY INCREASE

The intensity reach for the LHC is predicted to be limited by the achievable cleaning efficiency and the specified peak loss rate. An overall model has been presented and discussed [5]. This model is based on simulations of beam halo and losses in the superconducting aperture, as described in detail in references [10-13]. We define intensity reach as the maximum beam intensity that can be handled during a full LHC beam store without violating any interlock threshold, for example from beam loss monitors when maximum loss thresholds are exceeded.

The intensity reach model with collimation depends on several crucial parameters:

- Beam energy.
- Expected quench limits of the LHC superconducting magnets.
- Imperfections of the machine alignment, aperture and optics.
- Cleaning efficiency that can be achieved, including imperfections.
- Dilution of losses around the ring.
- Peak beam loss rate at collimators or minimum beam lifetime during a full LHC beam store (injection, energy ramp, beam optimization, beta squeeze, collisions).
- Thresholds for beam loss monitors.

A quantitative estimate was performed and the maximum intensity reach for various beam energies was evaluated [5]. The results were then used to determine the maximum intensity for 3.5 TeV, which agrees with the collimation performance estimates. A major parameter for this evaluation is the expected instantaneous peak loss rate at collimators, which was set to 0.2%/second of the total intensity lost at primary collimators (corresponding to an instantaneous drop of beam lifetime to 0.1 hour).

With this 2010 peak beam loss rate it is expected that the Phase 1 collimation system at 3.5 TeV will be compatible with the foreseen maximum intensity of 6×10^{13} protons per beam or 28 MJ of stored beam energy. It is notable that the stored energy per beam should then reach 15 times the present world record in super-conducting colliders, as set at the Tevatron in the United States.

Furthermore, the collimation system is beam-driven and must be adjusted and optimised at each major step in beam energy or intensity. During the increase in intensity as specified in this note, several beam-based collimation setup campaigns will be required for ensuring sufficient cleaning efficiency and adequate passive protection.

The expected maximum intensity vs. beam energy, with intermediate and tight collimator settings, with and without the constraints from beam-beam effects, is shown in Fig. 1 (see also Ref. [5]).

LIKELY EVOLUTION

It is useful to attempt to take into account the operational challenges of commissioning the LHC with beam and then probe the constraints detailed above while attempting to deliver stable beams and reasonable data taking conditions to the experiments. We emphasise the potential dangers of operating with higher intensities and the difficulties of LHC operations: care must be taken and the 2010 limits will not be achieved overnight.

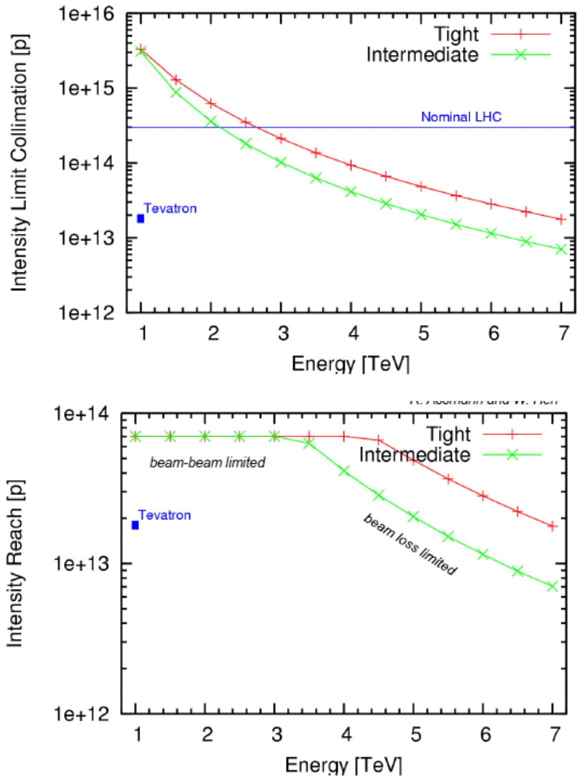

Figure 1: intensity reach vs. beam energy without (upper) and with (lower) beam-beam effect constraints.

Working with even these limited intensities requires: a fully qualified machine protection system; a fully commissioned collimation system capable of highly efficient beam cleaning; a fully qualified beam dump system and faultless operational procedures and software. To bed these systems in fully will take months rather than weeks.

The main phases of 2010 will include:

- Continued beam commissioning with the immediate goal of bringing safe beam intensities into collisions at 3.5 TeV unsqueezed.
- Commissioning of the squeeze to the stated target values.
- Commissioning of: machine protection; collimation; beam dump systems; instrumentation and feedback systems to allow the safe beam limit to be exceeded with confidence.
- To make absolutely sure that the machine protection is fully tested and capable of supporting the rigours of LHC operation, it is envisaged to run for some time at, or around, the safe beam limit.
- Pushing the number of bunches to 43 on 43. The estimated luminosity is around 2×10^{30} $cm^{-2}s^{-1}$ with 3×10^{10} protons per bunch and target squeeze values. This would mark a step up to around 0.5 MJ per beam and another extended period at this point is again envisaged to make sure that the machine protection, beam dump systems, collimation and other systems are fully capable of dealing with beam above the safe beam limit.
- Pushing the number of bunches to 156 on 156 – estimated luminosity is around 1.7×10^{31} $cm^{-2}s^{-1}$ with 5×10^{10} protons per bunch and target squeeze values. This represents 2.5% of nominal intensity and total stored beam energy of 4.4 MJ.
- Bringing on the crossing angle and run with a truncated 50 ns bunch scheme with up to, say, 432 bunches per beam. With 7×10^{10} protons per bunch this would give luminosities slightly below 10^{32} $cm^{-2}s^{-1}$.This represents approximately 10% of nominal intensity and a total stored beam energy of 17 MJ.

Making reasonable operational assumptions regarding fill length, luminosity lifetime and machine availability, the total integrated luminosity for the year would be about 100 pb^{-1}. Should an increase in energy part way through the year be a possible, it is estimated that around a month will be required to re-establish physics conditions at higher energy. An outline of the potential evolution of bunch configuration and the squeeze are shown in Table 1.

It is worth stressing that, depending on the performance obtained, the stage with collision of 156 bunches might be cut short or even cancelled, in order to move quickly to the stage with crossing angle.

MAIN CRITERIA DETERMINING BEAM PARAMETERS

The definition of the target beam parameters for the physics run at 3.5 TeV are based on a number of arguments presented in the previous sections. To summarise them [6]:

- The lower-than-nominal energy increases the beam size and hence the minimum value of β^* acceptable from aperture considerations.
- Intermediate collimator settings are assumed. This implies that the target value for n1 is ≥ 10.5, unlike the tight settings that are based on n1 ≥ 7.
- Intermediate collimator settings impose a limit on the total stored energy to 30 MJ and 6×10^{13} protons per beam at 3.5 TeV/beam.
- The run will begin with no crossing angle and a limited number of bunches (up to 156). Special bunch filling configurations were presented in Ref. [14.
- However, to get close to a luminosity of 10^{32} $cm^{-2}s^{-1}$ the bunch intensity should be pushed towards the nominal value. This would mean increasing beam-beam effects to levels characteristic of nominal regimes in the early phases of commissioning, not to mention the challenge of generating such high bunch intensity from the injector chain. On the other hand,

Table 1: Foreseen evolution of bunch configuration, intensity and β*

Step	Phase	E [TeV]	N	Fill scheme	I/I^{nom} [%]	E_{beam} [MJ]	β* [m] IP1/2/5/8	L (IP1/5) [$cm^{-2}s^{-1}$]	Run time (indicative)
1	Beam commissioning, safe beam limit	0.45	5×10^{10}	2×2	0.03	0.0072	11/10/11/10	2.6×10^{27}	
2			2×10^{10}	2×2	0.01	0.02	11/10/11/10	7×10^{27}	
3	Beam commissioning, safe beam limit, squeeze		2×10^{10}	2×2*	0.01	0.02	2/10/2/2	3.6×10^{28}	Days
4	Bunch trains from SPS		3×10^{10}	43×43	0.4	0.7	2/10/2/2	1.7×10^{30}	
5			5×10^{10}	43×43	0.7	1.2	2/10/2/2	4.8×10^{30}	Weeks
6	Increase intensity	3.5	5×10^{10}	156×156	2.4	4.4	2/10/2/2	1.7×10^{31}	
7			7×10^{10}	156×156	3.3	6.1	2/10/2/2	3.4×10^{31}	
8	Bring on crossing angle, truncated 50 ns.		7×10^{10}	50ns - 144**	3.1	5.7	2/3/2/3	3.1×10^{31}	
9			5×10^{10}	50ns - 288	4.4	8.1	2/3/2/3	3.3×10^{31}	Months
10	Increase intensity		7×10^{10}	50ns - 432	9.3	17	2/3/2/3	9.4×10^{31}	
11			7×10^{10}	50ns - 796	17.1	31.2	2/3/2/3	1.8×10^{32}	

the total beam intensity would be far from the limit imposed by the collimator settings. Therefore there is a particular interest in increasing the number of bunches rather than the bunch intensity. This would exercise the operation with crossing angles from the very beginning of the beam commissioning. It is worth mentioning that, with the proposed parameter set, the loss due to the geometrical reduction of the luminosity is abundantly compensated by the increased performance reach.

- The filling schemes will be based on 50 ns spacing and the standard number of SPS bunch trains. They are devised to produce the maximum number of collisions in IP1/5, while the number of collision in IP8 can be varied. Between 1 and 4 bunches can be made to collide in ALICE with a large enough spacing.
- It is worth stressing that the given target parameters are only indicative. For instance, if no difficulties are encountered reaching the first bunch population target value for physics (5×10^{10}), , then some time might be spent immediately to try pushing up this value until operation does becomes more difficult. Then, a small step back could be taken to settle on a more aggressive, but still operationally efficient, value than originally foreseen. Conversely, if it is difficult to achieve the target value, one may have to settle for a smaller for some time. The same applies to the target values of β*.

With these assumptions, the parameters of three proposed scenarios have been worked out and listed in Ref. [15], namely:

- Collisions at injection energy.
- Collisions at 3.5 TeV, without external crossing angle, 43 or 156 bunches, squeezed.
- Collisions at 3.5 TeV, with external crossing angle, 144 or up to 796 bunches, squeezed.

LONGITUDINAL PARAMETERS AND IBS

During this initial phase most of the beam parameters will differ from their nominal values, even at the beginning of a fill. The longitudinal emittance, in particular, will be smaller than 2.5 eV s, giving shorter bunches with smaller momentum spread. The dependence of these parameters on energy is shown in Fig. 2 for several values of the longitudinal emittance. In addition, these parameters will evolve from their initial values during a fill because of intra-beam scattering (IBS) and, possibly, other effects. The counter-effect of radiation damping is negligible at 3.5 TeV.

The longitudinal emittance takes various values depending on what is done to increase it, namely:

- 0.5 eV s is the natural longitudinal emittance delivered by the SPS.
- 0.75 eV s would result from longitudinal blow-up in the SPS (required for stability of nominal intensity beam in the SPS) and filamentation at LHC injection.
- 1.00 eV s corresponds to the combination of maximum blow-up in the SPS (not tried yet) and filamentation at LHC injection.
- 1.75 eV s would provide the same beam stability at 3.5 TeV as at 450 GeV and is achievable only with further controlled blow-up in the LHC.

The curve for 2.5 eV s (nominal value at 7 TeV) is also shown for reference.

The value of longitudinal emittance which ensures that the beam will be stable up to the intensities considered is not known. The value of 1 eV s would not require any special effort to blow up emittance in the LHC. The blow-up of the longitudinal emittance by IBS will also help to stabilise the transverse emittance.

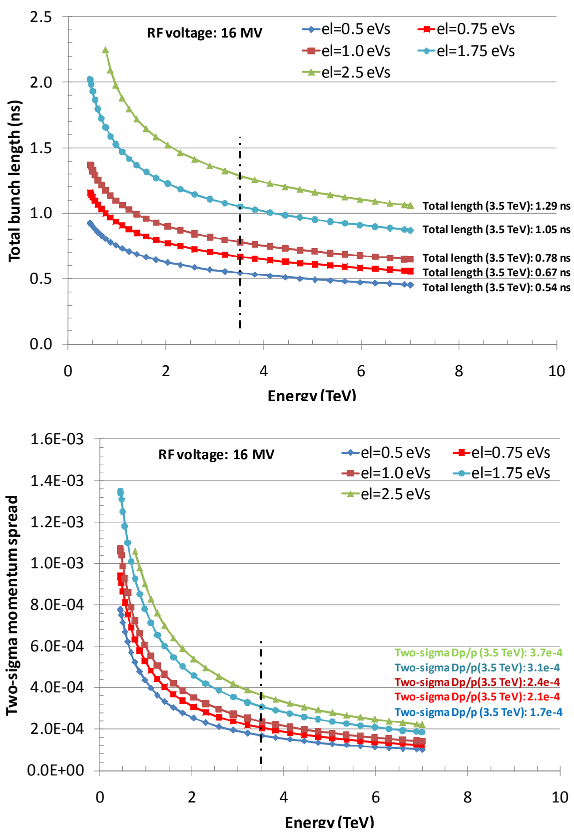

Figure 2: Dependence of the total bunch length (upper) and momentum spread (lower) on the beam energy. The various curves refer to different values of the longitudinal emittance.

However the initial transverse IBS growth rates are rather fast and might require some additional blow-up of the longitudinal emittance in the LHC. Some plots of the dependence of the IBS growth times on longitudinal emittance are shown in Fig. 3, assuming the design values of the transverse emittances and a total peak RF voltage of 16 MV (it is possible to reduce the growth rates by 10-20% by reducing the RF voltage). The growth rates are simply proportional to bunch intensity. The values shown are calculated in the absence of betatron coupling with the small vertical growth being due to the crossing-angle bumps. In reality, the coupling will tend to share the growth between horizontal and vertical planes, potentially lengthening the horizontal growth time by a factor ~1.8–2 beyond the blue curve in the plots. This curve can therefore be regarded as a worst case.

STATUS OF OPTICS FOR 2010 RUN

The optics to be used during the 2010 run are all available from the AFS optics database. A well-established procedure is in place to generate LSA settings starting from TFS tables generated by MAD-X [16]. In order to simplify the settings generation and avoid too long iterations, it was decided to split the optic settings proper, from those of the separation and crossing bumps. The latter are represented in LSA as “knobs”, easily and quickly updatable.

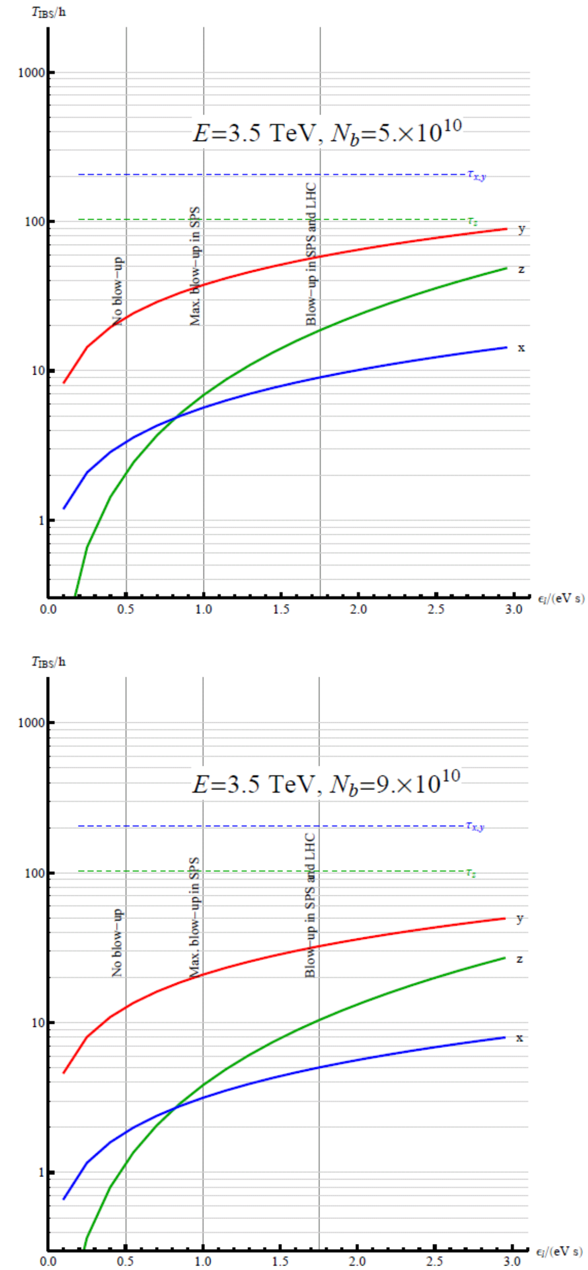

Figure 3: Dependence of the IBS growth rates on the values of the longitudinal emittance.

The squeeze sequences have been studied in terms of control of optical parameters during squeeze (e.g., beta-beating, tune and chromaticity variation) and the number of matched optics optimised [17].

The optics of the interaction regions (IR) 2 and 8 deserve a special consideration. Because of the constraints imposed by the injection process, the triplet quadrupoles are powered to a *normalised* strength exceeding the nominal maximum at 7 TeV. In consequence, the triplets’ strength has to be reduced between injection and top energy (and in any case below 6.3 TeV), the so-called pre-squeeze. While in nominal conditions this should take place before the actual squeeze, for the 3.5 TeV run it was decided to combine the pre-squeeze and the squeeze in a single process in order to gain time. An optical solution for IR8 has been fully determined and evaluated and is available in the official repository. That for IR2 is still in progress.

Note that some of the limitations observed during the hardware commissioning are now taken as constraints in the optics computations. For example, the excitation currents of the MCBX correctors in the crossing and separation bumps are now kept below 350 A, although the nominal was 550 A.

CONCLUSIONS

A complete set of beam parameters for the 3.5 TeV physics run has been derived based on considerations from machine protection, beam dynamics, performance reach, and operability. The document reporting these sets of beam parameters is presently under approval.

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