Options for Future High Luminosity Upgrades for the LHC

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Abstract

The following paper reviews the main challenges for bringing the LHC operation to nominal performance and summarizes proposals for future upgrade options. Future upgrade options could either facilitate the machine operation at nominal performance or possibly push the machine performance past the original nominal design values.

I. INTRODUCTION

The LHC performance is given by two key parameters: the machine luminosity and the centre of mass energy for the beam collisions. The nominal LHC machine parameters [1] are tailored for a peak luminosity of L = 10^{34} cm^{-2} s^{-1} and a centre of mass collision energy of 14 TeV and are summarized in Table 1. The peak luminosity depends on the bunch intensity N, the number of bunches per beam 'n', the revolution frequency 'f_{rev}', the beam emittance 'ε' and the optic β-function at the interaction point β^*:

$$L = n\ N^2\ f_{rev} / (4\pi\ \beta^*\ \varepsilon) \qquad (1)$$

The product of the peak luminosity and an event cross section specifies the maximum occurrence number of a particular event per second. The total number of events over a given time interval is given by the 'integrated luminosity'. An obvious route for optimizing the LHC performance is therefore to push all parameters in Equation (1) to their maximum acceptable values. However, while large beam currents and small β-function values at the interaction point increase the peak luminosity they also increase the risk of beam loss induced interruptions in the machine operation. This is particularly true for storage rings based on superconducting magnet technology where even small beam losses can result in the loss of the superconducting state of the magnets ('magnet quench'). In addition to the machine parameters in Equation (1) the integrated luminosity depends also on the beam lifetime, the machine cycle time, the machine 'turn around time' and the overall operational efficiency'. Any interruption in the machine operation due to beam loss induced magnet quenches therefore reduces the integrated luminosity and an optimisation of the overall LHC performance must be based on a well adjusted balance between the maximum beam parameters in Equation (1) and sufficient operational tolerances that are compatible with a safe and reliable machine operation.

The initial design study for an LHC machine inside the old LEP tunnel [2] provided what was at that time estimated to be acceptable safety margins for a reliable machine operation. Until the final approval of the LHC project the nominal LHC beam and machine parameters have been adjusted in order to provide a peak machine performance that is competitive with the SSC performance [3]. This process eliminated a large fraction of the initially retained safety margins for the LHC and implies that the LHC operation with nominal performance can only be achieved if all components work reliably up to their specifications and if all beam parameters can be controlled within tight tolerances.

In summer 2001 the CERN director general (DG) initiated a CERN task force for identifying possible staged upgrade options for the LHC [4]. The goal for such an LHC performance upgrade is two fold:

- to provide additional margins for the LHC operations that facilitate the operation at nominal performance and
- ultimately to push the LHC performance beyond the nominal values.

The task force identified three main upgrade phases:

- 0) performance upgrades without hardware modifications
- 1) performance upgrades with hardware modifications in the LHC insertion regions (IR)
- 2) performance upgrades with major hardware modifications.

Table 1: Nominal and 'ultimate LHC parameters'

Parameter \ value	**nominal**	**Ultimate**
# bunches	2808	2808
Particles / bunch	1.15 10^{11}	1.70 10^{11}
β-function at IP	55 cm	50 cm
Normalized emittance	3.75 μm	3.75 μm
Beam size at IP	16.7 μm	16 μm
Bunch length	7.55 cm	7.55 cm
Full crossing angle	285 μrad	315 μrad
Events per crossing	19	44
Peak luminosity	10^{34} cm^{-2} s^{-1}	2.4 10^{34} cm^{-2} s^{-1}
Luminosity lifetime	15 hours	10 hours
Beam energy	7 TeV	7.45 TeV
Stored beam energy	366 MJ	541 MJ

The phase 0 upgrade essentially eliminates any operation margins and represents the maximum LHC performance that is theoretically possible without hardware modifications. Table 1 summarizes the ultimate beam parameters and compares the values with the nominal LHC parameters. All LHC hardware components are designed to be compatible with these ultimate beam parameters. It should be repeated here that the nominal LHC parameters are already quite challenging. As we stated above, the first conceptual design studies for the LHC were based on more relaxed parameters and the 'nominal' LHC parameters are the results of the competition with the SSC. Table 2) summarizes the parameters of the initial conceptual design report [2] and highlights the margins of this first design with respect to the 'nominal' LHC parameters. Comparing Table 1) and 2) one observes that all parameters, except for the number of bunches (no realistic assumption on the kicker rise times) and the peak dipole field (technically not feasible), are significantly more challenging in the 'nominal' parameter table.

Table 2: Parameters of the 'Conceptual Design LHC Report' [2]

Parameter \ value	**nominal**	**Margin**
# bunches	3564	kicker rise time
Particles / bunch	$1.15\ 10^{11}$	0.3 * nominal
β-function at IP	100 cm	2 * nominal
Normalized emittance	1.07 μm	1/3 of nominal brightness
Beam size at IP	12 μm	comparable to nominal
Bunch length	7.55 cm	comparable to nominal
Full crossing angle	100 μrad	1/3 of nominal
Events per crossing	1 to 4	Order of magnitude smaller than nominal
Peak luminosity	10^{33} cm^{-2} s^{-1}	1/10 of nominal
Luminosity lifetime	56 hours	3.7 * nominal
Beam energy	8.14 TeV	16% larger than nominal
Stored beam energy	121 MJ	1/3 of nominal

The first detailed studies for hardware upgrade options focus on phase 2) of the staged upgrade and discuss options for the replacement of the LHC insertion region magnets [5]. The lifetime of the insertion region magnets is limited by the radiation coming from the interaction points and thus, is directly linked to the integrated luminosity of the LHC experiments. The studies in [5] are based on the assumption that the insertion region magnets need to be replaced after an integrated luminosity of 700 fb^{-1} corresponding to approximately 10 years of nominal LHC operation. Assuming an R&D lead time of approximately 10 years the design studies for future IR magnets must essentially start now. Because most of the CERN resources are currently involved in the hardware installation of the nominal LHC machine, these studies rely on contributions from laboratories outside of CERN. The need for coordinated R&D work beyond the borders of CERN was first addressed in an international ICFA workshop [6] and is reflected in two collaboration initiatives: The USLARP initiative in the U.S.A. [7] which aims at a coordination of the accelerator R&D work between U.S. laboratories and the CARE initiative in Europe [8] that focuses on collaborations between European laboratories and universities.

Phase 2) of the staged upgrade program addresses all remaining options such as increasing the injection energy into the LHC by additional booster rings (either in the SPS or the LHC tunnel) and more powerful proton injectors (e.g. a high intensity proton linear accelerator). A detailed description of the options for all three upgrade phases can be found in [4].

II. MAIN PERFORMANCE CHALLENGES

Bringing the LHC machine parameters to their 'nominal' and eventually 'ultimate' values implies overcoming four different types of performance limitations:

A. effects limiting the number of particles per bunch
B. effects limiting the total beam intensity and the number of bunches per beam
C. effects limiting the minimum beam size at the IP
D. effects limiting the integrated luminosity

A. *Effects limiting the number of particles per bunch*

The maximum number of particles per bunch is limited by the non-linearity of the beam-beam interaction and by the mechanical aperture of the LHC magnets. The non-linearity of the head on collisions is determined by the bunch brightness, the ratio of the bunch intensity and the transverse beam emittance. It is therefore possible to increase the bunch intensity with a constant beam-beam non-linearity if the beam emittance can be increased proportionally with the bunch intensity. However, the mechanical aperture of the LHC magnets limits the maximum acceptable beam size and thus the maximum permissible beam brightness. The maximum bunch intensity is therefore limited by the beam-beam non-linearity and the mechanical acceptance of the LHC magnets. Phase 2) of the staged LHC upgrade aims at a reduction of the injected beam size by increasing the injection energy into the LHC and thus an increase of the bunch intensity with constant beam brightness.

A crossing angle scheme at the interaction points avoids unwanted beam collisions in the long straight sections of the LHC machine where both LHC beams share the same beam pipe. However, even with a crossing angle scheme the particles of one beam will 'see' bunches of the other beam at some distance. These so called 'long range' beam encounters are also a source for non-linear fields and perturb the particle motion in the LHC. The nominal bunch spacing of 25 ns generates approximately 30 long-range interactions per experimental insertion. The strength of the long range beam-beam interactions decreases with the bunch intensity and the amplitude of the beam separation (and therefore with the crossing angle). The maximum crossing angle value is limited by the mechanical aperture of the triplet magnets which are located in the common part of the long straight sections. The maximum acceptable bunch intensity therefore depends on the maximum acceptable non-linearity and the mechanical aperture of the triplet magnets. Phase 0) of the staged LHC upgrade aims at an operation at the beam-beam limit (head-on and long-range) and gives up any operational margins. Phase '1)' of the staged LHC upgrade program aims at an increase of the mechanical aperture of the triplet magnets and thus, at a reduction of the non-linearity due to the long-range beam-beam interactions. It should be noted here that a large crossing angle also increases the effective beam size of the head-on collision and thus reduces the instantaneous luminosity. This 'geometric' luminosity reduction factor is given by:

$$F = \frac{1}{\sqrt{1 + \left(\frac{\theta \cdot \sigma_s}{2\sigma^*}\right)^2}}$$

where θ is the total crossing angle and σ_s the bunch length. The geometric reduction factor becomes non-negligible for crossing angles above 300 μrad (for the nominal bunch size). An interesting feature of the geometric reduction factor is that it reduces the luminosity and the non-linearity generated by the head-on beam-beam interactions. One has therefore two different strategies for a luminosity optimization: a strategy based on maximizing the geometric reduction factor and an optimization based on large bunch intensities and large crossing angles (-> small geometric reduction factor). An optimization with a large geometric reduction factor implies higher than nominal beam currents in the LHC and thus an upgrade of the LHC injector complex (Phase 2 of the staged upgrade proposal). An extreme variant of the optimization with small geometric reduction factor is the concept of 'super bunches'. All options are discussed in detail in [4].

B. *Effects limiting the total beam intensity*

Fife main effects limit the maximum total beam intensity in the LHC:

- the electron cloud effect
- the cleaning efficiency of the collimation system and the quench level of the superconducting magnets
- the impedance of the collimator jaws
- hardware components
- radiation dose in the cleaning insertions and the experiments.

Figure 1 show the electron cloud induced heat load on the LHC beam screen per meter as a function of the bunch intensity for various bunch spacings and surface properties [1]. The 'yield' parameter is also called the 'secondary emission yield'. It specifies the maximum number of secondary electrons that an impacting primary electron can release from the vacuum chamber surface. The blue curve without data points and starting at 2 W/m for zero bunch intensities indicates the maximum heat load compatible with the LHC cryogenic system. The lowest curve corresponds to a bunch spacing of 50 ns. All other curves correspond to a bunch spacing of 25 ns. One clearly recognizes that only a secondary emission yield of 1.1 or an operation with a bunch spacing of 50ns (or larger) allows an operation above nominal bunch intensities. It is currently assumed that the initial secondary emission yield at the LHC start up is of the order of 1.5 and that smaller values require a conditioning of the beam screen surface via electron bombardment. Further simulations and code benchmarking for the electron cloud simulations are still ongoing.

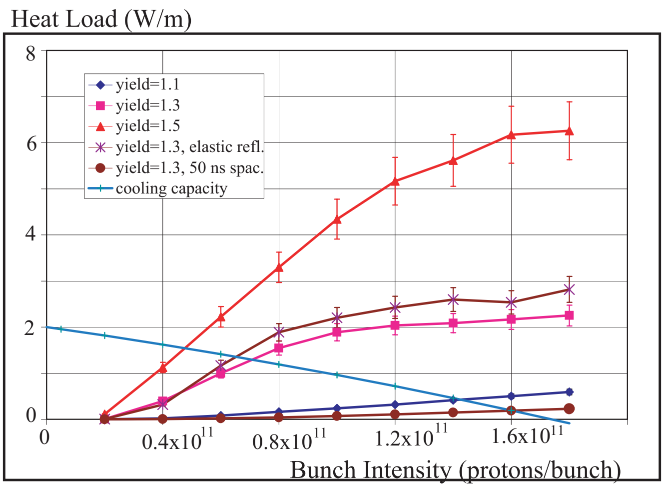

Figure 1: electron cloud induced heat load per meter as a function of the bunch intensity for various bunch spacings and surface properties.

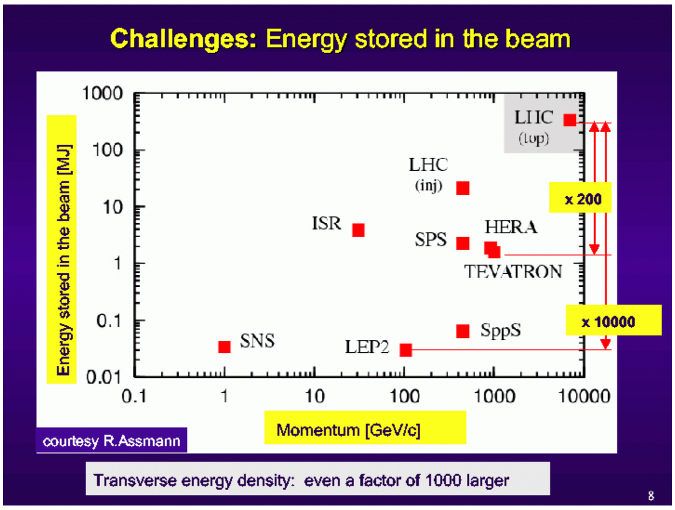

Figure 2: Overview of the stored beam energy and the particle energy in various storage rings.

This treatment is also referred to as 'beam scrubbing'. It is not yet clear what minimum secondary emission yield can be achieved with the ‘beam scrubbing’ runs but a value of 1.1 is clearly a lower limit for what can be hoped for. The data in Figure 1 shows that an operation with a bunch spacing below 25 ns (e.g. 12.5 ns) is excluded and that higher than nominal bunch intensities for a bunch spacing of 25 ns can only be expected after a successful conditioning of the beam screen surface.

Figure 2 shows an overview of the stored beam and particle energies for various storage rings [9]. The figure illustrates that the stored beam energy in the LHC is two orders of magnitudes larger than the stored beam energy in previous superconducting storage rings (Tevatron and HERA). At the same time the quench limit of the LHC magnets require much smaller beam losses during operation. While storage rings like the Tevatron and HERA could lose up to 30% of the nominal beam intensity at injection energy and a few percent at top energy the LHC magnets can tolerate beam losses only of the order of a few 10^{-6} of the nominal beam intensities.

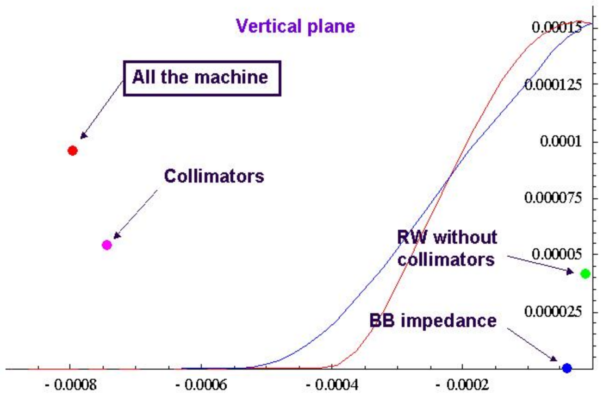

Figure 3: Impedance of the LHC machine and the collimator jaws.

Figure 3 shows the real (horizontal axis) and imaginary (vertical axis) tune shifts in the vertical plane for various impedance components. The solid lines indicate the stability limits for the machine operation for positive and negative anharmonicities (amplitude dependence of the transverse oscillation frequency) in the machine. Stable beam operation requires either that the tune shifts due to the machine impedance lie within the stability lines or that the total beam intensities stays below a stability threshold. While the tune shifts due to the broad band impedance (BB) and the resistive wall impedance (RW) without collimators are clearly within the stable the impedance due to the collimator jaws at a amplitude of 6 σ is clearly outside the stability limit. The collimator impedance in Figure 3 therefore limits the maximum acceptable beam intensity in the LHC. Another option for coping with the collimator impedance is to change the beam size inside the triplet magnets during luminosity operation. The collimator impedance is a function of the collimator jaw opening and can be lowered by increasing the collimator jaw opening. The machine protection aspects of the collimation system require a reduction of the maximum beam size in this case. The maximum beam size at top energy occurs in the triplet magnets and increases with decreasing β^*. For nominal beam intensities the collimator jaw impedance therefore limits the minimum acceptable beam size at the experimental IP’s and thus the performance of the LHC.

All hardware components in the LHC are designed for ultimate beam intensities. An operation above ‘ultimate’ beam intensities implies hardware upgrades of the LHC beam dump and machine protection devices. Furthermore, the LHC injector complex is just compatible with ultimate beam intensities. Increasing the beam intensities in the LHC beyond the ultimate values therefore implies an upgrade of the LHC injector complex. All these options are part of the Phase 2) upgrade studies.

Radiation issues in the cleaning insertions and the experimental detectors are already at high values for the nominal and ultimate LHC performance and are at the limit of what can be accepted from the radiation protection point of view. Increasing the LHC beam intensities beyond the ultimate values implies re-evaluation of all radiation issues in the LHC machine.

C. Effects limiting the minimum beam size at the IP

The minimum beam size at the IP is limited by the triplet quadrupole apertures. Assuming a symmetric machine optics with respect to the IP the beam cross section increases linearly with the distance from the IP in a drift space without magnetic elements and inversely proportional to the beam cross section at the IP. For a fixed distance of the triplet magnets from the IP the triplet aperture therefore limits the smallest possible beam size at the IP. Phase 1) of the staged upgrade program addresses options for increasing the effective mechanical aperture of the triplet magnets.

D. Effects limiting the integrated luminosity

The minimum ramp time required for bringing the magnetic field of the LHC dipole magnets from their injection to their collision values is approximately 20 minutes. The time required for bringing the magnetic field back down to the injection values is of the same order of magnitude. Another 12 minutes is the minimum time required for injecting the two LHC beams from the SPS into the LHC. Assuming another 8 minutes of the adjustments at top energy to prepare the physics operation (squeeze) one obtains a minimum turnaround time of 1 hour for the LHC. The above time scales are of the same order of magnitude as the time scales for the HERA operation. Any unforeseen interruptions or difficulties in the machine operation (for example a beam abort due to magnet quenches or beam losses) will increase the average turnaround time. For example, the HERA machine achieved an average turnaround time of 6 hours after 10 years of operation [10]. While the HERA machine features only one superconducting storage ring the LHC has two superconducting machines and approximately an order of magnitude more hardware components. It is therefore reasonable to assume that the initial average machine turnaround time in the LHC will not be smaller than the value of the HERA machine. Estimates for the integrated luminosity in the LHC are currently based on an average turnaround time of 10 hours and an average physics run length of 14 hours. Unforeseen beam loss, lower than expected cleaning efficiencies of the collimation system or reliability problems with the large number of power converters in the LHC will clearly increase the average machine turnaround time and thus, reduce the integrated luminosity.

III. UPGRADE GOALS

Table 3 summarizes the upgrade goals of phase 1) of the staged LHC upgrade program. The readuced bunch spacing of 12.5 ns is now excluded by the electron cloud effect and the estimated peak luminosity must be reduced by a factor 2 yielding a total increase by a factor of 5 with respect to the nominal LHC performance. The average turnaround time of the LHC will probably increase in view of the much larger beam intensities and stored energies and the increase age of most of the LHC equipment at the time of the upgrade installation. The increase in the integrated luminosity will therefore most likely be only a factor of 2 to 3.

Table 3: Initial goals for phase 1) of the staged upgrade program [4]

Parameter \ value	**nominal**
# bunches	5616
Particles / bunch	$1.7\ 10^{11}$
β-function at IP	25 cm
Normalized emittance	1.07 μm
Beam size at IP	11.3 μm
Bunch length	3.8 cm
Full crossing angle	445 μrad
Events per crossing	88
Peak luminosity	$9.6\ 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Luminosity lifetime	5 hours
Beam energy	7.45 TeV
Stored beam energy	1082 MJ

IV. REFERENCES

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