LHC CHALLENGES AND UPGRADE OPTIONS

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Abstract. The presentation summarizes the key parameters of the LHC collider. Following a discussion of the main challenges for reaching the nominal machine performance the presentation identifies options for increasing the operation tolerances and the potential performance reach of the LHC by means of future hardware upgrades of the LHC and its injector complex.

1. LHC Performance Goals
The LHC performance can be measured by three key parameters:

- The beam energy.
- The event rate in the experimental insertions is measured by the instantaneous machine luminosity.
- The total number of events that can be recorded in the experimental insertions over a given period of time measured by the integrated luminosity.

The LHC has been designed for the discovery of the Higgs boson, requiring centre of mass (CM) collision energies in excess of 1 TeV, high event rates inside the experimental detectors and a reliable injector chain that assures an efficient machine operation and thus a large integrated luminosity. The LHC features 2 high luminosity Interaction Points (IPs) [1]. The collisions are generated by 2 counter rotating proton beams. Since protons are composite particles the collisions actually occur between pairs of quarks and gluons each carrying only a fraction of the total proton energies. The CM energy of these collisions can therefore vary significantly, and, in order to ensure a sufficiently large fraction of collisions with CM energies above 1 TeV, the proton beam energies in the LHC have been chosen to be 7 TeV. The event rate at the collision points is given by the instantaneous machine luminosity:

\[ \mathcal{L} = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{\text{rev}} \cdot F(\Phi, \sigma_x, \sigma_y)}{\sigma_x \cdot \sigma_y} \]  

where \( N_1 \) and \( N_2 \) refer to the number of particles inside the colliding particle packages (bunches), \( n_b \) to the number of bunches within each beam, \( f_{\text{rev}} \) the revolution frequency of the bunches, \( \sigma_x \) and \( \sigma_y \) are the transverse RMS beam sizes of the two colliding bunches at the interaction points (IPs) and \( F(\Phi, \sigma_x, \sigma_y) \) is a geometric reduction factor that depends on the transverse beam size and the crossing angle of the two beams at the IP. Studying rare events such as the decay channels involving the Higgs particle requires a minimum luminosity value of \( \mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ sec}^{-1} \). The target luminosity value for the nominal LHC operation is set at \( \mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ sec}^{-1} \). In the following sections we discuss the optimization strategy and limitations for achieving such a high luminosity value in the LHC.
2. Main Limitations for the Luminosity

Looking at the instantaneous luminosity formula in Equation (1) one will try to maximize the instantaneous luminosity in order of priority by increasing the number of particles in each bunch, the beam size at the IP and then number of bunches in each beam.

2.1. Limitations for the Bunch Intensity

A test particle, passing head-on though a bunch, experiences a transverse force due to the coulomb field of the charge distribution inside the opposing bunch. For small amplitudes the force is approximately linear which changes the transverse oscillation frequencies of the test particle (the machine tune ‘Q’). As the amplitude of the test particle increases the slope of the beam-beam force, and thus the additional focusing, decreases. Looking not only at a single test particle, but rather an ensemble of particles with different transverse oscillation amplitudes the above focusing effect of the beam-beam interaction results in slightly different transverse oscillation frequencies for all particles inside a bunch. This spread in the transverse oscillation frequencies is referred to as the beam-beam tune spread. If the amplitudes of the test particle become larger than the RMS beam size of the opposing bunch distribution, the beam-beam force becomes strongly non-linear and changes its slope for amplitudes above 2 RMS beam sizes. This non-linearity of the beam-beam force generates resonance driving terms that can destabilize the particle trajectories whenever the transverse oscillations frequencies fall on a resonance:

\[ n \cdot f_x + m \cdot f_y = r \cdot f_{rev} \]  

where \( f_x \) and \( f_y \) are the transverse oscillation frequencies and \( f_{rev} \) is the revolution frequency of the particles in the storage ring. Both effects, the tune spread and the resonance driving terms, are proportional to the number of IPs and the charge density of the bunches. With increasing bunch intensities and number of IPs it becomes therefore more difficult to find transverse oscillation frequencies for the beam that are sufficiently far away from strong resonances for all particles in the beam. Above a certain threshold value for the bunch intensity it becomes therefore impossible to guarantee a stable motion for all particles in the bunch distribution. This threshold value is referred to as the beam-beam limit in a collider ring. Based on the operational experience from existing and past collider machines this limit has been estimated to be \( N_b = 1.5 \times 10^{11} \) particles per bunch (ppb) for the LHC with 3 IPs featuring head on collisions and \( N_b = 1.7 \times 10^{11} \) ppb for the LHC with 2 IPs. The nominal bunch intensity in the LHC has been chosen to be 1.15 \( \times 10^{11} \) ppb in order to provide some margins for the operation with head on collisions in 3 IPs. A bunch intensity of \( N_b = 1.7 \times 10^{11} \) ppb is referred to as the ‘ultimate’ bunch intensity and no longer provides operational margins.

2.2. Limitations for the Beam Size at the IP

The beam size and divergence can be best characterized with the help of the optical beta function [1]:

\[ \sigma_{ip} = \sqrt{\beta^* \cdot \varepsilon}, \sigma = \frac{\varepsilon}{\sqrt{\beta^*}} \]  

with \( \beta(s) = \beta^* + \frac{s^2}{\beta^*} \Rightarrow \sigma(s) = \frac{\varepsilon}{\sqrt{\beta^*}} \cdot s \)  

where \( \beta^* \) is the optical beta function at the IP and \( \varepsilon \) the beam emittance. For a symmetric optics around the IP the \( \beta \)-function increases approximately quadratically with the distance from the IP (for small \( \beta^* \) values) up to the first quadrupole magnets next to the IP. The lower bound for the beam emittance in a hadron collider is determined by the performance of the injector chain while \( \beta^* \) can be adjusted with the help of the focusing quadrupole magnets next to the IPs. Equations (3) show that reducing the beam size at the IP via \( \beta^* \) implies automatically an increase of the beam size in the neighbouring quadrupole magnets. A large \( \beta \) function inside the triplet magnets presents 3 problems for the machine operation:
- A reduced mechanical acceptance of the triplet magnets.
- Increased chromatic aberrations that deteriorate the machine performance.
- Enhanced effect of the triplet magnet field imperfections on the single particle dynamics that can result in increased particle losses.

The nominal LHC triplet magnet design is just compatible with $\beta^*$ values of 0.5m. In order to provide some additional operational margins for the orbit stabilization and $\beta$-function errors during optic adjustments the nominal $\beta^*$ value of the LHC has been set to $\beta^* = 0.55m$.

![Figure 1: the geometric luminosity reduction factor as a function of $\beta^*$.](image)

Furthermore, together with a crossing angle (see the next section) a reduction of $\beta^*$ also implies an increase in the effective collision cross sections at the IPs and thus a reduction of the luminosity. Figure 1 shows this geometric luminosity reduction factor as a function of $\beta^*$ assuming that the crossing angle is scaled for generating a constant normalized beam separation of $9\sigma$ between the two LHC beams. The nominal value $\beta^* = 0.55m$ results in a luminosity loss of 15% compared to head-on collisions without crossing angle. Decreasing $\beta^*$ below 0.55m implies a further reduction of the luminosity which reaches 40% for $\beta^* = 0.25m$.

### 2.3. Limitations for the total Number of Bunches

The 400 MHz LHC RF system features 35640 RF buckets (potential bunch positions) in the LHC ring, spaced by 2.5ns or 0.7m. However, the total number of bunches is limited to 2808 bunches by the following seven effects:

- Long range beam-beam interactions.
- The total beam power and damage potential.
- The beam lifetime and cleaning efficiency of the collimation sections.
- Heat load and beam instabilities due to the Electron cloud effect.
- Machine impedance and beam instabilities.
- Required gaps for the injection and extraction kicker rise times.
- Performance of the LHC injector chain.

The LHC straight sections around the IPs have a total length of approximately 120m [1]. A bunch separation of less than 250m therefore implies additional head-on beam-beam collisions that would further limit the maximum number of particles per bunch. Assuming a 25 ns bunch spacing in the LHC (only every $10^{th}$ RF bucket is filled with a bunch) one obtains approximately 30 additional, unwanted beam collisions per IP. In order to avoid a further reduction of the maximum acceptable bunch intensity due to these additional head-on collisions the LHC features a crossing angle along the experimental insertions. The minimum required beam separation and the amplitude of the crossing angle depend on the beam size (proportional to $1/\beta^*$) and the number of long range beam-beam interactions. The drawback of the additional crossing angle is that it reduces the available aperture.
inside the triplet magnets and increases the effective collision cross section of the two beams at the IP. The stored beam energy in the LHC exceeds 350 MJ per beam with 2808 bunches and $1.15 \times 10^{11}$ ppb and thus exceeds the beam energies in existing and past storage rings by more than 2 orders of magnitude [2]. One MJ can melt 2 kg of Cu and the stored beam energy in the LHC represents an enormous damage potential to the equipment and the machine operation requires a sophisticated machine protection system. Increasing the number of bunches beyond the nominal value of 2808 bunches further increases this damage potential and implies additional complications and restrictions for the machine operation that can only be fully evaluated once the operation experience from the nominal LHC becomes available.

Operating the superconducting magnets in the LHC requires a tight control of the energy deposition inside the magnets during operation. The LHC features a 2 stage collimation system plus additional dedicated absorbers and collimators at special locations in the ring in order to minimize the beam losses inside the superconducting magnets. The required cleaning efficiency of the LHC collimator sections is defined by the maximum acceptable losses, the total number of particles per beam and the beam lifetime. Assuming a minimum beam lifetime of 0.2 h for a maximum length of 10 seconds or a continuous minimum beam lifetime of 1 h one obtains for the nominal beam parameters (2808 bunches with $1.15 \times 10^{11}$ ppb) a maximum acceptable cleaning inefficiency (number of particles reaching the cold magnet / by number of particles impacting onto the primary collimator jaws / distribution length of the losses) of $2 \times 10^{-5}$ m$^{-1}$ which is at the performance limit of the LHC cleaning insertions [2]. Increasing the number of bunches in the LHC requires therefore either larger beam lifetimes than 0.2h and 1h or an improved collimation system.

The impact of secondary electrons due to the electron cloud effect [3] results in a heat deposition on the beam screen and a potential emittance growth [4]. The heat load increases with the ppb and a decreasing bunch spacing. A Secondary Emission Yield (SEY) of $\delta_{\text{sec}} = 1.3$ is just compatible with the cooling capacity of the beam screen for the nominal LHC beam parameters. Increasing the number of bunches (and thus reducing the bunch spacing) in the LHC implies a heat load that is incompatible with the cooling capacity of the beam screen and therefore requires a reduction in the ppb. Image charges on the metallic surfaces of the LHC vacuum system can couple the motion of different bunches and particles in the LHC and result in instabilities and particle losses. This effect is proportional to the machine impedance and the total beam intensities in the LHC. The current LHC impedance estimates are barely compatible with an operation with nominal beam parameters. Any increase of the beam intensities above the nominal value with $\beta^* = 0.55$ m will further jeopardize the beam stability in the LHC.

The bunch pattern of the LHC must provide sufficiently long gaps in the bunch train for the rise time of the LHC injection and extraction kicker magnets. These rise times are significantly larger than the nominal bunch spacing of 25 ns. The LHC can therefore not feature a uniform bunch spacing all along the machine but has to provide increased bunch gaps at the beginning and end of each bunch train that it receives from the injector chain.

2.4. **Global Collider Efficiency**

Maximizing the integrated luminosity in the LHC requires not only large values for the instantaneous luminosity but also an efficient operation of the whole accelerator complex. The later requires an optimization of the following parameters:

- Luminosity lifetime.
- Machine turnaround time (time between the end of a physics run and the start of the next one).
- Reliability of the injector complex.
- Transfer efficiency of the beam in the injector complex.

The maximum achievable luminosity lifetime in the LHC is defined by the nuclear interactions at the IPs, the loss of particles due to collisions with the rest gas molecules in the LHC vacuum system and a blow up of the RMS beam sizes due to the Coulomb interaction of the particles within each bunch. For
the nominal LHC operation one expects an effective approximate exponential luminosity lifetime of 15 hours [2]. Depending on the machine ‘turn around’ time, a physics run should not last longer than the effective luminosity lifetime. The minimum ‘turn around’ time of the LHC machine is defined by the time it takes to bring the LHC magnets back to their injection current settings (ca. 20 min [1]), the time needed to fill the LHC (16 min [1]), the time needed to accelerate the beam from 450 GeV to 7 TeV (ca. 20 min) and the time needed to prepare the beams for collisions (ca. 10 min) and amounts in an ideal operation scenario to ca. 70 min. A similar interruption time applies for almost any unforeseen interruption of the machine filling and acceleration process (e.g. equipment failure during the beam acceleration). A high reliability of all LHC components and its injector complex are therefore key ingredients for maximizing the integrated luminosity in the LHC experiments.

3. Summary of the LHC parameters

Table 2 summarized the main nominal LHC parameters, together with the initial design parameters of the white book [5] and the ‘ultimate’ parameters. The ‘White book’ parameters still provide reasonable operation margins. The ultimate LHC performance level is only a factor two larger than the nominal value but no longer features any operational margins. The achievement of the nominal LHC parameters is therefore already a challenging task on its own and might require additional upgrades to the LHC infrastructure in order to overcome operational limitations.

| Parameters                        | ‘white book’ | nominal | ultimate |
|----------------------------------|-------------|---------|----------|
| # bunches                        | 3564        | 2808    | 2808     |
| ppb                              | 0.34 10^{11} | 1.15 10^{11} | 1.7 10^{11} |
| βX / γ                           | 1 m         | 0.55 m  | 0.5 m    |
| ε / γ                            | 1.07 μm     | 3.75 μm | 3.75 μm  |
| full crossing angle              | 100 μrad    | 285 μrad | 315 μrad |
| events / crossing                | 1 <-> 4     | 19.2    | 44.2     |
| L [cm^{-2} sec^{-1}]             | 0.1 10^{34} | 1 10^{34} | 2.4 10^{34} |
| luminosity lifetime              | 56 h        | 15 h    | 10 h     |
| stored beam energy               | 121 MJ      | 366 MJ  | 541 MJ   |

Table 2: Initial, nominal and ‘ultimate’ beam parameters for the LHC with 25ns bunch spacing. *: Including contributions from IBS and rest gas collisions

4. Main Upgrade Options

In 2002 CERN identified 3 main options for the LHC upgrade and grouped them according to their impact on the LHC infrastructure into three stages [6]. The required R&D efforts have been conducted within the 6th European Framework Program (FP6) on Coordinated Accelerator Research in Europe (CARE) [7] prepared by the European Steering Group on Accelerator R&D (ESGARD) [8]. Additional international collaborations have been started with laboratories in the U.S.A. within the US LHC Accelerator research Program (USLARP) [9]. In 2007 CERN has launched the implementation of the most urgent upgrade options within the ‘White paper’ initiative. The ‘White paper’ initiatives addresses three options: upgrade of the interaction regions (IRs), upgrade of the LHC injector complex [11] and consolidation. The IR upgrade has been divided into 2 sub phases: an initial phase aiming at larger operational margins and an efficient routine operation with ultimate beam parameters and β^∗ = 0.25m (L = 2.5 10^{34} cm^{-2} sec^{-1}) and a second phase aiming at a 10 fold increase of the nominal LHC luminosity. The initial phase is based on the development of low gradient, large aperture NbTi magnets using the spare cables of the LHC dipole production and has been launched within a CNI on ‘LHC upgrade options’ of the 7th European Framework Program (FP7). The second upgrade phase addresses the challenges of an extremely high radiation dose near the IPs for a peak luminosity of L = 10^{35} cm^{-2} sec^{-1}. Options for the second upgrade phase focus on the development of new magnet technologies which feature higher peak fields and heat margins compared to the established NbTi magnet technology (e.g. Nb₃Sn). The current studies include: R&D on Nb₃Sn magnet technologies; studies for active absorbers at the transition of the IRs to the machine arcs (integration of a magnetic spectrometer inside an absorber block); and R&D on open mid-plane magnets with dedicated heat and
radiation absorbers. Both phases of the Stage 1 upgrade suffer from an operation close to the beam-beam limit and a large geometric reduction factor for small $\beta^*$. The following studies for reducing the head-on beam-beam force and the geometric reduction factor at the IPs with crossing angle operation could therefore benefit both phases of the Stage 1 upgrade [10]:
- Compensation of the beam-beam force with the help of electron lenses.
- Compensation of the long range beam-beam interactions (beam-beam wire compensators).
- Means for reducing the crossing angle at the IP by installing separation dipole magnets deep inside the LHC experiments.
- Crab cavities that tilt bunches longitudinally at the IPs.

| Parameters   | 25ns option | 50ns option | ultimate |
|--------------|-------------|-------------|----------|
| ppb          | $1.7 \times 10^3$ | $4.9 \times 10^3$ | $1.7 \times 10^4$ |
| Beam current | 0.86 A      | 0.86 A      | 1.22 A   |
| $\beta^*$    | 0.08 m      | 0.25 m      | 0.5 m    |
| bunch length | 7.55 cm     | 11.8 cm     | 7.55 cm  |
| crossing angle | 0 \(\mu\)rad | 381 \(\mu\)rad | 315 \(\mu\)rad |
| events / crossing | 294 | 403 | 44.2 |
| L \([\text{cm}^2 \text{sec}^{-1}]\) | $15.5 \times 10^{24}$ | $10 \times 10^{24}$ | $2.4 \times 10^{24}$ |
| luminosity lifetime@ | 2.2 h | 4.5 h | 14 h |
| Stored beam energy | 541 MJ | 767 MJ | 541 MJ |

Two different parameter sets are currently studied for the second upgrade phase: One that is compatible with the ‘ultimate’ LHC parameters but implies major modifications to the existing detector infrastructure (e.g. installation of additional dipole and quadrupole magnets deep inside the experiments) and one that leaves the detector region unaffected but implies larger than ultimate beam currents in the LHC and its injector chain. Table 3 summarizes the two parameter options [10]. Both options suffer from rather short luminosity lifetimes (2h and 4h respectively). To which extend the increase in peak luminosity can be translated into an increase in integrated luminosity depends strongly on the average ‘turn around’ time in the LHC. At the most, one can hope for a three fold increase of the integrated luminosity in both scenarios. Options for an upgrade of the LHC injector complex are discussed in [11].

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