IMPLICATIONS OF HIGHER INTENSITIES IN THE LHC

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Abstract

Various upgrade programs are being studied at CERN for improving the performance of the injector complex and LHC. The final goal is to increase the beam intensity, which is injected into the LHC. In the context of an overall optimized upgrade plan, the implications of higher intensity for the LHC have been reviewed. A simple formula has been derived for the limitation of LHC luminosity from robustness constraints of the accelerator.

INTRODUCTION

The LHC has two sets of design parameters [1]:

1. **Nominal design:** The so-called "nominal" design lists machine parameters that will provide nominal luminosity of 10^{34} cm^{-2} s^{-1} at 7 TeV. A total beam intensity of 3.2×10^{14} protons is stored in each beam. The bunch intensity and the resulting beam-beam tune shift are compatible with collisions in all 4 interaction points and with beam-beam limitations observed in previous colliders.
2. **Ultimate design:** The so-called "ultimate" design assumes that beam collisions are only occurring in the two main interaction points of ATLAS and CMS. The bunch intensity can then be increased by 50% while keeping the same total beam-beam footprint. Peak luminosity is increased by less than a factor 2.

All technical systems of the LHC had the design goal to be compatible with ultimate beam intensity. For many LHC systems this was achieved, some others must be pushed to their technological limits for ultimate intensity and a few systems require completion or upgrades for even allowing nominal intensity. This report gives a first overview on known issues and work to be done.

EVOLUTION OF LHC DESIGN GOALS

In the context of this report it is interesting to review the evolution of LHC design parameters. The luminosity L can be written as follows:

$$L = \frac{1}{4\pi \cdot m_p c^2} \cdot \frac{f_{rev} \cdot N_p \cdot F}{\beta^* \cdot \varepsilon_n} \cdot E_{stored} \qquad (1)$$

$$E_{stored} = N_p \cdot N_b \cdot \frac{E_b}{(\mathrm{GeV})} \cdot 1.6022\times10^{-10}\,\mathrm{J} \qquad (2)$$

Here, E_b is the beam energy in GeV and N_b are the number of bunches. Luminosity is determined by the following terms:

1. A constant factor including the rest mass m_p of the proton and the light velocity c.
2. The revolution frequency f_{rev}, which is a direct consequence from the length of the old LEP tunnel used for LHC.
3. A factor N_p F that is determined by beam-beam considerations. N_p is the number of protons per bunch and its maximum value is given by the beam-beam limits. The factor F gives the luminosity reduction factor due to the crossing angles that are required with more than 156 bunches.
4. The normalized transverse emittance ε_n is given by the injector complex but is also constrained by robustness limits of accelerator components. Here we assume round emittances.
5. The beta function β^* at the interaction point is fixed by IR optics limits and, in particular, the available triplet aperture.
6. The term E_{stored} described the energy that is carried by the beam of protons. It is defined in Eq. 2 and depends on the total beam intensity and the beam energy.

Two important insights should be noted from Eq. 1. First, it is seen the LHC requires much higher stored energy for achieving the same luminosity as previous colliders. The revolution frequency is much lower than in other colliders, as the circumference is much larger (protons travelling at light velocity). Second, it is seen that LHC luminosity is most conveniently pushed in the design phase by increasing the design stored energy.

Stored Energy

The maximum stored energy in a collider has no commonly accepted "hard" limits. Limits depend on so-called "soft" limits like RF transients, assumed beam lifetimes, collimation efficiency, vacuum instabilities etc. The LHC performance was therefore optimized over the years by increasing stored energy per beam.

The evolution of LHC peak luminosity is illustrated in Fig. 1 while the according stored energy per beam is shown in Fig. 2. It can be seen that the LHC aims at extending the stored energy records by 2-3 orders of magnitudes. The LHC will enter into new territory at less than 1% of its nominal beam intensity.

Extremely high stored beam energies are challenging in a number of areas: The RF system must handle large transients, beam dumps must be extremely robust and reliable, collimation must intercept stray protons with efficiencies in excess of 99.99% to prevent magnet quenches, radiation protection must handle long tunnel sections with high activation, … The transport of high stored energy through the 56 mm aperture of super-conducting magnets (quench limits of 5-30 mJ/cm^3) is illustrated in Fig. 3. Known issues will be listed in a later section with more details.

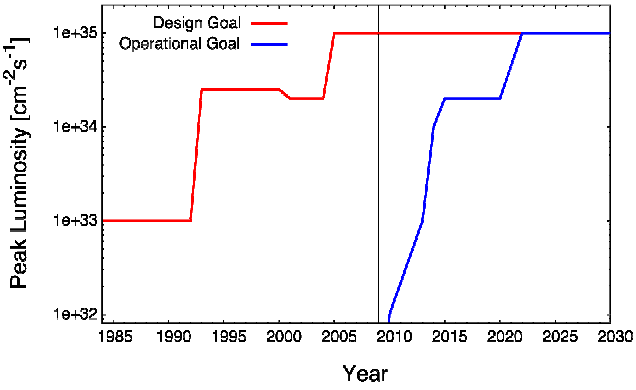

Figure 1: Evolution of the goal peak luminosity (red) for LHC versus time and operational goals (blue).

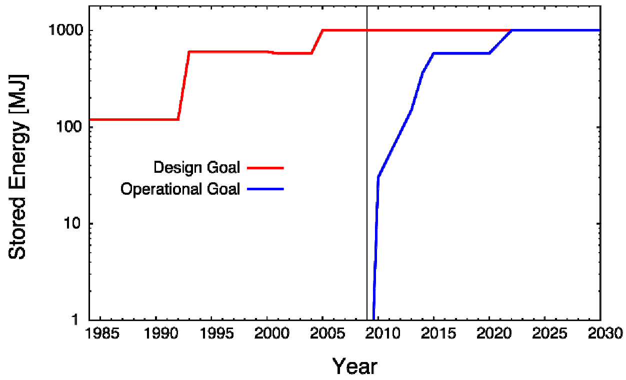

Figure 2: Evolution of the goal stored energy (red) for LHC versus time and operational goals (blue). The present world record in super-conducting proton colliders is at 2-3 MJ.

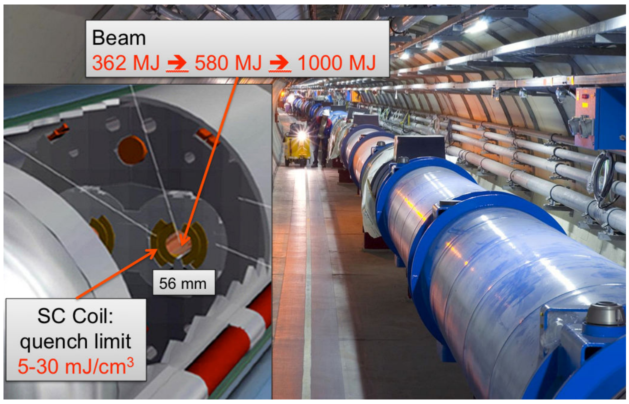

Figure 3: Illustration of the challenge to transport very high stored energy through small aperture super-conducting magnets with low quench limits.

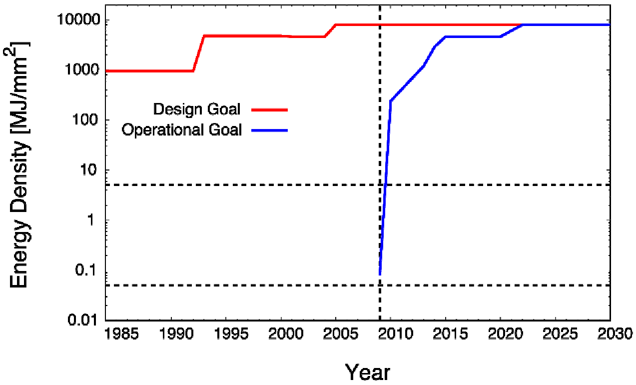

Figure 4: Evolution of the goal energy density (red) for LHC versus time and operational goals (blue). The damage limit for a copper block is about 50 kJ/mm^2 and for a fiber-reinforced carbon block of the collimators about 5 MJ/mm^2.

Energy density

The LHC does not only operate in a regime of high stored energy but the energy is also concentrated in a small transverse cross-section. The energy density ρ_E can be written as:

$$\rho_E = \gamma^2 \cdot \frac{N_p^{tot}}{\varepsilon_n} \cdot C \quad \text{with} \quad C = \frac{m_p c^2}{\pi \sqrt{\beta_x \beta_y}} \qquad (3)$$

Here, γ is the relativistic Lorentz factor of the protons (given by beam energy), N_p^{tot} is the total number of protons per beam and $\beta_{x,y}$ are the beta functions at a given location.

For a given location, the energy density increases linearly with beam intensity and by square with proton beam energy. It also depends inversely on the normalized beam emittance. The evolution of energy density for the LHC is shown in Fig. 4.

The damage potential of a charged beam depends to a large extent on its power density. Damage limits of a few important accelerator materials have been studied in experiment and theory. The following damage limits have been derived:

1. Copper block: 50 kJ/mm^2
2. CFC collimator block: 5 MJ/mm^2

The CFC acronym stands for fiber-reinforced carbon. This is a highly robust material that has been used for primary and secondary collimators in the LHC.

Survival of the LHC machine elements has been established for the specified failure modes of operation. For example, the primary and secondary collimators can survive an asynchronous beam dump without damage at up to 7 TeV, for ultimate beam intensity and for nominal emittance. The robustness of the LHC collimator has been verified with beam tests of up to 2 MJ/mm^2, which is the maximum intensity available for such tests at CERN.

In another example, the LHC beam dump has been designed to survive at 7 TeV the extracted ultimate beam with nominal emittance.

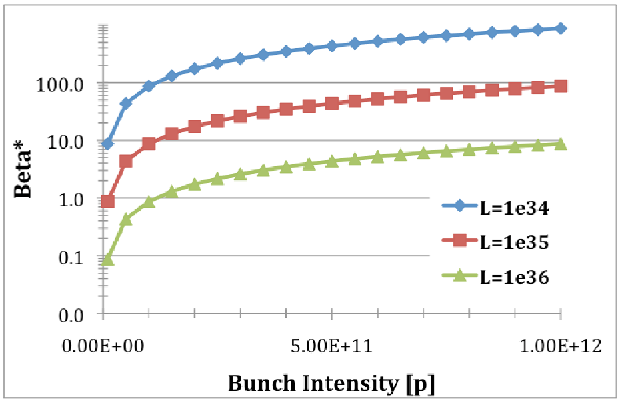

Figure 5: Possibilities at 7 TeV to achieve different luminosities while respecting the robustness limit defined in this report (simplified model).

Robustness and Luminosity Limits

A few simplifying assumptions are being made for deriving some practical formulae:

1. Bunches are spaced equidistantly.
2. The damage potential for beam dump, protection and collimators is limited by total beam intensity. E.g. over a 50 ns window the damage potential of 1 bunch with 3.4×10^{11} protons is the same as that of two bunches with each 1.7×10^{11} protons, separated by 25 ns. This might be slightly optimistic and holds true only up to a bunch population of about 5×10^{11} protons.

Under these assumptions, the LHC machine can be considered sufficiently robust as long as the following condition is fulfilled (robustness for ultimate beam):

$$\frac{N_b N_p}{\varepsilon_n} \leq 1.3\times10^{20}\ \mathrm{m}^{-1} \qquad (4)$$

Here, N_b is the number of bunches per beam. It is seen that the ratio of total stored intensity over normalized beam emittance must be constrained. Therefore, at the robustness limit a reduction of normalized emittance must be compensated by an according reduction in beam intensity. The gain in luminosity due to smaller emittance is then at least cancelled.

We can easily derive the luminosity limit from the robustness constraint in Eq. 4:

$$L \leq \frac{1}{4\pi}\cdot\frac{\gamma\cdot f_{rev}\cdot N_p\cdot F}{\beta^*}\cdot 1.3\times10^{20}\ \mathrm{m}^{-1} \qquad (5)$$

Evaluating the given factors in this equation and approximating F=1 we obtain a simple luminosity limit due to the robustness of LHC protection, collimation and dump systems:

$$L \leq 1.2\times10^{21}\ \mathrm{cm}^{-1}\cdot\frac{\gamma\cdot N_p}{\beta^*} \qquad (6)$$

At 7 TeV (γ = 7461) this translates into the following straight-forward luminosity limitation:

$$L \leq 8.7\cdot10^{24}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-1}\cdot\frac{N_p}{\beta^*} \qquad (7)$$

It is seen that any luminosity upgrade must involve one or several of the following measures:

1. Increase the number of protons per bunch (N_p) while keeping the total bunch intensity constant.
2. Decrease the value of the beta function at the interaction point (β^*).
3. Improve robustness of the collimation, beam dump and protection elements.

The simple relationship in Eq. 7 is shown in Fig. 5 for different target luminosities. Note that the geometric factor F is assumed to be one in this evaluation and the predicted performance is too high by about 50%. However, the derived formulae allow correctly constraining and optimizing luminosity upgrades for the LHC.

OVERVIEW INTENSITY LIMITATIONS

Before listing the detailed issues that were identified in the various systems, we show in Fig. 6 a summary graph on various limitations and possible working points for number of bunches and bunch charge. It can be seen that a number of issues must be addressed before the LHC would be ready for a luminosity upgrade with 2808 bunches and 2.3×10^{11} protons per bunch at 7 TeV. In order of urgency (first listing the solutions for the lowest intensity limits) the following LHC work should be envisaged:

1. Complete the LHC collimation system with the installation of phase 2.
2. Install 3 new cryo plants in the IR's, complementing the existing 8 plants.
3. Design and implement major LHC changes on the RF system and the vacuum system. Change protection and collimator design to increase robustness against beam impact. Implement required improvements for radiation protection.

After completion of these steps it is expected that the final limits be reached, namely the cryo limits in the main magnets. These limits come from the beam screen cooling loop and can only be overcome after changing all magnets. Such a major rebuild is not considered here and we therefore stick to the final limit as coming from the beam screen cooling loops. Fig. 6 also shows the possibilities with a lower number of bunches and increased bunch intensity.

Next we go through a number of sub-systems and list the issues that were identified with system experts.

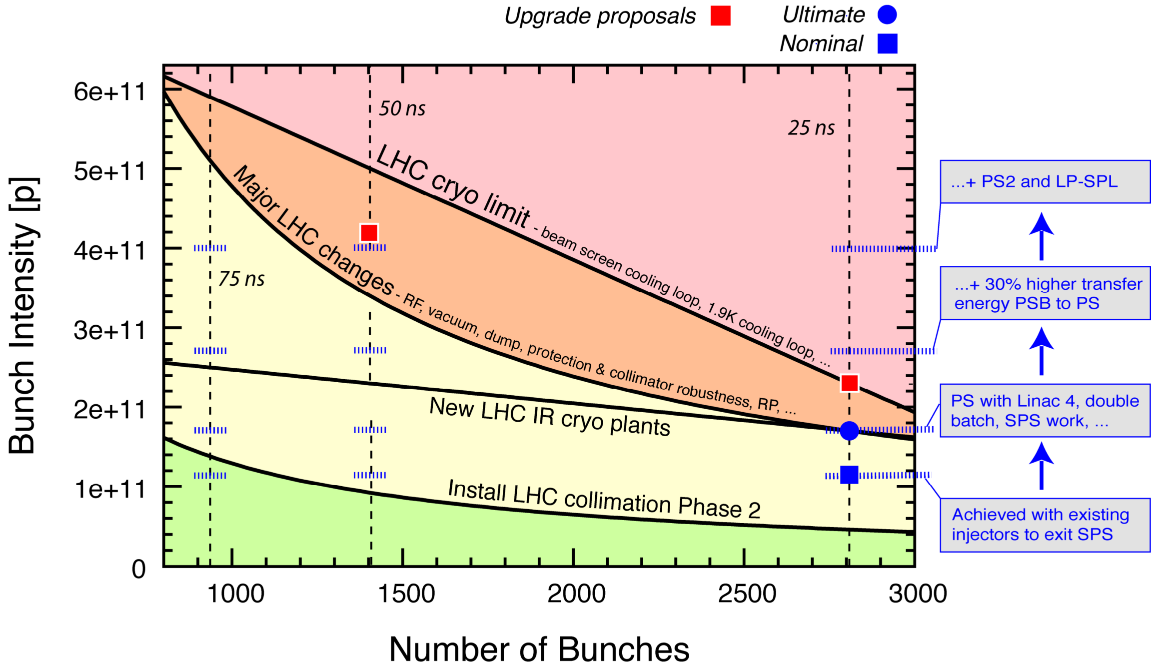

Figure 6: Overview of various bunch intensity limitations in the LHC, evaluated versus number of bunches stored. To move above a particular curve, the quoted work must be done (for example phase 2 of collimation must be installed to reach more than 5×10^{10} protons per bunch in 2808 bunches). The dashed lines indicate the maximum bunch intensities available from various injector upgrade scenarios. Nominal and ultimate beam parameters are indicated, as well as two upgrade proposals presented at Chamonix 2010 [2]. It is noted that this summary shows an optimistic case and refers to the ideal machine without imperfections. Realistically, limitations can occur much earlier (up to a factor 10 below than shown here). It s also noted that the bunch intensity from the injectors will be lower due to unavoidable beam losses.

ISSUES SYSTEM BY SYSTEM

Experts were contacted for various hardware systems of the LHC and issues were collected. At this stage, this can only be a superficial overview of issues that need to be addressed with detailed technical work.

RF System

The following issues were identified with the help of Joachim Tuckmantel:

1. Handling of transients, e.g. at the edge of the abort gap. To go beyond ultimate intensities one must increase the available RF power in the cavity.
2. This requires new transmitters and might imply civil engineering in IR4.
3. The power capability of the higher-order mode coupler must be assessed for higher intensity.
4. Already planned upgrades and additional installations (as the 200 MHz capture system or the 800 MHz HH) are not foreseen for higher currents than ultimate.

It is concluded that currents higher than ultimate will require substantial work on the LHC RF systems including transmitters, couplers, cavities and space.

Vacuum System

The following issues were identified with the help of Miguel Jimenez and Frank Zimmermann:

1. Fast pressure transients can lead to the closure of the sector valves during setup of collimators. Improvements are required.
2. Thermal induced desorption must be evaluated for higher intensities.
3. The lifetime of the bake-out material in highly radioactive zones might become unacceptably low and could need new and more resistant bakeout equipment.
4. The electron cloud heat load will increase with higher bunch intensities and low secondary emission yields are mandatory.

LHC Cryogenic System

The following issues were identified with the help of Laurent Tavian and Serge Claudet:

1. Above ultimate intensity a total of three additional cryoplants are required in IR1, IR4 and IR5. These must be added to the 8 existing cryo-plants.
2. The limitations in the beam screen cooling loops are somewhat fundamental if we assume that a replacement of all magnets is not part of a future upgrade. The limitations must be taken into

account and be addressed. A limit at 2.3×10^{11} protons per bunch was quoted for 7 TeV.

LHC Magnets

The following issues were identified with the help of Lucio Rossi:

1. The magnet system has been designed to withstand ultimate intensity with 25 ns spaced bunches. Risks are in the limited quench margins at high energy.
2. Limitations in the IR triplets exist and must be addressed [3].
3. Special magnets might be more critical than the main magnets. Critical could be the corrector magnets that are potted.
4. The DSL (super-conducting link cable in 3-4) is not far from the quench limit.
5. Radiation damage to magnets might become a limit.

LHC Injection and Dump Protection

The following issues were identified with the help of Brennan Goddard:

1. The SPS extraction protection devices TPSG4/6 are just below their damage limit for ultimate intensity. Any upgrade is difficult due to constraints in longitudinal space.
2. The transfer line collimators TCDI, the TDI and the injection ring collimator TCLI are at their damage limits for ultimate intensity (the MSI mask temperature reaches over 990 degree C). Devices and concepts require redesign work.
3. The septum protection element TCDS will deform plastically above ultimate intensity.
4. The dump protection TCDQ requires an upgrade even for nominal intensity and will afterwards be suitable for up to ultimate intensity. Anything beyond requires a redesign and LHC layout changes.
5. The dump blocks TDE are OK up to ultimate intensity. Beyond this an upgrade of the dilution kicker system is required. Conceptually this can be achieved by installing more MKB tanks to increase frequency and sweep length. However, no technical feasibility or integration study has so far been performed.
6. Any upgrade with super-bunches is strongly advised against.
7. The VDWB and BTVDD devices require study before concluding on maximum intensity reach.

It was concluded that there are lots of potential issues with the various protection devices. Most are already at their technological limits. Probably one needs to start working on "disposable" or "sacrificial" absorbers and/or significant layout changes.

LHC Collimation System

The following issues were identified [4]:

1. The phase 1 primary and secondary collimators are robust for ultimate intensity. Beyond ultimate any abnormal dump is expected to induce damage due to thermo-mechanical shock waves.
2. Damage effects can later be tested in the HiRadMat beam test facility and then more accurate estimates can be given. In case collimators are not robust enough for higher than ultimate intensity, 38 collimators must be redesigned and replaced.
3. Radiation damage to collimators and surrounding equipment will be more severe.
4. Collimation efficiency is presently expected to be limited at 5-40% of nominal intensity. The new limit after installation of collimation phase 2 will need to be established, also from operational experience.
5. The collimators induce high resistive impedance, which will become worse for higher beam intensity. The presently expected intensity limit is at 40% of nominal intensity. Once overcome with transverse feedback, phase II collimators and high chromaticity, a new limit must be established, also from operational experience.

LHC Radiation Protection

The following issues were identified with the help of Stefan Roesler:

1. Dose rates for intensities, which are 10 times higher than nominal, can reach 200 mSv/h in collimation regions and 20 mSv/h in low-beta insertions. Large fractions of the machine will then become high radiation areas or even prohibited areas.
2. Remote handling becomes mandatory. Fast accesses are difficult or impossible. High reliability of equipment is essential.
3. Additional service galleries could be required.
4. Additional measures for for air treatment and the ventilation system will be required. This includes installation of absolute filters and modifications or replacements of ventilation systems.
5. The shielding of accessible underground areas might need to be strengthened to protect personnel from normal losses (e.g. pp collisions) as well as accidental beam losses. Examples are the LHCb counting rooms between UX85A and UX85B.

CONCLUSIONS

The ultimate intensity is already challenging for the LHC. Many systems are at their technological limits with little or no margin. However, on the good side, there is presently no show-stopper for increasing LHC beam intensity.

A long (and incomplete) list of work was collected. This work would prepare the LHC for increased performance. The far goal would be to increase bunch intensity from 1.7×10^{11} protons to 2.3×10^{11} protons per bunch.

Finally, a few practical formulae were given for describing the achievable performance with the present damage limits of the accelerator.

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