LHC UPGRADE SCENARIOS

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Abstract

An LHC high-luminosity upgrade has been studied by various European and international collaborations since about 2001. Ingredients of such an LHC upgrade include the optimization of the interaction-region (IR) layout, new high-field or large-aperture triplet quadrupoles, chromatic correction, possibly detector-integrated slim magnets, crab cavities, beam-beam compensators, operation in a regime of large Piwinski angle, luminosity levelling for reduced detector pile up, heat-load, background, radiation damage due to the collision debris, and a renovation of the injector complex. Scenarios, decision paths, and present R&D efforts will be presented.

INTRODUCTION

The LHC is about to start, planning several years of operations and consolidations (collimators) before reaching its nominal performance. Yet, this paper has to do with its future upgrades and might appear premature. However, any significant improvement of the LHC performance reach is a major challenge, liable to require upgrades with a long lead time. This is why LHC upgrade studies started as early as 2001 and have been pursued, mostly in the framework of the FP6-CARE Project, in collaboration with US-LARP. Several of the initial scenarios have been abandoned, with the identification of show-stoppers. New scenarios have emerged, relying on challenging options, such as significant injector upgrades, new beam dynamics concepts, unconventional technologies or implementations. After a brief review of the motivations, the main performance limitations of the nominal LHC are presented together with new approaches designed to overcome them. This allows shaping some possible scenarios, including robust luminosity levelling called for by the large peak luminosity.

MOTIVATION

The LHC at its nominal luminosity of 10^{34} cm^{-2}s^{-1} is expected to open a new and possibly revolutionary window on the High Energy Physics beyond the Standard Model. Higher luminosity increases the LHC discovery reach: a factor of 10 in luminosity extends the sensitivity to new physics by roughly 30% in energy or particle mass, as well as allowing for higher-precision measurements [1].

A first upgrade has been planned since the LHC design stage. It consists in increasing the beam current at given emittance until the beam-beam limit reaches a value of 0.015 (0.01 is the nominal value). This 'ultimate' value had been identified as the highest beam-beam tune shift allowing reliable operations in the CERN S$p\bar{p}$S. At the time, this upgrade was deemed not to require any hardware changes. The corresponding 'ultimate luminosity' is 2.3×10^{34} cm^{-2}s^{-1}. Albeit useful, this is far insufficient to qualitatively modify the LHC physics reach. For that purpose, the integrated luminosity per year should be increased by a factor 10. Although this ambition would have been unconceivable at the time of the LHC design, the deeper theoretical understanding of the machine combined with experimental observations at existing hadron colliders suggest that this ambition is no longer purely speculative.

PERFORMANCE LIMITS OF NOMINAL LHC AND NEW APPROACHES

In this article, we shall concentrate on the luminosity parameters and two important technological aspects. The short bunch spacing in the LHC (one bunch every 7.5 m) requires collision at an angle of typically 300 μrad in the horizontal or vertical plane to prevent multiple head-on collisions, and to reduce the so-called long-range beam-beam effect to an acceptable perturbation, which is obtained when the angle reaches about 10 times the beam r.m.s. divergence at the crossing point. The classical luminosity formula then becomes complicated by a form factor F that depends on the other parameters, to the extent that straightforward parameter dependences are significantly modified in a non-transparent way. The LHC luminosity for Gaussian beams is given by (most background information may be found in [2]):

$$L = \left(\frac{\beta_r \gamma_r f_{\rm rev}}{4\pi}\right) \frac{k_b N_p}{\beta^*} \left[\left(\frac{N_p}{\epsilon_N}\right) F\left(\Phi_p\right)\right] \qquad (1)$$

with

$$F(\Phi_p) \approx \left(1+\Phi_p^2\right)^{-1/2} , \qquad (2)$$

$\Phi_p = \theta_c \sigma_z/(2\sigma^*)$ denoting the "Piwinski angle," $\sigma^* = \sqrt{\beta^* \epsilon_N/(\beta_r \gamma_r)}$ the rms beam size at the interaction point (IP), $d^* = \sqrt{\epsilon_N/(\beta_r\gamma_r\beta^*)}$ the IP rms divergence, and the minimum full crossing angle

$$\theta_c \approx a d^* \left(0.7 + 0.3\, b\, \sqrt{\tilde{k}_b \tilde{N}_p/\tilde{\epsilon}_N}\right) , \qquad (3)$$

derived from [3]. In the above expressions, β_r and γ_r denote the relativistic factors, $f_{\rm rev}$ designates the revolution frequency, k_b the number of bunches, N_p the number of protons per bunch, β^* the beta function at the IP, ϵ_N the rms normalized transverse emittance, F the form factor, and σ_z the rms bunch length,. We have also introduced the normalized parameters $\tilde{k}_b = k_b/k_{b,0}$ with $k_{b,0} = 2808$ the nominal value, $\tilde{N}_p = N_p/N_{p,0}$ with $N_{p,0} = 1.15 \times 10^{11}$, $\tilde{\epsilon}_N = \epsilon_N/\epsilon_{N,0}$ with $\epsilon_{N,0} = 3.75$ μm. The value of θ_c that allows a sufficient dynamic aperture cannot be calculated and is estimated from simulations [3]. For the nominal LHC parameters, the coefficient a is close to 10 and b about 1. In the parameter range considered, the hourglass effect is always negligible and therefore not included in the above luminosity formula. In the simplifying case of two

IPs with alternate crossing (one crossing in the horizontal plane and one in the vertical), the total beam-beam tune shift assumes the simple form

$$\Delta Q_{bb} \approx \frac{r_p}{2\pi} \left[\left(\frac{N_p}{\epsilon_N} \right) F(\Phi_p) \right] , \tag{4}$$

where r_p is the classical proton radius. This tune shift is proportional to the brilliance and, up to a constant factor, it equals the last factor in the luminosity equation (1).

A key observation for a luminosity increase beyond nominal is that the beam-beam tune shift decreases with the crossing angle while the beam-beam limit is empirically assumed to be independent of it.

We shall now investigate the feasibility and impact of modifying each parameter of the luminosity equation (1) while keeping the others at their nominal values.

Bunch Number k_b

Although the luminosity increases only approximately linearly with the number of bunches, this option has two interesting advantages: (1) The beam-beam tune shift is not increased. (2) The multiplicity (number of events per crossing) is equally not increased. This is a critical parameter for the detector upgrades.

For the long-range beam-beam effect, an increase of the number of bunches is equivalent to an increase of bunch charge. The impact on performance is not a leading term and shall be discussed in the section dealing with bunch charge. The transverse stability of the beam does not appear to be of concern over a large current range (up to 10 times the nominal) using the existing low-noise transverse feedback system. Except for the electron cloud, the heat load generated by image currents and synchrotron radiation is reasonably below the cooling capacity of the beam screen for bunch charges up to two times the nominal charge.

However, the heat load from electron cloud increases steeply for shorter bunch spacing due to multipacting (Fig. 1, taken from [4]). For 12.5 ns bunch spacing, it significantly exceeds the local cooling capacity of 2.4 mW/m, with large error bars due to the uncertainty on the secondary electron yield ($\delta_{\max}$). Unless an economically implementable remedy suppressing the electron cloud effect is rapidly identified, an LHC upgrade based on an increased number of bunches is a priori excluded. Among possible remedies, amorphous carbon coatings produced by magnetron sputtering will be tested in the CERN-SPS in 2009 [5],, when the electron density in coated and bare beam pipes will be monitored by microwave transmission. Laboratory tests and SPS beam studies with prototype coatings in 2008 have already demonstrated a $\delta_{\max}$ of about 1 with little degradation after air exposure. This favourable result can be obtained without in-situ bakeout and without reduction in physical chamber aperture.

Figure 1 clearly shows the advantage of a larger bunch spacing (e.g. 50 ns) that suppresses the electron-cloud issue. In isolation, this option reduces the luminosity. In combination with other options, it can enhance it (see later: "Large Piwinski Angle" scenario).

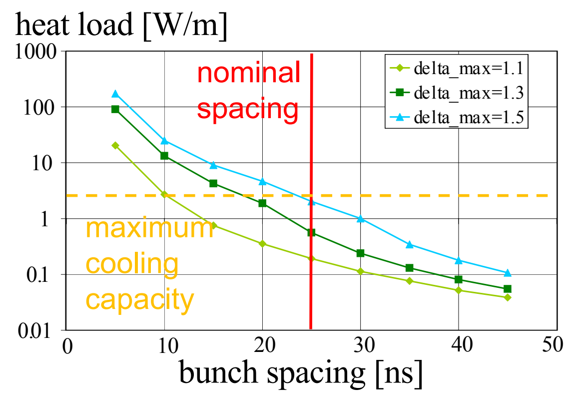

Figure 1: Simulated electron-cloud heat load per unit length for the LHC arc, assuming nominal bunch charge $N_p = 1.15 \times 10^{11}$ and 50% probability of elastic scattering for low-energy electrons; the three curves correspond to three values of $\delta_{\max}$ [4].

Bunch Charge

The bunch charge is limited by the LHC injectors. The SPS can presently deliver to the LHC the nominal charge of 1.15×10^{11} protons per bunch (ppb), while upgrade scenarios assume up to 4.9×10^{11} ppb. As the LHC luminosity lifetime is dominated by the proton-proton collisions, it is essential to reach the maximum bunch charge allowed by the LHC, without being constrained by the injectors. The SPS is primarily limited by the onset of an electron cloud, the lower-energy pre-injectors by space charge.

Final Focus

In a machine where the beam current and beam power are large, there is an incentive to gain luminosity by a stronger final focus, i.e. a lower β^*. In the specific case of the LHC, a β^* reduction however only brings a potential gain; to become effective a combination of other options is required. Indeed, the crossing angle (3) scales with the beam divergence at the IP, and the geometrical luminosity loss (2) increases rapidly with decreasing β^*. In isolation, the reduction of β^* below its nominal value of 55 cm would thus bring only a modest improvement for the nominal crossing angle of 9.5σ (Fig. 2).

Assuming that other collision schemes allow overcoming this difficulty, the limitation for LHC β^* reduction shall come from a subtle interplay between higher-order chromatic effects and momentum collimation. The lattice sextupoles have been designed to correct the linear and second-order chromaticity generated by 4 insertions, two tuned at $\beta^* = 25$ cm and two tuned at $\beta^* = 50$ cm. Since then, the requirement of momentum collimation at collision energy was identified, to protect the dispersion suppressors or the triplets from off-momentum secondaries or from particles diffracted by the collimators themselves. The collimation efficiency is sensitive to off-momentum β-beating (chromatic phase shifts and possible exposure of secondary collimators to primary particles) [8]. The latter reaches 100% at $9\sigma_\delta$ ($\sigma_\delta \approx 1.1 \times 10^{-4}$) for $\beta^* = 25$ cm [6]; see Fig. 3.

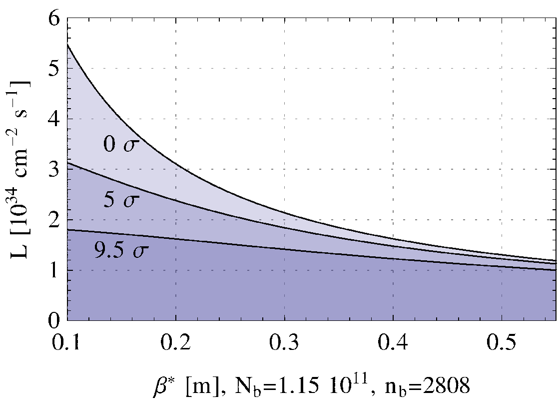

Figure 2: Luminosity versus beta* for various values of the crossing angle (expressed in units of rms beam divergence) and nominal LHC parameters [7].

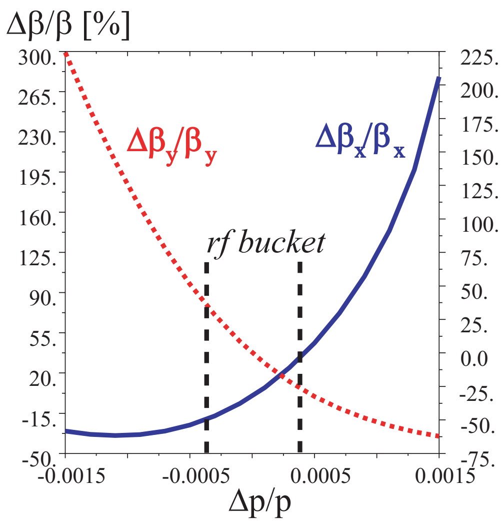

Figure 3: LHC chromatic beta beating in IP3 for $\beta^* = 25$ cm [6].

An exhaustive study [6] shows that the flexibility of the existing lattice and sextupole families allows fully correcting the off-momentum β-beating down to β^*=30 cm for a Nb-Ti triplet. It is estimated that the same requirements for a Nb_3Sn triplet would allow reaching a β^* of about 22 cm. If the momentum collimation scheme can be made more robust against off-momentum β-beating (see e.g. [9]), the ultimate value of β^*, limited by the linear chromaticity correction, is about 15 cm for the nominal experimental drift space length of $\pm$23 m.

Emittance

Initially the beam emittance had not been considered as a parameter for the LHC upgrade, except for in conjunction with a new higher-energy SPS(+) [2]. Rather, the emittance had been kept at its nominal value, consistent with the parameter list of the rejuvenated LHC pre-injectors. Lately, two new approaches have been proposed:

Lowering the emittance [10]: Combining equations (2) and (4) gives the remarkable result that lowering the emittance leaves the luminosity loss factor unchanged. This is qualitatively different from lowering the focusing function β^*, due to the different impact on the beam divergence. The gain in luminosity is simply inversely proportional to the emittance decrease. This strategy is limited by the increase of the beam-beam tune shift, and the reduction of the intra-beam scattering lifetime, but it is favourable at injection where the impact of the field non-linearities can be significantly weakened. The impedance increase due to smaller collimator gaps could be mitigated by a larger separation between primary and secondary collimators, providing in addition a more robust collimation scheme. A numerical assessment of these effects remains to be done.

Increasing the emittance [11]: Experience at the SPS shows that it should be possible to blow up the transverse emittance by a factor 2 to 3 during the LHC ramp without producing significant beam loss. If the unavoidable small losses can be efficiently collected by the collimation system, it would become possible to inject the maximum bunch charge compatible with beam stability and heat load, irrespective of the beam-beam limit that can be satisfied by adjusting the emittance. Assuming the maximum bunch charge of 2.3×10^{11} set by the electron cloud heat load for a bunch spacing of 25 ns, the potential gain in luminosity is about 3 with respect to the nominal parameters. This option requires, like for a reduction of the β^*-function, an increased aperture in the final focus.

Collision Schemes

The nominal collision scheme requires a crossing angle that separates the beams in the common machine sections by some $10\sigma_\beta$. The resulting luminosity loss factor increases rapidly (Fig. 2). This drawback can actually be put to good use.

The *long-range beam-beam compensation* aims at cancelling the de-stabilizing effect of the long-range beam-beam encounters. The principle is to suitably mimic and counteract this interaction by a current carrying wire of opposite effect [12]. The compensation is effective for amplitudes up to the beam separation minus 2σ. It was demonstrated to be robust in simulations [13] and effective in an SPS experiment [14]. This compensator can be used to reduce the crossing angle, thereby gaining in the luminosity loss factor and in the required triplet aperture.

The *"Large Piwinski Angle" (LPA) scenario* [15] actually uses the concomitant reduction of the beam-beam tune shift (4), to increase the bunch charge by a factor of 4 with respect to nominal. The increased bunch charge more than compensates the luminosity loss due to the crossing angle.

The *"early separation scheme"* [16, 17] aims at decoupling the crossing angle at the IP from the beam separation in the common sections by installing dipoles (D0) inside the detectors, as close as possible to the IP (Fig. 4). Its initial use was to minimize the crossing angle until it was realized that a dynamical control of the crossing angle provides a simple and powerful luminosity levelling scheme [18]. The orbit correctors OC confine the change of trajectories to the straight section.

Crab crossing produces effectively a crossing scheme very similar to the above. The notable difference is the absence of dipoles inside the detectors, replaced by a longitudinal rotation of the bunches produced by transverse deflecting modes in RF 'crab cavities'. This principle is under test at KEKB [19].

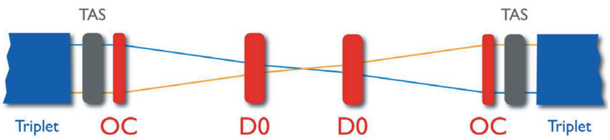

Figure 4: Layout of early separation scheme [7].

Heat Load from Collision Debris

An increase of the luminosity by a factor of 10 would bring the nominal LHC triplets well above their quench limit and reduce their lifetimes to below one year. Drastic actions are thus required for the luminosity upgrade. On-going studies clarify the importance of pertinent parameters like the quadrupole inner aperture and length, e.g. Fig. 5 [20], and the efficiency of the inner shielding made of stainless steel or tungsten.

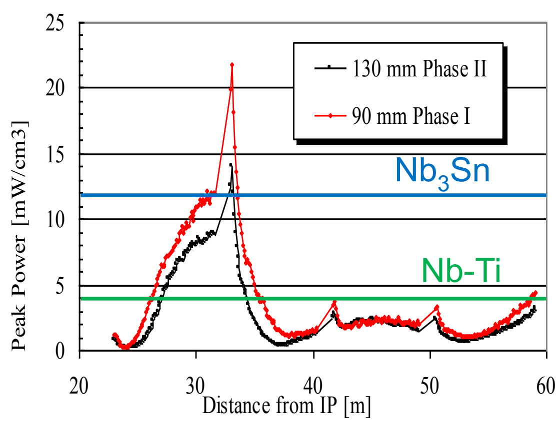

Figure 5: Peak power deposition in the coil for the 36 m long triplet, with 90 mm ("Phase I") and 130 mm aperture ("Phase II") [20]. Design limits (equal to one third of the quench limit) for Nb-Ti and Nb_3Sn are also indicated.

Larger apertures and shorter triplets made possible by Nb_3Sn technology are an advantage, like their higher temperature margin allowing a 3 times higher heat deposition. Inner shielding can then easily decrease the heat deposition below the Nb_3Sn quench limit of 12 mW/cm^3 [20].

Machine Protection

For the nominal LHC parameters, the stored energy in each beam is about 400 MJ. This is two orders of magnitude higher than in the Tevatron. The LHC luminosity upgrade implies a further increase in stored beam energy by a factor 2–3, which appears quite moderate compared with the step from the Tevatron to the nominal LHC. Hence no show-stopper could be identified, but a further tightened beam control is required, that should be expected after several years of LHC machine operation. In case of an irregular asynchronous beam dump, the energy impact on the collimators requires appropriate provisions to be included in the design of the next collimation phase [21].

An upgrade of the beam dump system components for higher beam intensity looks feasible. The material of beam dump and protection would have to be modified by reducing the carbon density, and the sweep length of the dilution system would need to be doubled [21].

In summary, there is no fundamental obstacle from the viewpoint of machine protection [22].

LUMINOSITY LEVELLING

In the LHC luminosity upgrade scenarios, it is expected to observe a very fast decay of the luminosity (hours) dominated by the proton burn off in collision. Luminosity levelling becomes a powerful strategy to reduce the event pile up in the detectors and the peak power deposited in the IR superconducting magnets. Three different parameters can be used to level the luminosity: the beam crossing angle, the beta* and the bunch length. Levelling with the crossing angle has several distinct advantages. It reduces the beam-beam tune shift as well as the luminosity, allowing storing more beam current. Rather than decreasing the average luminosity as a levelling through beta* would do, it increases it if the beam current is not limited by other phenomena. If implemented with the early separation scheme or crab cavities, the side effects are drastically minimized. This is an important operational aspect in seeking to maximize the actual integrated luminosity.

Figure 6 presents a luminosity-levelling scenario [18] for $N_p = 2.5 \times 10^{11}$ ppb ($\beta^* = 0.15$ m and 2808 bunches). The starting luminosity can be chosen by the initial crossing angle (large Piwinski angle regime): in the plots, it ranges between 12 and 16σ separation. The luminosity decay is shown considering 9.5 (nominal), 6, 5 (early separation scheme) and 0 σ (crab crossing) as the ultimate beam separation at the end of the levelling process.

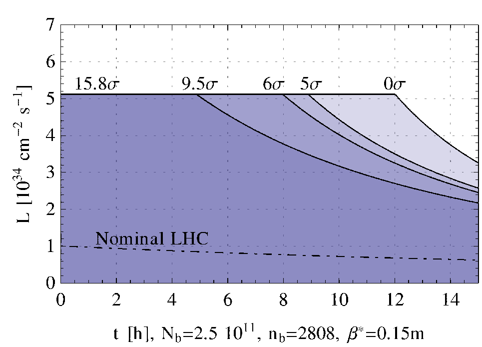

Figure 6: Scenario for luminosity levelling with $N_p = 2.5 \times 10^{11}$ ppb and $\beta^* = 0.15$ m [7, 18].

UPGRADE STRATEGY

The measure of success of an LHC upgrade is the integrated luminosity. It is not only related to the strategies to increase the peak performance of the LHC rings and its injectors. As is well known, the reliability of the whole complex will play a determinant role. To provide the necessary reliability a phased renewal of the entire CERN injector complex is foreseen; see Fig. 7. The new injectors also allow for superior beam parameters that the LHC can take advantage of [23]. In particular, they can supply the LHC with up to 4×10^{11} protons per bunch at 25 ns spacing, as well as with flat bunches of 5×10^{11} at 50 ns spacing. The rejuvenated injector chain will raise the injection energy for most machines (except for the LHC itself) by typically a factor of two, thereby relaxing space-charge effects and instability thresholds. The injector upgrade is synchronized with the upgrade of the LHC IRs. Linac4 will come into operation at the time of the LHC IR Phase-I upgrade, around 2014. The SPL and PS2 will operate from about 2018 onward, together with the LHC Phase-II upgrade. The integrated luminosity projected by the LHC experiments is about 100 fb^{-1} per year for the nominal LHC and 1000 fb^{-1} per year after the Phase-II upgrade [24].

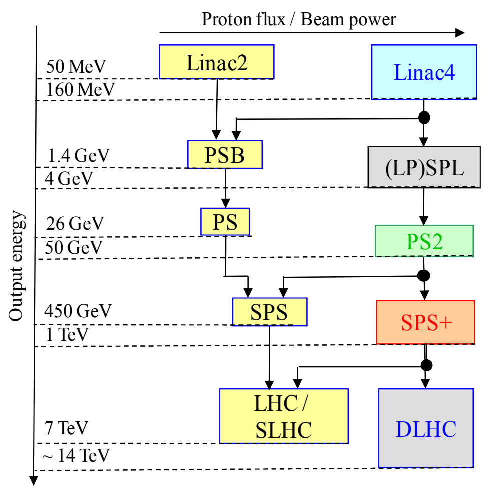

Figure 7: CERN accelerator-complex upgrade plan [23].

Implementation Plan for Phase I

The LHC Phase-I upgrade consists of new Nb-Ti triplets with larger aperture, new separation dipoles, and a new front quadrupole absorber (TAS), which may allow reaching a β^* of 0.25 m in the interaction points 1 and 5. The beam would be accelerated through the new Linac4, readily providing the ultimate intensity of 1.7×10^{11} ppb for the LHC. The Phase-I upgrade should be completed by 2014.

Scenarios for Phase II

Phase II would be realized around 2018. It coincides with the commissioning of two new injector-accelerators, the Superconducting Proton Linac (SPL) and the Proton Synchrotron 2 (PS2), which will replace the PS Booster and the PS, respectively, and permit reaching twice the ultimate beam brightness with 25 ns spacing in the LHC. The LHC interaction region may need to be rebuilt for Phase II. A promising option is a new triplet made from Nb_3Sn that might allow squeezing β^* down to about 15 cm.

CONCLUSIONS & PERSPECTIVES

Several upgrade options have been identified which could raise the LHC peak and average luminosity by a factor of ten beyond nominal. A larger-aperture Nb_3Sn triplet benefits all these options. It would therefore mitigate the risk and lead to a safe upgrade approach. The rejuvenation of the CERN injector complex will lead to beams of higher brightness, improve overall reliability, minimize the turnaround time, raise the integrated luminosity, and increase the flexibility. A concomitant upgrade of the LHC collimation system appears critical, whether for larger beam current or larger transverse density.

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