Possible Scenarios for an LHC Upgrade

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Abstract

After discussing the rationale for an LHC upgrade and various performance limitations of the nominal LHC, several alternative upgrade scenarios and options are presented.

1 THE NEED FOR AN UPGRADE

There are two reasons for considering an upgrade of the LHC after about 6 years of operation. They are illustrated in Fig. 1, which goes back to J. Strait [1]. The figure illustrates two possible evolutions of peak luminosity as a function of the year, as well as the corresponding integrated luminosity and the run-time needed to halve the statistical error of experimental measurements. Both scenarios assume an LHC start up in 2007, and that 10% of the design luminosity is reached in 2008, and 100% in 2011 [2, 3]. In one case, the luminosity is taken to be constant from then on, in the other it continues to increase linearly until the so-called ultimate luminosity (2.3 times the nominal) would be reached by 2016. The radiation damage limit of the LHC low-β quadrupoles is estimated at an integrated luminosity of 600–700 fb\(^{-1}\) [4]. As the figure shows, this value would be exceeded in 2014 or 2016 depending on the scenario. The additional run-time required to halve the statistical error rises more steeply. It would exceed 7 years by 2011 or 2013, respectively.

Since the life expectancy of the interaction-region (IR) magnets is, therefore, estimated to be less than 10 years due to the high radiation doses and since the time needed to halve the statistical error will exceed 5 years by 2011–2012, it is reasonable to plan a machine luminosity upgrade based on new low-β IR magnets before about 2014.

2 CHRONOLOGY OF UPGRADE STUDIES

In the summer of 2001 two CERN task forces investigated the physics potential [6] and accelerator aspects [5] of an LHC upgrade. Also in 2001 T. Sen, J. Strait, and A. Zlobin published a first paper on the LHC IR upgrade [7]. It was followed by several others from US and CERN teams [8, 9, 10, 2]. In March 2002 an LHC IR upgrade collaboration meeting was held at CERN [11], followed in October 2002 by an ICFA seminar on ‘Future Perspectives in High Energy Physics’. Also the first LHC performance workshop, Chamonix 2003, addressed questions relevant for an upgrade [12]. Since 2004, as part of the 6th framework programme of the European Union the CARE-HHH European Network on High-Energy High-Intensity Hadron Beams [13] is pursuing the LHC upgrade. This network has hosted the HHH-2004 workshop.

3 PERFORMANCE LIMITATIONS

Past studies [5], have identified a number of LHC performance limitations.

The existing beam dumping system limits the total current and may require an upgrade. The present system is compatible with the ultimate bunch intensity of \(1.7 \times 10^{11}\) protons per bunch. Increases to \(2.0 \times 10^{11}\) could be tolerated with reduced safety margin or after a moderate upgrade.

The detector architecture also limits the luminosity. A detector upgrade can take place in parallel with the accelerator upgrade. It could allow moving the low-β quadrupoles closer to the IP. In their present configuration, the ATLAS and CMS detectors can accept a maximum luminosity of 3–5×10\(^{34}\) cm\(^{-2}\)s\(^{-1}\).

The collimation system and machine protection restrict the total current and the minimum achievable β* value. The machine protection is challenging already for the nominal LHC: The transverse beam energy density is 1000 times that of the Tevatron. The use of simple graphite collimators may limit the maximum transverse energy density to one half of the nominal value, in order to prevent collimator damage and beam instabilities. Closing collimators to 6σ...
yields an impedance at the edge of instability. A local fast loss of $2.2 \times 10^{-6}$ of the beam intensity quenches nearby arc magnets.

The electron-cloud effect may constrain the minimum bunch spacing. The electron cloud in the LHC arcs gives rise to additional heat load on the beam screen. The value of this heat load depends on the surface parameters. At 75-ns bunch spacing, no problem is anticipated. Initial bunch populations at the nominal 25-ns spacing will be limited to about half of the nominal intensity.

As in previous colliders, the beam-beam effect will limit the ratio of bunch intensity and normalized emittance $N_b/\gamma \epsilon$ and the crossing angle. Beam-beam compensation schemes may help to relax the associated constraints.

In the following, we will review two of the limiting effects in more detail, namely the electron cloud and the beam-beam interaction.

### 3.1 Electron Cloud

Figure 2 shows a schematic of the electron build-up process inside the LHC beam pipe. Photo-electrons are created by synchrotron radiation at the beam-pipe wall. These photo-electrons are then accelerated in the electric field of the photon-emitting bunch which passes simultaneously. They gain a maximum energy of 200 eV, close to the energy where the secondary emission yield is maximum, and hit the opposite side of the vacuum chamber after about 5 ns. Upon impact on the wall, the accelerated primary electrons generate low-energy secondary electrons, which may stay inside the beam pipe until the following bunch arrives, 25 ns behind the previous one. The secondary electrons are then accelerated by the field of this bunch, producing new secondary electrons in turn. The repetition of this process leads to an avalanche-like generation of electrons. The build-up of electrons only saturates, when the electron space-charge field prevents further secondary electrons from penetrating into the inside of the vacuum chamber. The survival of electrons between bunches and, hence, the rate and magnitude of the electron build-up are enhanced by a high probability of elastic reflection of low-energy secondary electrons [14], i.e., ones which hit the wall before being accelerated by a passing bunch.

An exponential electron cloud build up, as described above, with saturation after about 30–40 bunches has been observed in the SPS with LHC beam [15]. This demonstrates that, even in the absence of synchrotron radiation and a large number of photoelectrons as primary source, the amplification via acceleration by the beam and subsequent secondary emission is strong enough to lead to a rapid increase in the number of electrons, presumably starting from the small rate of electrons generated by gas ionization. In consequence, an electron-cloud effect is anticipated in the LHC also at injection.

It is expected that after some bombardment with electrons, the maximum secondary emission yield will decrease to values close to 1, whereas the electron-cloud effect will disappear. In other words, it is thought that the electron cloud will cure itself (so-called 'scrubbing effect'), which will allow reaching the nominal LHC parameters. Experiments in the SPS have verified the scrubbing phenomenon and have established that the desired low values of secondary emission can be reached.

Nevertheless, it must be emphasized that the electron-cloud build up steeply increases for lower bunch spacing. Only experience with LHC operation will clarify whether bunch spacings lower than the nominal 25 ns are prohibited.

![Figure 2: Schematic of electron-cloud build up in the LHC vacuum chamber. Primary electrons are generated on the chamber wall illuminated by synchrotron radiation via photoemission. The number of electrons is then amplified exponentially by beam-induced multipacting.](image-url)
experimental data. In Fig. 4 the bunch population at which an electron-cloud effect is observed at various accelerators is displayed as a function of the bunch spacing [18]. Note that both axes carry a logarithmic scale. Data for positron as well as hadron storage rings are included. For a large class of storage rings the threshold bunch population seems to scale linearly with the bunch spacing:

\[ N_b^{\text{thr}} \propto \Delta t_{\text{sep}}. \]  

(1)

At a spacing of 20–25 ns, the points for the SPS, PS, Tevatron with uncoalesced beam, and the APS fall on top of each other. For the SPS, data of electron-cloud thresholds are available for three different spacings (5 n, 25 ns and 50 ns), and follow the empirical scaling of (1). Also RHIC data reveal a large sensitivity to the bunch spacing, but the observed thresholds are much lower than for the other machines. A tentative explanation is that the surfaces in RHIC may be less well conditioned, and, therefore, exhibit a larger secondary emission yield. The thresholds found at DAFNE and KEKB are looser than for the proton machines and the APS, possibly due to extensive surface cleaning by synchrotron radiation. Shown in red are design operating points of several planned accelerators, including the nominal and ultimate LHC. From here the upgrade path could go in two different directions, either parallel to the SPS ‘threshold line’ towards larger spacing and higher intensity with \( N_b \propto \Delta t_{\text{sep}} \), staying at a constant distance from the electron-cloud threshold, or towards shorter bunch spacings \( \Delta t_{\text{sep}} \) for constant bunch intensity \( N_b \), which would require an additional improvement in the surface conditions.

Figure 5 visualizes the consequences of a shorter bunch spacing for the heat load in LHC, presenting simulation results for two different values of \( \delta_{\text{max}} \). The figure shows that the change of \( \delta_{\text{max}} \) result in a roughly constant vertical shift on a vertical logarithmic scale. Elastically reflected low-energy electrons were taken into account (here assuming 50% reflection probability in the limit of 0 incidence electron energy.

At low and moderate bunch intensities the electron-cloud build up saturates, if the average electron line density equals the average beam charge line density [19]. This leads to an equilibrium electron density which scales linearly with the beam intensity. However, the electron density no longer increases for high bunch intensities [20, 21], or at \( N_b > N_{\text{trans}} \), with the critical or transition intensity given by

\[ N_{\text{trans}} = \frac{E_s \Delta t_{\text{sep}}}{m_e c r_e}, \]

(2)

where \( E_s \) denotes the typical kinetic energy of the emitted
secondary electrons, \( \Delta t_{\text{rep}} \) the bunch spacing in seconds, \( m_e \) the electron mass, and \( r_e \) the classical electron radius. For the LHC bunch spacing, we have \( N_{\text{trans}} \approx 10^{11} \), assuming \( E_s \approx 1.9 \) eV [22]. The transition occurs, when the initial kinetic energy \( E_s \) of the secondary electrons is too low for them to penetrate into the space-charge field of the electron cloud [20].

The saturated electron line density in the high-intensity regime is estimated as

\[
N_e^{\text{sat}} \approx \frac{E_s}{r_e m_e c^2} \approx 1.3 \times 10^9 \text{ m}^{-1},
\]

where again we have taken \( E_s \approx 1.9 \) eV as the typical secondary-electron energy (see [22]).

Figure 6 shows simulations which reveal the predicted saturation for high intensity. Shown is the simulated electron line density evolution in time during the passage of four consecutive LHC bunch trains, with bunch populations of \( N_b = 2.3 \times 10^{11} \) and \( 4.6 \times 10^{11} \), respectively. However, the fact that the electron density barely changes for higher intensity does not mean that the heat load remains constant. Since the energy transfer to an electron roughly scales with the square of the bunch charge (if the electron is “far” from the beam), the electron-induced heat load continues to grow for increasing intensities.

![Figure 6: Simulated build up of electron-cloud line density (in m\(^{-1}\)) vs. time (in s) for bunch populations of \( N_b = 2.3 \times 10^{11} \) and \( 4.6 \times 10^{11} \), at the nominal 25-ns bunch spacing. Assumed were a maximum secondary emission yield \( \delta_{\text{max}} = 1.3 \), the energy for which the yield is maximum \( E_{s,\text{max}} = 230 \) eV, and a primary photo-electron emission rate \( d\lambda_{e,p}/ds = 7.25 \times 10^{-4} \text{ m}^{-1} \) per proton [18].](image)

Figure 7 illustrates electron motion during the passage of a long superbunch [23] with nearly uniform profile. Photo-electrons generated at the head of the bunch are trapped in the increasing beam potential and released only at the end of the bunch passage. Electrons emitted at the wall during most of the bunch passage move in a quasi-static beam potential, and do not gain any net energy from the beam. They traverse the beam, being first accelerated and then decelerated, and hit the opposite side of the chamber with their original emission energy, which is too low to produce a significant amount of secondary electrons. Only electrons generated near the very tail of the bunch experience a beam potential decreasing in time and, as a result, experience a net energy gain. These electrons can therefore contribute to an amplification process, which is appropriately called “trailing-edge multipacting” [24]. The severity of the trailing-edge multipacting depends on the detailed shape of the bunch profile. In any case, the large majority of protons in a superbunch do not participate in the multipacting process, and, therefore, the heat loads calculated for superbunches tend to be negligible, orders of magnitude below those for the nominal LHC bunched beam [25].

![Figure 7: Schematic of reduced electron-cloud build up for a superbunch (after V. Danilov [24]).](image)

### 3.2 Beam-Beam Interaction

Figure 8 shows a layout of the LHC double ring with its four main experimental insertions. The beam-beam interaction in LHC consists of two components: quasi-head-on beam-beam collisions at the four primary interaction points (IPs) in the four experiments and a total of 120 long-range collisions experienced when approaching or leaving these IPs. The long-range collisions are illustrated in Fig. 9. Of particular importance are so-called PACMAN bunches at the head or tail of a bunch train [26], which do not suffer the nominal number of long-range collisions, and, in consequence, have orbits and tunes different from the nominal bunches. The long-range collisions perturb the motion at large betatron amplitudes where particles come close to the opposing beam. They thereby may cause a “diffusive” (or dynamic) aperture [27], possibly resulting in high background and poor beam lifetime. The number of long-range collisions has increased from only 9 at the SppS collider, over 70 for the Tevatron, to 120 in the LHC, rendering their effect more and more significant.

The LHC dynamic aperture due to the long-range collisions, normalized to the rms beam size \( \sigma \), can be estimated as [28, 29, 5]

\[
\frac{d\Delta a}{\sigma} \approx \theta \left( \frac{\beta^*}{\gamma e} \right) - 3 \sqrt{\frac{3.75 \mu m m_{\text{bep}} N_b}{(\gamma e) 3 \times 10^{11}}},
\]
where \( n_{\text{par}} \) denotes the total number of parasitic (long-range) collisions around one IP (with a nominal number of 30), \( \theta_c \) is the full crossing angle, and \( \beta^* \) the beta function at the collision IP. If a certain diffusive aperture is required, (4) determines the minimum acceptable crossing angle. Note that for a smaller \( \beta^* \) or a larger bunch intensity, the crossing angle \( \theta_c \) must be increased to preserve the same diffusive aperture.

Figure 8: Layout of the LHC with its four interaction points [30]).

A variable describing the strength of the head-on beam-beam interaction is the beam-beam tune-shift parameter, which for one IP reads

\[
\xi_{\text{HO}} = \frac{N_0 \tau \rho}{4 \pi \gamma e} .
\]

If the acceptable beam-beam tune shift \( \xi_{\text{HO}} \) is limited, for example by vicinity to nearby resonances, the beam brilliance \( N_0/(\gamma e) \) is also limited via (5).

In a similar way, the tune shift induced by the long-range collisions around one IP can be quantified as [26]

\[
\xi_{LR} = 2n_{\text{par}} \frac{\xi_{\text{HO}}}{d^2} , \tag{6}
\]

where \( d \) signifies the normalized separation (in units of the rms beam size \( \sigma \)). The long-range tune shift increases as either the bunch spacing (larger \( n_{\text{par}} \)) or the crossing angle is reduced (smaller \( d \)).

Values of head-on tune-shift parameters for a single IP and the total beam-beam tune spread are compared in Table 1 for various hadron colliders. The LHC design parameters confine the total beam-beam tune spread to 0.01 (including long-range contributions), which, based on the SPS collider experience, is taken to be a conservative value of the tune spread.

<table>
<thead>
<tr>
<th></th>
<th>( \xi_{\text{HO}}/\text{IP} )</th>
<th>no. of IPs</th>
<th>( \Delta Q_{\text{bb}} ) total</th>
</tr>
</thead>
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<tr>
<td>SPS</td>
<td>0.005</td>
<td>3</td>
<td>0.015</td>
</tr>
<tr>
<td>Tevatron (pbar)</td>
<td>0.01–0.02</td>
<td>2</td>
<td>0.02–0.04</td>
</tr>
<tr>
<td>RHIC</td>
<td>0.002</td>
<td>4</td>
<td>~0.008</td>
</tr>
<tr>
<td>LHC</td>
<td>0.0034</td>
<td>2 (4)</td>
<td>~0.01</td>
</tr>
</tbody>
</table>

In the case of a superbunch, the transition between head-on and long-range collisions becomes continuous, as is illustrated by Fig. 10. One advantage of a uniform superbunch is that, according to calculations [33, 32, 34], the luminosity with long bunches with flat longitudinal distribution is 1.4 times higher than for conventional Gaussian bunches with the same beam-beam tune shift and identical bunch population.

Figure 9: Schematic of long-range collisions occurring around an LHC interaction point for nominal parameters, including ‘PACMAN’ bunches at the start and of a train [31].

Figure 10: Schematic of superbunch collisions consisting of head-on and long-range components [32].
4 UPGRADE SCENARIOS AND OPTIONS

The fundamental luminosity equation is

$$L \approx \frac{n_b N_s^2 f_{\text{rep}}}{4\pi \sigma^*^2} F,$$

where

$$F \approx \frac{1}{\sqrt{1 + (\frac{\theta \sigma^*}{2\sigma^*})^2}},$$

and the rms beam size is related to the IP beta function and emittance via the usual relation

$$\sigma^* = \sqrt{\beta^* \epsilon}.$$

From (7) and (8), below the beam-beam limit the luminosity is reduced for long bunches and large crossing angles. Hence, in this regime, one would like to shorten the bunch and reduce $\theta_c$ to maximize the performance.

The situation changes, if we introduce the limitations from the beam-beam interaction. For simplification, we consider two high-luminosity interaction points with alternating crossing (so that the linear beam-beam tune shift due to the long-range collisions cancels between the two IPs [26]). In this case, the total linear tune shift is reduced by a factor $F_{\text{bb}}$ which is approximately equal to the factor $F$ in (7) [33]. Namely, we have for the total tune shift

$$\Delta Q_{\text{bb}} = \xi_{x,HO} + \xi_{y,HO} \approx \frac{N_{\text{rep}}}{2\pi \gamma \epsilon} F.$$  \hspace{1cm} (10)

Combining (7) and (10), we may rewrite the luminosity as

$$L \approx \gamma (\Delta Q_{\text{bb}})^2 \frac{\pi (\gamma \epsilon) f_{\text{rep}}}{r_p^2 \beta_s^*} \sqrt{1 + \left(\frac{\theta \sigma^*}{2\sigma^*}\right)^2}.$$  \hspace{1cm} (11)

Equation (11) shows that at the beam-beam limit, the luminosity can be increased by increasing the bunch length or the crossing angle, which is the opposite of the behavior below the beam-beam limit. Closer inspection of (11) also reveals that a higher injection energy, which would allow injecting a more intense beam with a larger normalized emittance ($\gamma \epsilon$), would raise the luminosity. Another possibility to achieve higher luminosity is to operate with large crossing angle (either in a regime with large Piwinski angle [33] or, in the extreme case, ‘superbunches’ [23]). Figure 11 illustrates the potential luminosity gain in LHC luminosity vs. bunch length (or crossing angle) for Gaussian and flat (super-)bunches at constant beam-beam tune shift with alternating crossings in IP1 and IP5. A more precise prediction, taking into account the bunch-end effects, was derived by H. Damerau [35].

From (7)–(11) two alternative upgrade scenarios emerge.

4.1 Baseline Scheme

Figure 12 shows a flowchart of the baseline upgrade scheme. Starting with the nominal performance at 0.58 A beam current and luminosity 1 (in units of $10^{34}$ cm$^{-2}$s$^{-1}$), the bunch intensity is increased until the beam-beam limit is reached at a luminosity of about 2.3 with only two high-luminosity experiments. Then the form factor $F$ is increased. Here, several options exist. Long-range beam-beam compensation [36] allows reducing the crossing angle or squeezing $\beta^*$ with a constant $\theta_c$. Once the crossing angle cannot be decreased any further, $F$ can be further decreased by shortening the bunches using a higher frequency rf system and a 30% smaller longitudinal emittance.

A completely different approach would be the deployment of crab cavities. The crab-cavities provide effectively head-on collisions, as concerns luminosity, though the bunch centroids still intersect with a large crossing angle. The crab cavities would additionally permit a substantial increase in the crossing angle, to several mrad, whereby the two beams could be passed through separate magnetic channels, without sharing a quadrupole aperture. The crab cavities would lead to a simplified IR design with large $\theta_c$.

Independently from the procedure followed for maximizing the form factor $F$, the centerpiece of all LHC upgrades is the installation of new IR magnets, which can provide at least a factor 2 reduction in the IP beta function, to a value of 0.25 m or smaller. The smaller $\beta^*$ will double the luminosity to 4.6. In case the constraints from electron cloud, beam dump and impedance are not prohibitive, finally the number of bunches can be increased by a factor of about 2, yielding a total luminosity gain by a factor 9.2 above the nominal with a beam current of 1.72 A.

4.2 Piwinski Scheme

The alternative upgrade path moves in the direction of longer bunches with larger crossing angle. A flowchart for this upgrade scenario is depicted in Fig. 13. Again starting from the nominal LHC parameters, as for the baseline scheme, the beta function is reduced to half the nominal
value by means of new IR magnets. In this upgrade scheme we enlarge the Piwinski parameter and thus decrease the form factor $F$, by increasing the product of bunch length and crossing angle. To maximize the luminosity gain, the longitudinal profile should be flattened, so that the line density is roughly constant along the full bunch length. At the same time as the bunch is lengthened, the bunch charge must be increased to stay at the beam-beam limit. The total number of bunches can be reduced to limit the total beam current. In the extreme limit only a single superbunch would remain. At an average beam current of 0.86 A a luminosity increase by factor 7.7 above the nominal is possible. For a current of 1.72 A, as considered in the baseline scheme, the luminosity gain would be a factor 15.5, which is more than 50% higher than for the baseline scenario at equal current.

4.3 Additional Considerations

If the total beam current is limited, e.g., by electron cloud, machine protection, or dump, fewer bunches with more charge yield a higher luminosity, but also increase the event pile up in the physics detectors.

The minimum value of the IP beta function depends on the interaction-region magnets, the chromatic correction (more critical for scenarios with larger momentum spread), and the settings of the collimators. The integrated luminosity scales as $T_{bb}/(T_{bb} + T_{turn-around})$, i.e., with the ratio of collision time and the total time, which is the sum of collision and turn-around time. The turn-around time can be decreased by increasing the injection energy into the LHC (by a “Super-SPS”), which reduces injection time and snapback.

The compensation of long-range beam-beam encounters and the Super-SPS would enable operation with larger intensity at larger normalized transverse emittance. Increasing the injection energy by a factor of 2, the LHC luminosity also increases by roughly a factor 2.

As pointed out before, the luminosity at the beam-beam limit is higher for flat (long) bunches, instead of Gaussian ones.

The capability of the experiments, e.g., which bunch structures can be handled, must be taken into account.

4.4 Upgrades to the LHC Injector Complex

A possibility being considered also for the CNGS proton beam (CERN Neutrino beam to Gran Sasso) is to upgrade...
4.5 New Interaction Regions

The goal of the new interaction regions is to reduce $\beta^*$ by a factor 2–5. Various optics are being considered [7, 8, 9, 10, 2, 41]: a ‘cheap’ upgrade based on NbTi as well as stronger magnets made from NbTi(Ta) or Nb$_2$Sn. Both the low-$\beta$ quadrupoles and the separation dipoles should be upgraded.

Several factors drive the IR design [2]: (1) minimization of $\beta^*$, (2) minimization of long-range collision effects, (3) large radiation power directed towards the interaction regions, (4) accommodation of crab cavities or beam-beam compensators, and (5) compatibility with the upgrade path. Items (1) and (2) are addressed by maximizing the magnet aperture and minimizing the distance to the IP.

Figure 14 displays two ‘baseline’ upgrade schemes. Shown on the left is an option with short bunches colliding at a small crossing angle, facilitated by long-range beam-beam compensation schemes. It also reduces the turn-around time and increases the integrated luminosity. A Super-SPS would mark the first step in the direction of an LHC energy upgrade, since it reduces the energy swing by a factor of 2.

A superconducting linac could replace the PS Booster. Alternatives would be a fast cycling superconducting Super-PS and Super-PSB or a series of FFAGs (fixed-field alternating gradient synchrotrons) as proposed for the BNL site [37].

the existing proton linac from 50 to 120–150 MeV, in order to overcome space-charge limitations at injection into the PS booster. Then the ultimate LHC intensity could easily be achieved and a further 30% intensity becomes possible with the same emittance and filling time.

An SPS equipped with superconducting magnets (“Super-SPS”) and an upgrade of the transfer lines would allow LHC injection at 1 TeV instead of 0.45 TeV. This option increases the LHC peak luminosity by nearly a factor of two at constant beam-beam parameter $\varepsilon_0$.

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Figure 14 displays two ‘baseline’ upgrade schemes. Shown on the left is an option with short bunches colliding at a small crossing angle, facilitated by long-range beam-beam compensation, and on the right an alternative with crab cavities, large crossing angle and separate quadrupole channels. In this second case, the bunches do not need to be as short as on the left, since the crab cavities ensure de facto head-on collisions.

Two alternative IR upgrade schemes are illustrated in Fig. 15. Both of these alternative schemes have a dipole as the magnet closest to the IP, inspired by the example of RHIC. The left scheme employs a pair of separation and combination dipoles between the IP and the final triplet, realizing a small crossing angle. Advantages are a strongly reduced number of long-range collisions. On the negative side, collision debris from the IP will hit the first dipole, necessitating a special open-midplane design [38]. The other scheme, on the right-hand side, collides the beams under a large crossing angle, and uses only one dipole magnet to feed each beam into its quadrupole magnet channel. Be-
Figure 14: IR ‘baseline’ schemes with minimum crossing angle and possibly long-range beam-beam compensation (left) or with large crossing angle and possibly crab cavities (right); see also [2].

cause of the large crossing angle, this scheme must employ either long bunches (Piwinski regime) or operate with crab cavities.

alternative IR schemes

dipole first & small crossing angle
dipole first & large crossing angle & long bunches or crab cavities

Figure 15: Alternative IR schemes with dipole first for small (left) or large crossing angle (right). The right layout needs to either operate with large Piwinski angle or employ crab cavities; see also [2].

Lastly, in case the LHC luminosity must be doubled earlier than foreseen, a more conventional solution, based on NbTi quadrupoles, does also exist [41]. This solution is shown in Fig. 16. Here, the length and aperture of each quadrupole are individually optimized, and the IP-quadrupole distance is slightly reduced from 23 m to 22 m. A beta function of $\beta^* = 0.25$ m appears possible [41].

4.6 Bunch Structure

Various bunch structures correspond to the different upgrade paths. Figure 17 sketches the possible evolutions.

In the baseline upgrade path, we shorten the bunches and increase their number. Advantages of this path are that crab cavities can be used and the event pile up remains tolerable. Concerns are the electron cloud, long-range beam-beam interaction, and impedance.

In the alternative second upgrade path, the trend is towards longer and fewer bunches (e.g., 75 ns spacing). The merits of this scheme include the absence of an electron cloud and a higher luminosity for equal beam current. Concerns are the event pile up and also the impedance. The extreme version of this upgrade direction would be a superbunch, which has the same advantages, offering even slightly higher luminosity, but which, as a striking disadvantage, implies an enormous number of pile-up events, which cannot be handled by the present detectors or their moderate upgrade.

Transitions between the different bunch structures would be possible in the LHC itself, by employing new rf systems for bunch merging or bunch splitting (see also [35]).
Table 2: Parameters for the nominal and ultimate LHC compared with those for three upgrade scenarios with (1) shorter bunches at 12.5-ns spacing [baseline], (2) longer more intense uniform bunches at 75-ns spacing [large Piwinski parameter], and (3) a single superbunch per ring [very large Piwinski parameter].

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal</th>
<th>ultimate</th>
<th>shorter bunches</th>
<th>longer bunches</th>
<th>superbunch</th>
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<td>2808</td>
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<td>0.86</td>
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<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>norm. transv. emittance</td>
<td>$\gamma_e$ [$\mu$m]</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>longit. profile</td>
<td></td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>uniform</td>
<td>uniform</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\sigma_z$ [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>3.78</td>
<td>20</td>
<td>6000</td>
</tr>
<tr>
<td>beta function at IP1&amp;5</td>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>crossing angle</td>
<td>$\theta_c$ [$\mu$rad]</td>
<td>285</td>
<td>315</td>
<td>445</td>
<td>430</td>
<td>1000</td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>$\phi \equiv \theta_c/\beta^*$</td>
<td>0.64</td>
<td>0.75</td>
<td>0.75</td>
<td>2.8</td>
<td>2700</td>
</tr>
<tr>
<td>luminosity</td>
<td>$L$ [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1.0</td>
<td>2.3</td>
<td>9.2</td>
<td>8.9</td>
<td>9.0</td>
</tr>
<tr>
<td>events/crossing</td>
<td></td>
<td>19</td>
<td>44</td>
<td>88</td>
<td>510</td>
<td>5 $\times$ $10^5$</td>
</tr>
<tr>
<td>rms length of</td>
<td></td>
<td>44.9</td>
<td>42.8</td>
<td>21.8</td>
<td>36.3</td>
<td>16.7</td>
</tr>
<tr>
<td>luminous region</td>
<td>$\sigma_{lum}$ [mm]</td>
<td>44.9</td>
<td>42.8</td>
<td>21.8</td>
<td>36.3</td>
<td>16.7</td>
</tr>
</tbody>
</table>

4.7 Example Parameter Sets

Table 2 compares the beam parameters for the nominal and ultimate LHC with those typical for three different upgrades: (1) baseline scheme with 12.5 ns spacing, (2) a scheme with large Piwinski-angle and 75-ns spacing, and (3) a superbunch. The luminosity for all upgrade schemes is close to $10^{35}$ cm$^{-2}$s$^{-1}$. The average beam current is 70% higher for the baseline scheme. The number of events per crossing increases from 88 for the baseline, over 510 for option (2) to an impressive $5 \times 10^5$ for a single superbunch. For comparison, the nominal LHC produces about 20 events per crossing and the ultimate 45. Note also that the crossing angle is moderately increased from an about 2.8 $\mu$rad nominal value to values near 450 $\mu$rad in options (1) and (2) and to 1 mrad for option (3).

4.8 A Staged Approach — Review & Outlook

The LHC upgrade will likely occur in stages as outlined in the 2001 feasibility study [5]. Phase 0 of the upgrade refers to reaching the maximum performance without any hardware changes, phase 1 to the maximum performance with the arcs kept unchanged, and phase 2 to the maximum performance with ‘major’ changes. The starting point of all upgrades is the nominal performance at 7 TeV, which corresponds to a total beam-beam tune spread of $\Delta Q_{bb} \approx 0.01$ and to a luminosity $L = 10^{34}$ cm$^{-2}$s$^{-1}$ in IP1 and IP5 (ATLAS and CMS), halo collisions or collisions with large $\beta^*$ in IP2 (ALICE), and low-luminosity in IP8 (LHCb)\(^1\). The ingredients of upgrade phases 0 and 1 correspond to the scenarios already described in previous paragraphs. They are here repeated from the perspective of staging.

The phase-0 baseline is realized by colliding the beams only in IP1&5 with alternating horizontal-vertical crossing, by increasing the bunch charge to the beam-beam limit, which is expected to be reached at $L \approx 2.3 \times 10^{34}$ cm$^{-2}$s$^{-1}$, and, quench protection and beam losses permitting, by optionally increasing the dipole field to 9 T (ultimate field) which will raise the beam energy to 7.54 TeV.

The alternative phase-0 Piwinski scheme would increase the longitudinal emittance and rms bunch length, for example to a value $\sigma_z \approx 15.2$ cm. The crossing angle would be enlarged by about 10%. Increasing $N_b$ up to the beam-beam limit ($N_b \approx 2.6 \times 10^{11}$) would allow raising the luminosity to $3.6 \times 10^{34}$ cm$^{-2}$s$^{-1}$, without any hardware change [42].

Figure 18 compares tune footprints for the nominal LHC, the ultimate LHC (baseline phase 0) and the configuration with large Piwinski parameter (phase-0 Piwinski scheme). In all three cases, the beams are assumed to collide only at two IPs with alternating crossing. The tune spread for both upgrade variants is about the same, roughly 0.01, and, hence, comparable to the tune spread for the nominal LHC with 4 IPs. The Piwinski scheme promises about 50% more luminosity.

Phase 1 comprises various possible steps to increase the luminosity with hardware changes only in the LHC insertions and in the injector complex.

For the phase-1 baseline these steps are to modify the insertion quadrupoles and the IR layout so as to reduce $\beta^*$ to 0.25 m, to increase the crossing angle by a factor 1.4, to increase the bunch population to the ultimate intensity, which raises the luminosity to $3.3 \times 10^{34}$ cm$^{-2}$s$^{-1}$, to halve the bunch length $\sigma_z$ with a higher harmonic rf sys-

\(^1\)If in ALICE large-$\beta^*$ head-on collisions occur instead of halo collisions, the beam-beam tune spread of the nominal LHC is increased and the nominal luminosity may be reduced.
One of the most difficult challenges will be to produce the high-field magnets at a reasonable cost, e.g., for less than 5 kEuros per (double) Tesla-meter, including cryogenics, which is to be compared with 4.5 kEuros per (double) Tesla-meter for the present LHC. One promising approach is the common-coil design for a double aperture magnet sketched in Fig. 19. The coils couple the two apertures and can be flat, which avoids difficult ends. In 2003, a Nb₃Sn dipole with a different block-coil design reached a field of 16 T, as is shown in Fig. 20.

![Figure 19: Magnet design concept for a common-coil dipole (43).](image)

**Figure 19: Magnet design concept for a common-coil dipole (43).**

![Figure 20: Training history of the Nb₃Sn dipole magnet HD-1 at LBNL (first thermal cycle) (44).](image)

**Figure 20: Training history of the Nb₃Sn dipole magnet HD-1 at LBNL (first thermal cycle) (44).**

5 SUMMARY AND RECOMMENDATIONS FOR FUTURE STUDIES AND R&D

Reaching the nominal LHC performance is challenging. We need to learn how to overcome electron-cloud effects, how to inject, ramp and collide almost 3000 high-intensity
bunches, how to protect the superconducting magnets, how to safely dump the beams, and much more. Nevertheless, upgrades in beam intensity are a viable option. They require R&D for cryogenics, vacuum, rf, beam dump, and injectors, and they imply operation with larger crossing angles.

The radiation limit for the IR quadrupoles, corresponding to about 700 fb$^{-1}$ will be reached by 2013–2014. New triplet quadrupoles with high gradient and large aperture or alternative IR layouts are needed for the luminosity upgrade. Opening the quadrupole apertures has the additional merit of intercepting less collision debris. The triplet aperture should also be large to reduce the collimator impedance for squeezed $\beta^*$ and physics conditions.

Further studies are needed to specify the field quality of the new IR magnets, and the required upgrades of beam instrumentation, collimation and machine protection.

Experimental studies on electron cloud and on long-range or strong-strong beam-beam effects are important, and so are machine studies at existing hadron colliders with large Piwinski parameter and many (flat) bunches. An international collaboration (US-LALRP/CARE) is welcome — or needed — for LHC machine studies and commissioning.

Beam-beam compensation schemes with pulsed wires would reduce the tune footprints and the loss of dynamic aperture due to the long-range collisions. An experimental validation of such a compensation scheme is underway in the CERN SPS and may be extended to RHIC.

Interesting possibilities, currently under study, to pass each beam through separate final quadrupoles include alternative separation schemes with separation dipoles in front of the triplet quadrupoles, collision of long bunches with large crossing angle, and normal bunches at large crossing angle with crab cavities. Peak luminosities would approach $10^{35}$ cm$^{-2}$s$^{-1}$ for all schemes.

The superbunch and ‘large Piwinski angle’ options are interesting for large crossing angles, can potentially avoid electron-cloud effects, and minimize the cryogenic heat load. One could inject a bunched beam, accelerate it to 7 TeV, and then use a multiple harmonic rf system to form between 30 and 900 longer bunches. The larger the number of bunches, the smaller is the event pile up in the experiments.

Crab cavities are attractive, likely raise the beam-beam limit, and allow for separate magnet channels. First experience with crab cavities will be gained at KEKB from early 2006. Viability of crab cavities for hadron beams, e.g., the possible emittance growth due to rf phase noise, need to be further explored.

A major and sustained R&D effort on new superconducting materials and magnet design is needed for any LHC performance upgrade. For this, it is important to foster and extend collaborations with other laboratories, e.g., in the CARE and US-LARP frameworks. The development of new low-$\beta$ quadrupoles with high gradient and larger aperture based on Nb$_3$Sn superconductor requires 9–10 years for short-model R&D, component development, prototyping and final production.

An increased LHC injection energy of 1 TeV in conjunction with beam-beam compensation schemes would yield an integrated luminosity gain by more than a factor of 2. A pulsed Super-SPS (and new superconducting transfer lines from the SPS to the LHC) or cheap low-field booster rings in the LHC tunnel could be the first step towards an LHC energy upgrade.

6 ACKNOWLEDGEMENT

Many CERN, US, EU and KEK colleagues have contributed to the LHC upgrade studies and the various scenarios described in this paper.

7 REFERENCES


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