Abstract

This paper looks at the potential performance reach for the LHC and its upgrade projects based on first observations from the LHC 2010 operation and discusses options for pushing the LHC performance beyond the nominal design values at 7 TeV beam energy.

LHC PERFORMANCE

The LHC performance can be characterized by three main parameters:

- The center of mass collision energy $E_{CM}$ (in the following we will assume two beams with equal beam energies $E_{beam} = 2 \cdot E_{beam}$).
- The instantaneous luminosity specifying the rate at which certain events are generated in the beam collisions (number of events per second $= L(t) \cdot \sigma_{event}$ with $\sigma_{event}$ being the cross section of the event of interest).
- The integrated luminosity specifying the total number of events that are produced over a time interval $t - t_0$.

The instantaneous luminosity is given by

$$L = \frac{f_{rev} \cdot n_b \cdot N_1 \cdot N_2}{2\pi \sqrt{(\sigma_{x,1}^2 + \sigma_{x,2}^2) \cdot (\sigma_{y,1}^2 + \sigma_{y,2}^2)}} \cdot F \cdot H,$$

where $f_{rev}$ is the revolution frequency, $n_b$ is the number of bunches colliding at the Interaction Point (IP), $N_{1,2}$ are the particles per bunch and $\sigma_{x,1,2}$ and $\sigma_{y,1,2}$ the horizontal and vertical beam sizes of the two colliding beams. $F$ is the geometric luminosity reduction factor due to collisions with a transverse offset or crossing angle at the IP and $H$ is the reduction factor for the hour glass effect that becomes relevant when the bunch length is comparable or larger than the beta functions at the IP ($\rightarrow$ the transverse beta function varies over the luminous region where the two beams interact with each other). We neglect the hour glass effect assuming that $H$ is close to one for all parameter sets under consideration.

The geometric reduction factor due to a crossing angle is given by

$$F = 1 / \sqrt{1 + \left(\frac{\sigma_s}{\sigma_t} \cdot \frac{\phi}{2}\right)^2},$$

where $\sigma_s$ is the longitudinal bunch length, $\sigma_t$ the transverse bunch size in the plane of the crossing angle and $\phi$ the total crossing angle.

In the following we assume that all bunches of both beams have equal intensities ($N_1 = N_2 = N_b$) and the same size at the IP. The transverse beam sizes at the IP are given by

$$\sigma_{x,y} = \sqrt{\beta^*_{x,y} \cdot \epsilon_{x,y} + D^2_{x,y} \cdot \delta^2_p},$$

where $\delta_p$ is the relative rms momentum spread ($\delta_p = \frac{\Delta p}{p}$) of the particles within a bunch, $\beta^*_{x,y}$ and $D_{x,y}$ are the horizontal and vertical beta and dispersion functions at the IP and $\epsilon_{x,y}$ the horizontal and vertical emittances of the two beams.

Because the bunch intensities and beam sizes of a collider vary over time, the instantaneous luminosity is implicitly a function of time.

The integrated luminosity is defined by

$$\hat{L}(t - t_0) = \int_{t_0}^{t} L(\tau) \, d\tau,$$

where $t_0$ is an arbitrary starting point, $L(\tau)$ the instantaneous luminosity at a given time and $t - t_0$ the time period of interest.

The HL-LHC upgrade project aims at achieving a peak luminosity of $L = 5 \cdot 10^{34} cm^{-2} s^{-1}$ with leveling such that the peak luminosity can be sustained over a significant fraction of the run time and at an integrated luminosity of ca. 250 $fb^{-1}$ per year.

Maximizing the instantaneous luminosity implies (in order of priority):

- Maximize the number of particles per bunch (enters quadratically into the luminosity).
- Minimize the beam size at the interaction points (does not imply a "cost" in terms of total beam power but might require special large aperture focusing quadrupoles near the experiment and tighter settings for the collimation system).
- Maximize the number of bunches in the collider.
- Optimize the overlap of the two beams at the IP (for example, this could be achieved with the use of CRAB cavities for aligning the bunches of the two beams for an optimum overlap).

The single bunch intensity is limited by collective effects and by the strength of the non-linear beam-beam interaction that the particles experience when the bunches of both beams collide with each other at the IP. The total beam current is eventually limited by hardware limitations and collective effects (e.g. multi bunch instabilities). The maximum instantaneous luminosity might be limited by the existing hardware in the machine (e.g. the cooling capacity...
for the superconducting magnets of the triplet assembly) and by the detector performance (e.g. maximum permissible event pileup per bunch crossing).

**MAXIMIZING THE SINGLE BUNCH INTENSITY AND THE BEAM-BEAM LIMIT**

The single bunch limitation for the Transverse Mode Coupling (TMCI) instability is estimated to be of the order of $3.5 \cdot 10^{11}$ particles per bunch [1].

The strength of the beam-beam interaction can be characterized by the linear head-on beam-beam parameter which specifies the maximum tune shift due to the beam-beam interaction per IP that a particle at the center of a bunch experiences when the two bunches collide without a crossing angle and transverse offset. The beam-beam parameter is given by

$$\xi_{x,y} = \frac{N_b \cdot r_p \cdot \beta_x^{*}}{2 \pi \cdot \gamma \cdot \sigma_{x,y} \cdot \left(\sigma_x + \sigma_y\right)},$$

where $\gamma$ is the relativistic gamma factor and $r_p$ the classical proton radius $r_p = e^2/(4\pi\epsilon_0 mc^2)$.

For round beams with equal beam emittances in both planes the beam-beam force is independent of the transverse beta-functions at the IP and depends only on the normalized beam emittance. For such round beams the beam-beam parameter can be written

$$\xi = \frac{N_b r_p}{4\pi \epsilon_\gamma},$$

where $\epsilon_\gamma$ is the normalized emittance $\epsilon_n$ in a hadron storage ring.

Figure 1 shows a schematic picture for the dependence of the beam-beam force on the particle oscillation amplitude at the IP for the superconducting magnets of the triplet assembly) and by the detector performance (e.g. maximum permissible event pileup per bunch crossing).

**Figure 1:** Schematic dependence of the beam-beam force on the particle oscillation amplitude at the IP.

The tune spread due to the head-on beam-beam collisions (top left corner) together with the tune spread from long-range beam-beam encounters for different crossing angles and beam separations for the nominal LHC configuration with $\beta^* = 0.55$ m (top right corner: crossing angle of 200 $\mu$rad and a beam separation of approximately 7 $\sigma$, bottom left corner: crossing angle of 285 $\mu$rad and a beam separation of approximately 10 $\sigma$, bottom right corner: crossing angle of 400 $\mu$rad and a beam separation of approximately 13 $\sigma$) [2].

**Figure 2:** The tune spread due to the head-on beam-beam collisions (top left corner) together with the the tune spread from long-range beam-beam encounters for different crossing angles and beam separations for the nominal LHC configuration with $\beta^* = 0.55$ m (top right corner: crossing angle of 200 $\mu$rad and a beam separation of approximately 7 $\sigma$, bottom left corner: crossing angle of 285 $\mu$rad and a beam separation of approximately 10 $\sigma$, bottom right corner: crossing angle of 400 $\mu$rad and a beam separation of approximately 13 $\sigma$) [2].

The combined effect of head-on and long-range beam-beam collisions in the LHC results in a tune spread of the particles within the LHC beams. Figure 3 shows the resulting tune footprint for the nominal LHC collisions covering particle amplitudes from 0 to 6 $\sigma$ (the particles with zero amplitudes are located at the tip of the tune footprint [near the lower left corner of the tune diagram]). The total tune spread for the nominal LHC configuration is approximately 30 long range beam-beam encounters per Interaction Region (IR) and three head on collisions in the ATLAS, CMS and LHCb experiments (ALICE does not feature head on proton beam collisions for the nominal configuration). The tune spread due to the long-range beam-beam interactions depends on the crossing angle and the resulting beam separation at the parasitic beam encounters in the IRs. Figure 2 shows the tune spread due to the head-on beam-beam collisions (top left corner) together with the the tune spread from long-range beam-beam encounters for different crossing angles and beam separations for the nominal LHC configuration with $\beta^* = 0.55$ m (top right corner: crossing angle of 200 $\mu$rad and a beam separation of approximately 7 $\sigma$, bottom left corner: crossing angle of 285 $\mu$rad and a beam separation of approximately 10 $\sigma$, bottom right corner: crossing angle of 400 $\mu$rad and a beam separation of approximately 13 $\sigma$) [2].
ΔQ = 0.01 in both transverse planes.

The beam-beam limit in Hadron colliders without strong synchrotron radiation damping is loosely referred to as the maximum acceptable total tune spread that can still be accommodated in the tune diagram without exposing particles of the beam to too strong resonances. Experience of previous colliders has shown that resonances of order 12 or lower are detrimental to the beam distributions and the beam-beam limit can therefore be estimated as the maximum tune spread that can be accommodated in the tune diagram without exposing particles within the beam to resonances of order 12 or lower. The LHC working point is placed between the 1/3rd and 3/10th resonance and particles can experience the 4/13th and 5/16th or higher order resonances. Figure 4 shows schematically the LHC working point and beam-beam tune spread of the LHC in the tune diagram. Depending on the required distance to the coupling resonance, the total resonance-free space (up to 10th order or lower) in the tune space varies between 0.01 and 0.02. The nominal LHC parameters feature a total beam-beam tune spread of ΔQ = 0.01 and are compatible with conservative margins for coupling strength and additional sources for tune spread in the LHC. The beam-beam limit in the SppS collider was approximately ΔQ = 0.018 and the beam-beam limit in the Tevatron collider is approximately ΔQ = 0.02 for the anti-proton beam. Higher values are achievable for the total beam-beam related tune spread in the Tevatron (values of ΔQ = 0.03 have been reached) but the experimental conditions and beam performance degrade quickly in the Tevatron for beam-beam tune shifts larger than ΔQ = 0.02 [4].

Figure 5 shows the proton and anti-proton tune spread of the Tevatron beams in the tune diagram [5]. The red and green lines indicate resonance lines in the tune diagram. The yellow crosses are the average bunch tunes for each anti-proton bunch from Schottky measurements and the blue dots are the calculated tune distributions for the anti-proton bunches based on the measured bunch emittances and intensities (the orange dots are the calculated tune distributions for the proton bunches). Operating the machine with beam-beam tune shifts larger than ΔQ = 0.02 results in some particles either hitting with low amplitudes the 3/5th resonances or with large amplitudes the 7/12th resonances. Having the tune of particles with large amplitudes too close to the 7/12th resonances results in the Tevatron to the loss of halo particles (no net loss of performance as these particles do not significantly contribute to the luminosity productions). Having the tune of particles with small amplitudes too close to the 7/12th resonances results in the Tevatron in emittance growth (varying from bunch to bunch). Both sets of resonances therefore need to be avoided during operation.

Figure 6 shows the simulated dynamic aperture (maximum stable particle amplitudes over 10th turns in the LHC) for various angles for the starting conditions in the transverse plane (0 degrees equal to a purely horizontal motion and 90 degrees to a purely vertical motion) with beam-beam interactions as a function of the horizontal tune. The distance between the horizontal and vertical tunes has been kept constant at the nominal value of Qx − Qy = 5.01 [2]. The green vertical line indicates the nominal tune value for the LHC without beam-beam interaction, the blue line the tune value in the LHC with beam-beam interactions on (the defocusing force of the beam-beam interactions shifts the LHC tunes to lower values) and the red lines indicate the locations of the 3/10th, 4/13th, 5/16th and 1/3rd resonances. The simulations clearly indicate a reduction of the dynamic aperture for tune values close to any of the
above resonances. However, the dynamic aperture does not fall below 8 $\sigma$ for tune values close to the 4/13th and 5/16th order resonances. The 3/10th order resonances result in dynamic aperture values down to 4 $\sigma$ indicating that the 3/10th order resonances are potentially detrimental for the LHC performance and should therefore be avoided in the LHC operation. The simulations seem to indicate that larger than nominal beam-beam tune shifts could be accommodated in the LHC if the nominal tune values are shifted to higher values closer to the 1/3rd resonances.

Operation experience in 2010 has furthermore given indications that even resonance of 10th order might be tolerable for the LHC operation and that beam-beam parameters of more than $\Delta Q = 0.02$ might be feasible even for the nominal LHC tune values. For example, Fill 1409 featured 256 bunches with a normalized transverse emittance of $\epsilon_n \approx 1.4 \mu m$ and nominal bunch intensities of $10^{11}$ particles per bunch yielding a beam-beam parameter of $\xi = 7.7 \times 10^{-3}$ and a total beam-beam tune shift of $\Delta Q = 0.0231$ for bunches with three head-on collisions. Figure 7 shows the losses of the beams during Fill 1409 as a function of time for the different bunch classes with one, two and three head-on beam-beam collisions (blue, red and green lines respectively) [6]. While one clearly observes higher losses for bunches that have three head-on collisions as compared to bunches with one or two head-on collisions, the overall losses still seem to be acceptable.

Figure 8 shows the LHC tunes for the different collision classes of Fill 1409 superimposed onto the dynamic aperture simulations for the LHC with beam-beam interactions as a function of the horizontal tune in the machine. The red lines indicate the different resonances and the blue lines the tune values of the three bunch classes with one, two and three head-on beam-beam collisions. One observes that the tune of the bunches with three head-on beam-beam encounters falls right above the 2/7th resonances, the tune of the bunches with two head-on beam-beam encounters falls between the 2/7th and 3/10th resonances, and the tune of the bunches with one head-on beam-beam encounter falls right above the 3/10th resonances.

So far, the tune in physics operation has not been optimized during the 2010 operation and was fixed at the nominal design values that were optimized for a total beam-beam tune-spread of $\Delta Q = 0.01$. In order to optimize the machine operation for beam-beam parameters higher than $\Delta Q = 0.01$ the actual working point in the LHC should be optimized for a given beam-beam parameter and could be varied over a physics fill when the beam-beam parameter decreases due to the reduction in beam intensities and increase in beam emittances. One strategy for a further optimization of the LHC tunes for large beam-beam parameters.
ters could be to adjust the tunes in the LHC such that the tune of bunches with one head-on beam-beam encounter only lie right above the $4/13^{th}$ resonances, the tunes of bunches with two head-on beam-beam encounter lie right above the $3/10^{th}$ resonances and the tunes of bunches with three head-on beam-beam collisions lie between the $2/7^{th}$ and $3/10^{th}$ resonances. This strategy might imply an adjustment of the tunes as the beams are brought into collisions. Figure 9 illustrates this setup for a total beam-beam tune shift of $\Delta Q = 0.03$.

From the above observations and considerations one can conclude that a total beam-beam tune shift of $\Delta Q = 0.03$ might be in reach for the LHC operation. Based on the operational experience from the Tevatron we adopt in the following discussion of the performance reach of the LHC a slightly more conservative beam-beam limit of

$$\Delta Q_{\text{beam-beam-limit}} = 0.023, \quad (7)$$

which has already been achieved in the LHC operation in Fill 1409 (albeit without long-range beam-beam encounters). The corresponding beam-beam parameter of $\xi_{\text{beam-beam}} = 7.7 \times 10^{-3}$ corresponds to a maximum bunch intensity of $N_b = 2 \times 10^{11}$ to $N_b = 3.3 \times 10^{11}$ depending on the assumed bunch length and crossing angle (see Tables 1 to 6 for more details) which is consistent with the assumed single bunch intensity limit from TMCI. The actual beam-beam limit in the LHC as a function of number of long-range collisions and separation is certainly a vital ingredient for estimating the LHC performance and identifying an optimum set of beam parameters for the HL-LHC. Its experimental identification should therefore be pursued with high priority in the upcoming MD sessions for the LHC.

**LHC PERFORMANCE IN TERMS OF $\beta^*$ VALUES**

Aperture measurements in the LHC during the 2010 operation [7] indicate a better than specified mechanical aperture in the LHC. The resulting additional aperture could be used for a further squeeze of the optics at the Interaction Points (IPs) and could be compatible with $\beta^*$ values between 0.3m and 0.4m (neglecting other constraints than aperture [e.g. off momentum beta-beat] for the moment that might impose larger limits on the minimum attainable $\beta^*$ values).

The ATS optics scheme [8] brings $\beta^*$ values of 0.15 m (for round beam) and 0.3 m/0.075 m (for flat beam operation) within reach for the HL-LHC project even for NbTi technology provided new matching section elements can be built for the corresponding larger aperture specifications.

For the estimation of the beam-beam limit in the LHC we ignored sofar the effect of long-range beam-beam interactions, assuming that the added tune spread due to the long-range collisions is small compared to the tune spread of the head-on collisions and that the non-linear forces generated by the long-range interactions are small. These assumptions on the long-range beam-beam interactions can be satisfied provided the beam separation is sufficiently large (see Figures 1 and 2). A large long-range beam-beam separation can either be achieved by increasing the crossing angle (requiring additional aperture and reducing the luminosity via the geometric reduction factor) or by increasing slightly the $\beta^*$ values for a constant crossing angle (reducing slightly the luminosity via $\beta^*$ and increasing the geometric reduction factor). In the following discussion we introduce ad-
ditional operation margins for coping with the long-rage beam-beam effects and justifying their omission for our estimate of the LHC beam-beam limit by assuming an operational $\beta^*$ value which is 15% larger than the theoretical minimum attainable values yielding:

$$\beta^* = 0.5 \text{ m, for the nominal LHC machine} \quad (8)$$
$$\beta^* = 0.2 \text{ m, for the HL-LHC (round beams).} \quad (9)$$

**LHC INJECTOR COMPLEX PERFORMANCE**

A detailed discussion of the injector complex performance can be found in the proceedings of this workshop under the injector complex session. For the discussion of the LHC performance reach I used the following estimates.

**Existing Injector Complex**

For operation with 50 ns bunch spacing the existing LHC injector complex can provide:

- $1.2 \cdot 10^{11} \text{ ppb}; \quad \epsilon_n = 2.5 \mu \text{m} - 3 \mu \text{m} \quad \text{SB} \quad (10)$
- $1.2 \cdot 10^{11} \text{ ppb}; \quad \epsilon_n = 1.5 \mu \text{m} \quad \text{DB} \quad (11)$
- $1.7 \cdot 10^{11} \text{ ppb}; \quad \epsilon_n = 3 \mu \text{m} - 4 \mu \text{m} \quad \text{SB,} \quad (12)$

where SB indicates Single Batch and DB indicates double batch injection into the PS. The performance in (10) has been reached in the 2010 operation. The performance in (11) has been achieved in MD studies in 2008 [9]. And the performance in (12) is limited by single bunch effects in the SPS.

For operation with 25 ns bunch spacing the existing LHC injector complex can provide:

- $1.2 \cdot 10^{11} \text{ ppb}; \quad \epsilon_n = 3 \mu \text{m} - 4 \mu \text{m} \quad (13)$
- $1.4 \cdot 10^{11} \text{ ppb}; \quad \epsilon_n = 4 \mu \text{m} - 10 \mu \text{m.} \quad (14)$

The performance in (13) has been reached in the 2010 operation and the performance in (14) is limited by instabilities in the SPS.

**Existing Injector Complex with LINAC4**

In order to estimate the potential performance reach of the injector complex with LINAC4 and operation with 50 ns bunch spacing we take the reached performance in (11) and scale it up to the performance reach of the LINAC4 with constant brightness, assuming that the resulting beam is not limited by electron cloud effects in the PS and SPS and relying on the lower gamma-t lattice in the SPS in order to increase the single bunch instability limits in the SPS. Under these assumptions a performance reach of

$$2.5 \cdot 10^{11} \text{ ppb}; \quad \epsilon_n = 3.5 \mu \text{m} \quad \text{SB} \quad (15)$$

seems to be within reach for 50 ns bunch spacing and LINAC4. The performance estimate for 25 ns does not change with the LINAC4 operation as the limit in (14) is given by bottle necks in the SPS.

**Full Injector Complex Upgrade**

Assuming a Laslett space charge limit of $\Delta Q = -0.3$ in the PS one can hope to reach the following performance reach for operation with 50 ns bunch spacing [10] [11]

$$2.7 \cdot 10^{11} - 3.5 \cdot 10^{11} \text{ ppb; } \quad \epsilon_n = 1.1 - 1.5 \mu \text{m.} \quad (16)$$

For the operation with 25 ns bunch spacing one can hope to reach with a Laslett space charge limit of $\Delta Q = -0.3$ in the PS a performance of

$$1.7 \cdot 10^{11} - 2.0 \cdot 10^{11} \text{ ppb; } \quad \epsilon_n = 1.5 - 1.8 \mu \text{m.} \quad (17)$$

**SPS Space charge limit**

The above performance reach for operation with 50 ns bunch spacing might be slightly lower if one assumes a space charge tune spread limit of $\Delta Q = -0.13$ in the SPS [12]

$$3.3 \cdot 10^{11} \text{ ppb; } \quad \epsilon_n = 3.75 \mu \text{m.} \quad (18)$$

For the operation with 25 ns bunch spacing one can hope to reach with a Laslett space charge limit of $\Delta Q = -0.13$ in the SPS a performance of

$$2.0 \cdot 10^{11} \text{ ppb; } \quad \epsilon_n = 2.5 \mu \text{m.} \quad (19)$$

The actual space charge limit in the SPS and the PS is certainly a vital ingredient for the performance estimate of the LHC injector complex and its identification should get a high priority in the upcoming MD sessions for the LHC injector complex.

**TOTAL INTENSITY LIMITATION IN THE LHC**

In addition to limitations coming from single bunch effects such as the beam-beam interaction and the TMCI, the total beam intensity in the LHC is limited by electron cloud effects and hardware limitations of the existing machine. A first analysis of potential hardware limitation has been performed by Ralph Assmann for the Chamonix 2010 discussions [13]. These estimates indicated a maximum total beam current of approximately 0.85 A corresponding to 2808 bunches with ultimate bunch intensities. The findings given in [13] only provide first estimates and identifications of the maximum acceptable beam intensities in the LHC. A thorough estimate of the maximum beam intensities and an analysis of ways and implications for increasing it in the framework of the LHC upgrade program should clearly be part of the upcoming HL-LHC studies.
ESTIMATES OF THE PERFORMANCE REACH FOR LHC MACHINE

Performance Estimate for the nominal LHC machine for operation at 7 TeV beam energy with the existing injector complex

First operation experience with the LHC in 2010 showed that the LHC can be operated with smaller than nominal beam emittances and larger than nominal values for the beam-beam parameters. Table 1 summarizes the resulting performance reach for the nominal LHC machine when considering these larger values for the beam-beam limit and bunch intensities. The table shows the nominal design parameters together with two distinct sets of parameters: a set for operation with nominal beam emittances for operation with 25 ns and 50 ns and one set for operation with 50 ns bunch spacing and smaller than nominal transverse beam emittances. It is interesting to note, that with the revised assumption on the beam-beam limit in the LHC the two options with 50 ns bunch spacing can provide with the existing injector complex a larger than nominal LHC performance with smaller than nominal total beam currents (and thus with smaller than nominal stored beam power). The total beam-beam tune shift remains for all cases below $\Delta Q = 0.02$ if one assumes three IPs with head-on collisions and that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions. The total beam current remains in all cases below the ultimate LHC beam current (2808 bunches with $1.7 \times 10^{11}$ particles per bunch correspond to a total beam current of 0.85 A).

However, none of the parameter sets given in Table 2 can reach the design goal for the peak luminosity of the HL-LHC project ($L = 5 \times 10^{34} cm^{-2} s^{-1}$) not to mention the requirement to reach such a peak luminosity with margins for leveling (e.g. with a virtual peak performance in excess of $L = 5 \times 10^{34} cm^{-2} s^{-1}$).

Table 2 summarizes the resulting maximum performance reach for the nominal LHC machine when considering the increased beam brightness from LINAC4 and operation with nominal beam emittance. The table shows the nominal design parameters together with two sets of parameters: one for operation with 25 ns and one for operation with 50 ns. It is interesting to note, that for both options with larger than nominal bunch intensities the total beam-beam tune shift remains below $\Delta Q = 0.02$ if one assumes three IPs with head-on collisions and that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions. The total beam current remains in all cases below the ultimate LHC beam current (2808 bunches with $1.7 \times 10^{11}$ particles per bunch correspond to a total beam current of 0.85 A).

### Table 1: LHC Performance Reach for Nominal Configuration at 7 TeV with the existing injector complex.

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>50 ns</th>
<th>50 ns</th>
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<td>2.5</td>
<td>2.5</td>
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1The IBS growth rates in all tables have been calculated by John Jowett.

### Table 2: LHC Performance Reach for Nominal Configuration at 7 TeV beam energy with the existing PS and PSB and LINAC4.

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<tr>
<td>E spread</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
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<td>7.5</td>
<td>7.5</td>
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</tr>
<tr>
<td>IBS h [h]</td>
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<td>80</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>IBS 1 [h]</td>
<td>60</td>
<td>41</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Piwinski</td>
<td>0.68</td>
<td>0.76</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>0.83</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>b-b $[10^{-3}]$</td>
<td>3.1</td>
<td>3.6</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>event pileup L</td>
<td>$10^{34}$</td>
<td>$1.6 \times 10^{34}$</td>
<td>$2.5 \times 10^{34}$</td>
<td></td>
</tr>
</tbody>
</table>
Performance Estimate for the nominal LHC machine for operation at 7 TeV beam energy with a full injector complex upgrade

Table 3 summarizes the resulting maximum performance reach for the LHC machine when considering the increased beam brightness from a complete injector complex upgrade and operation with nominal $\beta^*$ values. The table shows the nominal design parameters together with two sets of parameters: one for operation with 25 ns and one for operation with 50 ns.

Both options with larger than nominal bunch intensities feature a total beam-beam tune shift that is larger than $\Delta Q = 0.02$ if one assumes three IPs but stay below $\Delta Q = 0.023$ (the value achieved in Fill 1409 during the 2010 operation). The total beam current for the operation with 50 ns bunch spacing remains below the ‘ultimate’ beam current of 0.85 A. But the beam current for the 25 ns option exceeds this assumed maximum value by approximately 20%.

Both parameter sets given in Table 3 remain slightly ($\approx 10\%$) short of the design goal for the peak luminosity of the HL-LHC project ($L = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$) but do provide 20% to 10% margins for leveling (e.g. via Crab cavities or beam-beam long-range wire compensators that allow operation with smaller crossing angles).

Table 3: LHC Performance Reach for Nominal Configuration at 7 TeV with a full injector complex upgrade.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25 ns</th>
<th>50 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_b[10^{11}]$</td>
<td>1.15</td>
<td>2.0</td>
<td>3.3</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>$I$ [A]</td>
<td>0.58</td>
<td>1.02</td>
<td>0.84</td>
</tr>
<tr>
<td>$x$-ing</td>
<td>300</td>
<td>270</td>
<td>320</td>
</tr>
<tr>
<td>$[\mu\text{rad}]$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b-b sep. [$\sigma$]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$\epsilon_n$ [\mu m]</td>
<td>3.75</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>$\epsilon_s$ [eVs]</td>
<td>2.51</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>E spread</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$\sigma_s$ [cm]</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>IBS h [h]</td>
<td>106</td>
<td>25</td>
<td>37</td>
</tr>
<tr>
<td>IBS l [h]</td>
<td>60</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Piwinski</td>
<td>0.68</td>
<td>0.78</td>
<td>0.76</td>
</tr>
<tr>
<td>R</td>
<td>0.83</td>
<td>0.79</td>
<td>0.8</td>
</tr>
<tr>
<td>b-b sep. [$10^{-3}$]</td>
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<td>7.7</td>
<td>8.6</td>
</tr>
<tr>
<td>event pileup</td>
<td>19</td>
<td>91</td>
<td>167</td>
</tr>
<tr>
<td>$L$ [cm$^{-2}$s$^{-1}$]</td>
<td>$1.1 \times 10^{34}$</td>
<td>$4.8 \times 10^{34}$</td>
<td>$4.4 \times 10^{34}$</td>
</tr>
</tbody>
</table>

Performance Estimate for the HL-LHC machine for operation at 7 TeV beam energy with a full injector complex upgrade

Table 4 summarizes the resulting maximum performance reach for the LHC machine when considering the increased beam brightness from a complete injector complex upgrade and operation with small $\beta^*$ values [8]. The table shows the nominal design parameters together with two sets of parameters: one for operation with 25 ns and one for operation with 50 ns.

Both upgrade parameter sets given in Table 4 clearly exceed the design goal for the peak luminosity of the HL-LHC project ($L = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$) (by ca. 15% to 20%) and almost a factor two margin for leveling (geometric reduction factor $R < 0.5$) (e.g. leveling via Crab cavities or beam-beam long-range wire compensators that allow operation with smaller crossing angles).

It is interesting to note, that for both options with larger than nominal bunch intensities the total beam-beam tune shift remains well below $\Delta Q = 0.02$ if one assumes three IPs and assumes that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions. The total beam current for the operation with 50 ns bunch spacing remains below the ‘ultimate’ beam current of 0.85 A. But the beam current for the 25 ns option exceeds this assumed maximum value by approximately 20%.

Table 4: LHC Performance Reach at 7 TeV with HL-LHC and a full injector complex upgrade.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25 ns</th>
<th>50 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_b[10^{11}]$</td>
<td>1.15</td>
<td>2.0</td>
<td>3.3</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>$I$ [A]</td>
<td>0.58</td>
<td>1.02</td>
<td>0.84</td>
</tr>
<tr>
<td>$x$-ing</td>
<td>300</td>
<td>420</td>
<td>520</td>
</tr>
<tr>
<td>$[\mu\text{rad}]$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b-b sep. [$\sigma$]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$\epsilon_n$ [\mu m]</td>
<td>3.75</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>$\epsilon_s$ [eVs]</td>
<td>2.51</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>E spread</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$\sigma_s$ [cm]</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>IBS h [h]</td>
<td>106</td>
<td>25</td>
<td>37</td>
</tr>
<tr>
<td>IBS l [h]</td>
<td>60</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Piwinski</td>
<td>0.68</td>
<td>1.92</td>
<td>1.95</td>
</tr>
<tr>
<td>R</td>
<td>0.83</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>b-b sep. [$10^{-3}$]</td>
<td>3.1</td>
<td>4.5</td>
<td>4.9</td>
</tr>
<tr>
<td>event pileup</td>
<td>19</td>
<td>133</td>
<td>239</td>
</tr>
<tr>
<td>$L$ [cm$^{-2}$s$^{-1}$]</td>
<td>$1.1 \times 10^{34}$</td>
<td>$7.0 \times 10^{34}$</td>
<td>$6.3 \times 10^{34}$</td>
</tr>
</tbody>
</table>
**Performance Estimate for the HL-LHC machine for operation at 7 TeV beam energy with a full injector complex upgrade and operation with long bunches**

The IBS growth rates given in Tables 3 and 4 reach rather small values which are comparable with the radiation damping times of the LHC at 7 TeV (ca. 25 h and 12.5 h in the transverse and longitudinal planes). In order to maximize the net luminosity lifetime it might be desirable to reduce the IBS growth rates by operating the machine with larger longitudinal emittances.

Table 5 shows one option for such an operation scenario for the full injector upgrade and operation with small $\beta^*$ values. The resulting IBS growth rates are almost a factor two smaller than those for the operation with the nominal bunch length.

Both upgrade parameter sets for operation with 25 ns and 50 ns bunch spacing are still capable of reaching the design goal for the peak luminosity of the HL-LHC project ($L = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$) and provide more than a factor two margin for leveling (geometric reduction factor $R < 0.4$) (e.g. leveling via Crab cavities or beam-beam long-range wire compensators that allow operation with smaller crossing angles).

The total beam-beam tune shift still remains well below $\Delta Q = 0.02$ (if one assumes three IPs and assumes that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions) and the total beam current for the operation with 50 ns bunch spacing remains still below the "ultimate" beam current of 0.85 A while the beam current for the 25 ns option exceeds this assumed maximum value by approximately 20%.

Table 6 a similar option for a operation with long bunches for the full injector upgrade and operation with nominal $\beta^*$ values ($\beta^* = 0.5$ m). Both upgrade parameter sets for operation with 25 ns and 50 ns bunch spacing fall slightly short (by ca. 15% to 20%) of the design goal for the peak luminosity of the HL-LHC project ($L = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$) but still provide a significant margin for leveling (geometric reduction factor $R < 0.7$) (e.g. for leveling via Crab cavities or beam-beam long-range wire compensators that allow operation with smaller crossing angles).

The total beam-beam tune shift exceeds $\Delta Q = 0.02$ but still remains below $\Delta Q = 0.023$, the value that has been achieved in Fill 1409 during the 2010 operation (if one assumes three IPs and assumes that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions). The total beam current for the operation with 50 ns bunch spacing remains below the "ultimate" beam current of 0.85 A while the beam current for the 25 ns option exceeds this assumed maximum value by approximately 20%.

**SUMMARY**

The above performance evaluations show that the design goal of the HL-LHC project can only be achieved with a full upgrade of the injector complex and the operation with $\beta^*$ values below 0.5 m. Significant margins for leveling can only be achieved for $\beta^*$ values close to 0.2 m. However, these margins can only be harvested during the HL-LHC operation if the required leveling techniques have been demonstrated in operation. Options for leveling include:

- The use of Crab cavities (not yet demonstrated for operation of hadron storage rings).
- The use of wire compensators for compensating the long-range beam-beam interaction. While it has been experimentally demonstrated that wires have a measurable effect on the stability of halo particles it has not yet been demonstrated that wires can compensate beam-beam induced long-range collisions in operation. It is therefore desirable to install LRBB wire compensators during the first long shutdown of the LHC (currently scheduled for 2013 to 2014) so that their applicability can be experimentally investigated in the LHC before the implementation of the HL-LHC upgrade (currently planned at the earliest for 2020).
- Dynamic squeeze of the optic functions at the IP during luminosity operation. Feasibility of such a procedure has never been demonstrated during operation of an existing machine, not to mention for a machine.

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**Table 5: LHC Performance Reach at 7 TeV with HL-LHC and a full injector complex upgrade and operation with long bunches.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25 ns</th>
<th>50 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_b [10^{11}]$</td>
<td>1.15</td>
<td>2.0</td>
<td>3.3</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>$I [\text{A}]$</td>
<td>0.58</td>
<td>1.02</td>
<td>0.84</td>
</tr>
<tr>
<td>$\text{x-ing}$</td>
<td>300</td>
<td>420</td>
<td>520</td>
</tr>
<tr>
<td>$[\mu \text{rad}]$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b-b sep. [$\sigma$]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$\beta^* [\text{m}]$</td>
<td>0.55</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$\epsilon [\mu \text{m}]$</td>
<td>3.75</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>$\epsilon_s [\text{eVs}]$</td>
<td>2.51</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>E spread</td>
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<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$\sigma_s [\text{cm}]$</td>
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<td>10</td>
<td>10</td>
</tr>
<tr>
<td>IBS h [h]</td>
<td>106</td>
<td>39</td>
<td>56</td>
</tr>
<tr>
<td>IBS l [h]</td>
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<td>58</td>
<td>56</td>
</tr>
<tr>
<td>Piwinski</td>
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<td>2.57</td>
<td>2.59</td>
</tr>
<tr>
<td>$R$</td>
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<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>b-b [10$^{-3}$]</td>
<td>3.1</td>
<td>3.6</td>
<td>4.9</td>
</tr>
<tr>
<td>event pileup</td>
<td>19</td>
<td>105</td>
<td>186</td>
</tr>
<tr>
<td>L</td>
<td>$1.1 \times 10^{34}$</td>
<td>$5.5 \times 10^{34}$</td>
<td>$4.9 \times 10^{34}$</td>
</tr>
</tbody>
</table>

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**Table 6: LHC Performance Reach at 7 TeV with HL-LHC and a full injector complex upgrade and operation with long bunches.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25 ns</th>
<th>50 ns</th>
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</thead>
<tbody>
<tr>
<td>$N_b [10^{11}]$</td>
<td>1.15</td>
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<tr>
<td>$n_b$</td>
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<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>$I [\text{A}]$</td>
<td>0.58</td>
<td>1.02</td>
<td>0.84</td>
</tr>
<tr>
<td>$\text{x-ing}$</td>
<td>300</td>
<td>420</td>
<td>520</td>
</tr>
<tr>
<td>$[\mu \text{rad}]$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>b-b sep. [$\sigma$]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$\beta^* [\text{m}]$</td>
<td>0.55</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$\epsilon [\mu \text{m}]$</td>
<td>3.75</td>
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<td>3.75</td>
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<td>$\epsilon_s [\text{eVs}]$</td>
<td>2.51</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>E spread</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$\sigma_s [\text{cm}]$</td>
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<td>10</td>
<td>10</td>
</tr>
<tr>
<td>IBS h [h]</td>
<td>106</td>
<td>39</td>
<td>56</td>
</tr>
<tr>
<td>IBS l [h]</td>
<td>60</td>
<td>58</td>
<td>56</td>
</tr>
<tr>
<td>Piwinski</td>
<td>0.68</td>
<td>2.57</td>
<td>2.59</td>
</tr>
<tr>
<td>$R$</td>
<td>0.83</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>b-b [10$^{-3}$]</td>
<td>3.1</td>
<td>3.6</td>
<td>4.9</td>
</tr>
<tr>
<td>event pileup</td>
<td>19</td>
<td>105</td>
<td>186</td>
</tr>
<tr>
<td>L</td>
<td>$1.1 \times 10^{34}$</td>
<td>$5.5 \times 10^{34}$</td>
<td>$4.9 \times 10^{34}$</td>
</tr>
</tbody>
</table>
Table 6: LHC Performance Reach at 7 TeV with nominal $\beta^*$ values and a full Injector Complex upgrade and operation with long bunches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25 ns</th>
<th>50 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_b[10^{11}]$</td>
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<td>2.0</td>
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<tr>
<td>$n_b$</td>
<td>2808</td>
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<tr>
<td>$I$ [A]</td>
<td>0.58</td>
<td>1.02</td>
<td>0.84</td>
</tr>
<tr>
<td>x-ing [\mu rad]</td>
<td>300</td>
<td>270</td>
<td>320</td>
</tr>
<tr>
<td>b-b sep. [\sigma]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$e_n[\mu m]$</td>
<td>3.75</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>$e_x$ [eVs]</td>
<td>2.51</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>E spread $10^{-4}$</td>
<td>10</td>
<td>10^{-4}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>$\sigma_r$ [cm]</td>
<td>7.5</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>IBS h [h]</td>
<td>106</td>
<td>39</td>
<td>56</td>
</tr>
<tr>
<td>IBS 1 [h]</td>
<td>60</td>
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<tr>
<td>Piwinski</td>
<td>0.68</td>
<td>1.04</td>
<td>1.0</td>
</tr>
<tr>
<td>R</td>
<td>0.83</td>
<td>0.69</td>
<td>0.7</td>
</tr>
<tr>
<td>b-b $[10^{-3}]$</td>
<td>3.1</td>
<td>6.8</td>
<td>7.6</td>
</tr>
<tr>
<td>event pileup</td>
<td>19</td>
<td>80</td>
<td>148</td>
</tr>
<tr>
<td>L $[cm^{-2}s^{-1}]$</td>
<td>$1 \times 10^{34}$</td>
<td>$4.2 \times 10^{34}$</td>
<td>$3.9 \times 10^{34}$</td>
</tr>
</tbody>
</table>

like the LHC with unprecedented stored beam energies and small margins for losses during operation. An experimental validation of this option would be very interesting for the planning of the HL-LHC upgrade.

- Luminosity leveling via transverse offsets of the beams at the IPs. While first operation experience in the LHC has shown that the operation with beam offsets at the IP is in principle possible, the feasibility of such a procedure has never been demonstrated during operation with many long range beam-beam interactions. An experimental evaluation of this option would be very interesting for the planning of the HL-LHC upgrade.

In addition to the validation of the above leveling options, the final parameters of the HL-LHC upgrade depend also on the replies to the following points that, where applicable, should be addressed with high priority during the Machine Development periods of the LHC and the injector complex:

- Need to verify the LHC beam-beam limit as function of beam separation and number of long-range collisions.

- Need for identifying the maximum achievable bunch intensities for operation with 25 ns and 50 ns in the LHC injector complex.

- Need for identifying the smallest achievable transverse emittance for nominal and ultimate bunch current for operation with 25 ns and 50 ns in the LHC injector complex.

- Need for identifying the maximum acceptable total beam current in the LHC. The presentation by Frank Zimmermann [14] highlights that the maximum attainable beam lifetime in the LHC is directly proportional to the maximum acceptable beam current.

- Interest in testing the ATS scheme in the existing LHC during MD studies.

Assuming a maximum limit for the total beam current in the LHC, the performance can clearly be maximized by putting the beam current in the smallest number of bunches. This gives a preference for operation with 50 ns bunch spacing. In all the scenarios discussed above, the 50 ns bunch spacing scenarios are the only options that can provide the HL-LHC design goals with less than ‘ultimate’ total beam currents. The operation scenarios with 25 ns bunch spacing imply approximately 20% larger total beam currents. Formulated the other way around, in case the beam current in the LHC is really limited to ‘ultimate’ beam currents, the performance of the 25 ns operation scenarios will be approximately 35% smaller than quoted in the above discussions.

However, the operation with 50 ns bunch spacing also implies larger bunch luminosities and therefore a larger event pile up per interaction. While the event pileup is approximately 100 for the operation scenarios with 25 ns bunch spacing (approximately a factor five larger than the nominal pileup), the maximum event pileup varies between 150 and 240 events per bunch crossing for the operation scenarios with 50 ns bunch spacing corresponding approximately to a tenfold increase with respect to the nominal LHC configuration. It still remains to be demonstrated that such high pile up rates are acceptable for the experiments.

REFERENCES

[1] Elias Metral, these proceedings.
[8] Stephane Fartoukh, these proceedings.
[12] Elena Chapochnikova, these proceedings.


[14] Frank Zimmermann, these proceedings.