HL-LHC Parameter Space and Scenarios

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Abstract

This paper looks at potential beam parameters that are compatible with the HL-LHC performance goals and discusses briefly potential variation in the parameter space.

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 $\rightarrow E_{CM} = 2 \cdot E_{beam}$);
- The instantaneous luminosity L, specifying the rate at which certain events are generated in the beam collisions (number of events per second $= L(t) \cdot \sigma_{event}$ with σ_{event} being the cross section of the event of interest);
- The integrated luminosity $\hat{L}$, specifying the total number of events that are produced over a time interval $t - t_0$.

The HL-LHC project aims at a total integrated luminosity of approximately 3000 fb^{-1} over the lifetime of the HL-LHC. Assuming an exploitation period of ca. 10 years this goal implies an annual integrated luminosity of approximately 200 $fb^{-1}$to 300 fb^{-1}per year. In the following we assume an annual target luminosity of

$$\hat{L}_{year} = 250\, fb^{-1}. \tag{1}$$

The experiments will be upgraded to be compatible with a peak event pile up of approximately 100 events per bunch crossing. The limit on the event pile up corresponds to a bunch luminosity of (scaled from the nominal LHC parameters with a quoted 19 events per bunch crossing)

$$L_{bunch} = 1.8\; 10^{31}\; cm^{-2} sec^{-1}. \tag{2}$$

For an operation with 25 ns bunch spacing (ca. 2808 bunches per beam), the limit on event pile-up per bunch crossing corresponds therefore to a maximum peak instantaneous luminosity of

$$L_{peak}(25\; ns) = 5\; 10^{34}\; cm^{-2} sec^{-1}. \tag{3}$$

For an operation with 50 ns bunch spacing (ca. 1404 bunches per beam), the limit on event pile-up per bunch crossing corresponds to a maximum peak instantaneous luminosity of

$$L_{peak}(50\; ns) = 2.5\; 10^{34}\; cm^{-2} sec^{-1}. \tag{4}$$

The instantaneous luminosity is given by

$$L = \frac{f_{rev} \cdot n_b \cdot N_1 \cdot N_2}{2\pi \sqrt{(\sigma_{x,1}^2 + \sigma_{x,2}^2)} \cdot \sqrt{(\sigma_{y,1}^2 + \sigma_{y,2}^2)}} \cdot F \cdot H, \tag{5}$$

where f_{rev} is the revolution frequency, n_b 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 (→ the transverse beta function varies over the luminous region where the two beams interact with each other). We neglect the hour glass effect in the following assuming that H is close to one for all parameter sets under consideration (e.g. we limit our discussion to $\beta^* \geq 15$ cm for an RMS bunch length of 7.5 cm; Werner Herr discusses the Hourglass effect for very short bunch length in his presentation [1]).

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

$$F = 1/\sqrt{1 + \left(\frac{\sigma_s}{\sigma_t} \frac{\phi}{2}\right)^2}, \tag{6}$$

where σ_s is the longitudinal bunch length, σ_t the transverse bunch size in the plane of the crossing angle and ϕ 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

$$\sigma_{x,y} = \sqrt{(\beta_{x,y}^* \cdot \epsilon_{x,y}) + D_{x,y}^2 \cdot \delta_p^2}, \tag{7}$$

where δ_p is the relative RMS momentum spread ($\delta_p = \frac{\Delta p}{p_0}$) 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. In the following we assume vanishing dispersion functions at the IPs.

Fig. 1 shows the geometric luminosity reduction factor and the expected increase in luminosity as a function of β^* for a 10 σ beam separation [1] at the long-range beam-beam encounters and neglecting the effect of dispersion at

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[1] The IR layout of the HL-LHC will feature significantly more long range interaction as for the nominal LHC configuration [up to factor 2 more long range interactions]. This increased number of long-range beam-beam interaction, together with larger bunch intensities for the HL-LHC parameters might require an even larger beam separation for the HL-LHC operation [2].

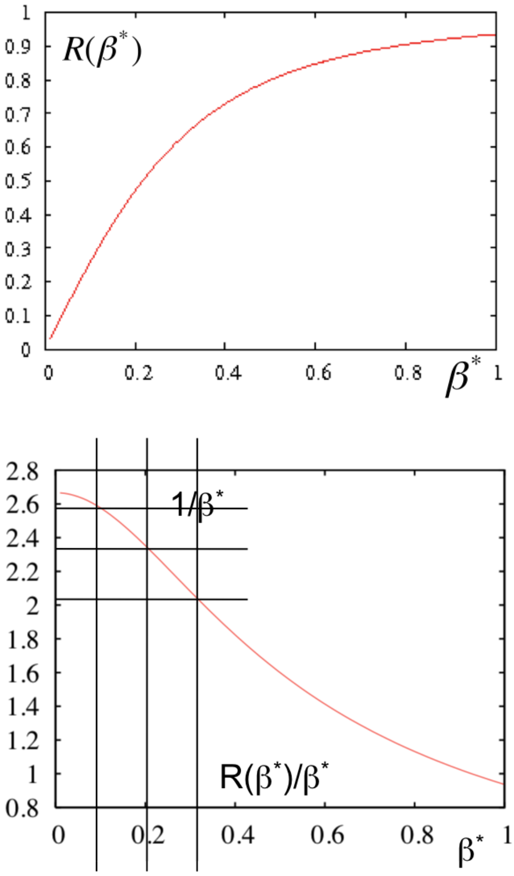

Figure 1: The geometric luminosity reduction factor (top) and the expected luminosity (bottom) as a function of β^* for a 10 σ beam separation at the long-range beam-beam encounters.

the IP and the Hour Glass effect. One clearly recognizes that the geometric luminosity reduction factor decreases sharply for small β^* values and that the expected luminosity gain becomes negligible for $\beta^* < 0.2m$. (If the Hour Glass effect is included, the luminosity even reduces when β^* becomes comparable to the RMS bunch length [approximately 10 cm for the case of the HL-LHC] [1]. Planing for $\beta^* < 0.2m$ therefore implies an operation with shorter than nominal bunch length.)

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

$$\hat{L}(t - t_0) = \int_{t_0}^{t} L(\tau) d\tau, \tag{8}$$

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 virtual luminosity that is higher than the values (3) and (4), which are imposed by the limit on the maximum event pile-up per crossing, and deploy a controlled reduction of the peak luminosity during operation (called 'luminosity leveling' in the following) so that the operational luminosity can be sustained over a significant fraction of the run time.

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 experiments 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

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 [3]. The head-on beam-beam tune shift limit is estimated to be

$$\Delta Q = 0.02 - 0.03. \tag{9}$$

Head-on beam-beam tune shifts of $\Delta Q > 0.023$ have already been achieved in the LHC operation (three experiments with head-on collisions but not yet with the nominal number of long-range beam-beam encounters). The corresponding beam-beam parameter (head-on beam-beam tune shift per IP) of

$$\xi_{beam-beam} = 7.7\ 10^{-3} \tag{10}$$

corresponds to a maximum bunch intensity of $N_b = 2\ 10^{11}$ to $N_b = 3.3\ 10^{11}$ depending on the assumed bunch length and beam emittance. For operation with crossing angle, the head-on beam-beam tune shift is reduced by the geometric reduction factor in a similar fashion as the luminosity, resulting in even higher single bunch limits due to the head-on beam-beam interaction. It is therefore justified to

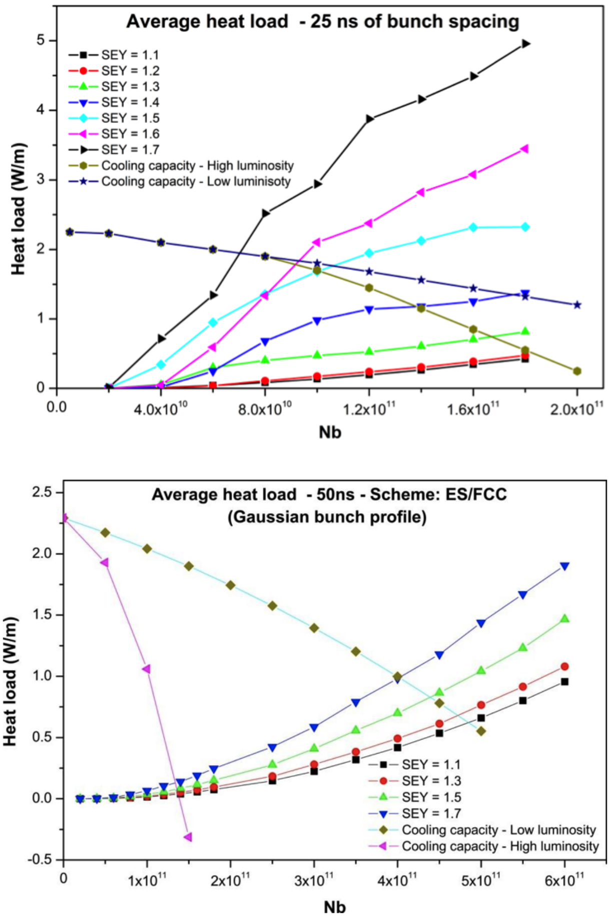

Figure 2: The heat load on the LHC beam screen due to electron cloud activity in W/m for different bunch spacings (25ns top and 50ns bottom) and various secondary emission yields (separate curves for different δ_{max} values) as a function of the bunch intensity [5]. Two lines in the vertical direction indicate the maximum acceptable heat load for the existing LHC cryogenic system and for the LHC Cryo upgrade in the IRs.

assume in the following that the beam-beam single bunch intensity limit for the HL-LHC is larger than the assumed single bunch intensity limit coming from the TMCI [4].

The electron cloud effect in the LHC imposes another limitation for the single bunch intensity that depends on the surface properties of the LHC beam screen (reflectivity and secondary emission yield) and the bunch spacing and total number of bunches. Figure 2 shows the heat load on the LHC beam screen due to electron cloud activity in W/m for different bunch spacings (25ns with 2808 bunches on the top and 50ns with 1404 bunches on the bottom) and various secondary emission yields (separate curves for different δ_{max} values) as a function of the bunch intensity [5]. Two lines in the vertical direction indicate for both bunch spacings the maximum acceptable heat load for the existing LHC cryogenic system and for the LHC Cryo upgrade in the IRs.

The heat load for 50ns bunch spacing is below the maximum acceptable value on the beam screen for all considered secondary emission yields ($\rightarrow \delta_{max} \leq 1.7$) and bunch intensities up to the TMCI single bunch limit. The electron cloud effect imposes therefore no lower limitation to the single bunch intensity as the TMCI. The heat load for an operation with 25ns bunch spacing can, on the other hand, exceed the cooling capacity of the LHC beam screens. Assuming that a secondary emission yield of $\delta_{max} = 1.3$ is the lower limit for the attainable emission yield in the LHC after conditioning the beam screens in the LHC during operation via beam scrubbing, one obtains for the operation with 25ns bunch spacing a maximum bunch intensity of $N_{bunch} \approx 2.2\ 10^{11}$ ppb even with an upgrade of the LHC IR cryogenic systems. Without upgrade of the LHC cryogenic system the electron cloud effect limits the maximum bunch intensity to less than $1.6\ 10^{11}$ ppb for a secondary emission yield of $\delta_{max} = 1.3$. The use of special filling schemes or the implementation of micro satellite bunches might elevate some of the electron-cloud limitations for operation with 25ns bunch spacing. However, until such measures have been experimentally demonstrated we assume for the HL-LHC operation a maximum bunch intensity of $N_{bunch} = 2.2\ 10^{11}$ ppb.

MINIMIZING β^* VALUES

Large β-function values in the triplet magnets generate chromatic aberrations that might limit the overall machine performance and impose rather challenging matching constraints to the transition points between the experimental insertions and the regular optics in the LHC arcs. Depending on the actual layout of the triplet magnets and LHC matching sections these constraints might limit the minimum β^* values to in the LHC to 0.3 meter. Reducing β^* below 0.3 meter (or rather accommodating for the associated peak β-functions in the triplet magnets) implies either the use of new magnet technologies that are compatible with high gradient and large aperture triplet magnets (e.g. Nb_3Sn technology) or special optics configurations. The ATS optics scheme [6] is such a special optics configuration that brings β^* 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 so far 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 that the beam separation is sufficiently large [7]. 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 β^* values for a constant crossing angle (reducing slightly the luminosity via β^* and increasing the geometric reduction factor). In the following discussion we assume that minimum β^* values of 0.1 meter are within reach for the HL-LHC and introduce additional 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 β^* value of

$$\beta^* = 0.15 \text{ m} \tag{11}$$

for the round beam operation which corresponds approximately to twice the RMS longitudinal bunch length in the LHC. The luminosity gain due to a further reduction in β^* becomes negligible below this value due to the Hourglass effect [1][8]. Furthermore, the β^* value in (11) corresponds also to the β^* value below which the potential luminosity gain without Crab cavities becomes rather small (only ca. 10% increase in luminosity for a reduction of β^* from 0.2 meter to 0.1 meter even when neglecting the additional luminosity reduction due to the Hourglass effect [see Fig. 1]).

MAXIMIZING THE TOTAL BEAM INTENSITY

The above discussions have identified maximum bunch intensities of

$$\begin{aligned} N_{b,max}(25ns) &= 2.2\ 10^{11} \quad (12)\\ N_{b,max}(50ns) &= 3.5\ 10^{11} \quad (13)\end{aligned}$$

resulting in maximum beam currents of

$$\begin{aligned} I_{tot,max}(25ns) &= 1.12A \quad (14)\\ I_{tot,max}(50ns) &= 0.84A, \quad (15)\end{aligned}$$

which are approximately twice the nominal LHC beam current. A first evaluation of the overall intensity limitations in the nominal LHC due to existing hardware was given in [9]. This first study showed that the above beam intensities appear to be compatible with the existing LHC hardware even though the maximum permissible intensity for 25 ns bunch spacing lies above the ultimate LHC beam current ($I_{ultimate} = 0.86\ A$). A more detailed analysis of the intensity limitations due to the existing LHC hardware is being conducted as a dedicated task within the framework of the HL-LHC project. But for the moment we assume that the beam intensities (14)(15) are compatible with the HL-LHC operation.

The beam lifetime in a collider with luminosity leveling is directly proportional to the total beam current [10]. The rate of proton burn off is given by:

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_{eff}} = n_{IP}\sigma_{tot}L_{lev}, \tag{16}$$

where N_{tot} is the total number of particles per beam, τ_{eff} the effective beam lifetime, n_{IP} the number of IPs with high luminosity (we assume $n_{IP} = 2$ in the following), σ_{tot} the total hadronic cross section (ca. 100 mbarn) and L_{lev} the leveled luminosity value during the run. The solution to Equation (16) is given by

$$N(t) = N_{tot} \cdot \left(1 - \frac{t}{\tau_{eff}}\right) \tag{17}$$

with

$$\tau_{eff} = \frac{N_{tot}}{n_{IP}\sigma_{tot}L_{lev}}. \tag{18}$$

The beam lifetime τ_{eff} with luminosity leveling is therefore linearly proportional to the total beam current in the machine. Maximizing the overall collider performance in terms of integrated luminosity therefore implies directly maximizing the total beam current in the machine. Assuming two high luminosity experiments one obtains from Equations (14), (15) and (18) for leveled luminosity values of $L = 5 \cdot 10^{34} cm^{-2}s^{-1}$ and $L = 2.5 \cdot 10^{34} cm^{-2}s^{-1}$ for the cases of 25 ns and 50 ns bunch spacing operation respectively expected beam lifetimes of

$$\begin{aligned} \tau_{eff}(25ns) &= 17.2 \text{ hours} \quad (19)\\ \tau_{eff}(50ns) &= 27.2 \text{ hours.} \quad (20)\end{aligned}$$

MINIMUM ACCEPTABLE BEAM EMITTANCE

The beam emittance is now the only remaining quantity for determining the virtual peak performance reach for the HL-LHC. The bunch length enters only indirectly into the performance evaluation via the geometric luminosity reduction factor, the Hourglass effect in combination with the minimum β^* value and the Intra Beam Scattering emittance growth rates. For the geometric luminosity reduction factor we assume that Crab cavities can recover the associated performance loss. For the Hourglass effect we assume that the bunch length is sufficiently smaller than β^* ($\rightarrow \sigma_s \leq 0.1$ m for $\beta^* = 0.15$ m which implies an RMS bunch length close to the nominal LHC value of $\sigma_s = 7.5$ cm). This leaves essentially the IBS growth rate as the criterion for limiting the smallest accessible beam emittance.

A systematic analysis of the LHC operation in 2010 showed that the beam emittances in the LHC grow by approximately [11]:

- 10% to 20% over 20 minutes during the injection process (e.g. Fill 2028 with a bunch intensity of 1.26 10^{11} ppb; a bunch length of approximately 1.1 ns [$\rightarrow \sigma_s \approx$ 8.3 cm] and a normalized emittance of $\epsilon_n = 1.4\ \mu$m).
- 20% during the acceleration process (ramp) and probably due to the reduced transverse damper gain during the ramp (required by the tune feedback system during the 2011 operation).
- Up to 10% during the transition to small β^* values (squeezing process), but not in all planes and varying from fill to fill.

The second and third points can hopefully be eliminated in time for the HL-LHC project by operational and diagnostic improvements. The third point should be further supressed in the HL-LHC by the stronger radiation damping at 7 TeV as compared to the operation at 3.5 TeV. We therefore assume in the following that the second and third contributions are not present for the HL-LHC operation.

The first point is consistent with the expected transverse emittance growth due to IBS. We assume that a similar emittance growth during injection is still acceptable for the HL-LHC operation. In order to assure that the emittance growth at injection is not larger than 10% to 20% we require in the following that the transverse IBS growth time at injection is of the order of 10 hours for the HL-LHC beam parameters. This requirement can then be used for calculating lower bounds for the transverse emittances for the HL-LHC parameters. Using the following longitudinal parameters [12]:

$$V_{RF} = 6\,\text{MV};\;\; \tau_s = 1.15\,ns, \epsilon_s = 0.38-0.53\,\text{eVs}, \quad (21)$$

τ_s being the 4σ bunch length, the above parameters correspond to an energy spread of

$$\sigma_{\delta E/E_0} = 2.86\;10^{-4} \text{ to } 3.25\;10^{-4}. \quad (22)$$

We use MADX [13] with the V6.503 LHC injection optics [14] for the calculation of the IBS growth rates. The IBS module of MADX uses the Bjorken-Mtingwa approach [15] which assumes Gaussian bunch distributions. The bunch distribution after RF capture in the LHC is certainly not Gaussian [16] and we can therefore not expect that the MADX results reproduce exactly the observed growth rates during the LHC operation. Rather, we use the MADX results obtained for the LHC 2011 operation parameters as a reference for the HL-LHC estimates and determine the minimum HL-LHC emittances at injection (exit SPS) by requiring that the MADX IBS growth rates for the HL-LHC parameters are smaller than those for the LHC 2011 operation parameters [17]. The MADX calculations yield for the LHC 2011 parameters (21) IBS growth rates of

$$\tau_{x,IBS}(\text{Fill 2028}) \approx 3 \text{ hours}. \quad (23)$$

In order to assure that the IBS emittance blowup for the HL-LHC parameters is well within the margin of 10% to 20% we require in the following for the HL-LHC parameters a minimum growth time of more than 5 hours in all planes.

Using the maximum bunch intensities from (12) and (13) one gets comparable IBS growth rates ($\tau_{x,IBS} \approx 9$ hours) for the following transverse beam emittances (assuming round beams):

$$\begin{aligned} \epsilon_{n,inj}(25ns) &\geq 2.0\mu m \quad (24)\\ \epsilon_{n,inj}(50ns) &\geq 2.5\mu m. \quad (25) \end{aligned}$$

We use the above values as target values for the SPS performance at extraction and injection into the LHC. Assuming an emittance increase by 10 % to 20 % between the beam delivered by the LHC injector complex and the beam parameters for LHC luminosity production at top energy. We thus obtain for the minimum transverse emittances (round beams) at collision for the HL-LHC:

$$\begin{aligned} \epsilon_{n,col}(25ns) &\geq 2.4\mu m \quad (26)\\ \epsilon_{n,col}(50ns) &\geq 3.0\mu m. \quad (27) \end{aligned}$$

For the calculation of the IBS growth rates at top energy we assume a longitudinal bunch blow-up during the ramp (increase in energy spread while keeping the longitudinal RMS bunch length smaller than β^*). Using for the IBS calculations at 7 TeV [18]:

$$V_{RF} = 16\,\text{MV};\;\; \tau_s = 0.6\,ns, \epsilon_s = 2.5\,\text{eVs}. \quad (28)$$

one obtains IBS growth rates of the order of 10 to 20 hours which is comparable to the radiation damping times at 7 TeV. It appears therefore reasonable to assume that the HL-LHC operation should be able to preserve the emittance values (26) and (27) throughout the whole luminosity run (no emittance growth due to RF noise has been observed during the 2011 operation).

The IBS estimates for the HL-LHC at injection can be improved by taking advantage of the fact that the longitudinal emittance could even be slightly larger then compared to the 2011 operational values [19]. For the HL-LHC operation we therefore assume:

$$V_{RF} = 6\,\text{MV};\;\; \tau_s = 1.5\,ns, \epsilon_s = 0.83\,\text{eVs}. \quad (29)$$

Using the above parameters for the HL-LHC IBS calculations one obtains with MADX IBS growth rates of approximately 10 hours.

As a final check of the acceptable minimum transverse emittance, we estimate the head-on beam-beam parameter. For the estimated maximum bunch intensities (12) (12) and minimum beam emittances (26)(27) one obtains

$$\begin{aligned} \xi_{max}(25ns) &= 0.011 \quad (30)\\ \xi_{max}(50ns) &= 0.014. \quad (31) \end{aligned}$$

Assuming two IPs with head-on collisions, the total head-on beam-beam tune shift is slightly larger than the maximum values obtained during the LHC operational experience in 2011 (9). However, the values in (10) are certainly smaller than the actual LHC beam-beam limit at 7 TeV when radiation damping and the geometric luminosity reduction factor (which reduces the beam-beam tune shift in a similar fashion as the luminosity) are taken into account. For round beams and two IPs with alternating crossing angle planes, the reduction of the beam-beam tune shift is in fact exactly the same as for the luminosity [20]. With luminosity leveling via an adjustment of the crossing angle at the IP (e.g. with the help of CRAB cavities), the geometric reduction factor reduces therefore the head-on beam-beam parameter per IP to $\xi_{level}(50ns) = 3.1\,10^{-3}$ which is

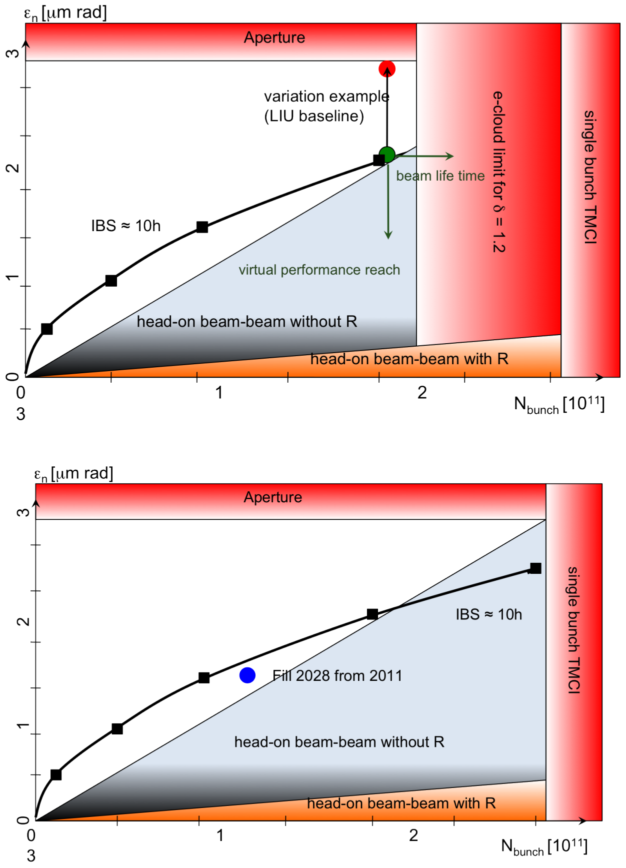

Figure 3: The accessible beam parameter space for the HL-LHC operation for the 25ns (top) and 50ns (bottom) bunch spacing options.

clearly smaller than the maximum attained head-on beam-beam tune shift during the LHC operation in 2011. The total beam-beam induced tune spread in the HL-LHC operation is then even for 4 IPs still smaller then the maximum attained beam-beam tune spread during the 2011 LHC operation period. We therefore conclude, that the IBS estimates for the minimum acceptable transverse emittances are compatible with the head-on beam-beam limit.

Inserting the above values for the maximum bunch intensities, minimum transverse beam emittances and minimum β^* values into Equation (5) and using the longitudinal parameters in (29) one obtains for both bunch spacings of 25 ns and 50 ns peak luminosities of

$$L_{peak} = 9\ 10^{34}\ cm^{-2} sec^{-1}. \tag{32}$$

Assuming the viability of CRAB cavities for compensating the geometric luminosity reduction factor R, the virtual performance reach can be further boosted by a factor $1/R$, yielding a virtual peak luminosity reach of

$$L_{virtual,peak} = 25\ 10^{34}\ cm^{-2} sec^{-1}. \tag{33}$$

Table 1 summaries the main HL-LHC parameters and Figure 3 illustrates the accessible beam parameter space (bunch intensity versus emittance). The quoted values for peak luminosity, event pile-up and beam-beam parameter refer to a scenario without luminosity leveling. With luminosity leveling the luminosity is, off curse, $L = 5\ 10^{34} cm^{-2} s^{-1}$ and $L = 2.5\ 10^{34} cm^{-2} s^{-1}$ for the 25 ns and 50 ns bunch spacing cases respectively, and the beam-beam tune shift and event pileup are reduced accordingly. The event pile-up with luminosity leveling becomes 94.

Table 1: Summary of the derived HL-LHC beam parameters and the corresponding maximum HL-LHC performance reach for the configurations with 25 ns and 50 ns bunch spacing together with the nominal LHC parameters. The quoted IBS growth rate refer to the MADX calculations for the injection optics at 7 TeV assuming Gaussian distributions and using a longitudinal emittance that requires a dedicated beam bow-up during the ramp.

Parameter	**nominal**	**25 ns**	**50 ns**
$N_b [10^{11}]$	1.15	2.2	3.5
n_b	2808	2808	1404
I [A]	0.58	1.12	0.89
$N_{tot} [10^{14}]$	3.2	6.2	4.9
full x-ing $[\mu rad]$	300	480	550
b-b sep. $[\sigma]$	10	10	10
β^* [m]	0.55	0.15	0.15
$\epsilon_n [\mu m]$	3.75	2.5	3.0
ϵ_s [eVs]	2.5	2.5	2.5
E spread	$1.2\ 10^{-4}$	$1.2\ 10^{-4}$	$1.2\ 10^{-4}$
σ_s [cm]	7.5	7.5	7.5
IBS h [h] @ col	106	20.0	20.7
IBS l [h] @ col	60	15.8	13.2
Piwinski	0.68	2.54	2.66
R	0.83	0.37	0.35
b-b $[10^{-3}]$	3.1	3.9	5.0
b-b head-on / IP	3.75	0.011	0.014
L_{peak} $[cm^{-2}s^{-1}]$	$1\ 10^{34}$	$9\ 10^{34}$	$9\ 10^{34}$
event pileup without leveling	19	169	344
$L_{virtual,peak}$ $[cm^{-2}s^{-1}]$	$1\ 10^{34}$	$25\ 10^{34}$	$25\ 10^{34}$

LUMINOSITY LEVELING

The above performance estimates clearly exceed the peak performance levels (3) and (4), which are imposed by the limit on the maximum event pile-up per crossing. The operation of the HL-LHC therefore requires a controlled reduction of the peak luminosity during operation (called 'luminosity leveling' in the following). Options for luminosity leveling include:

- The use of CRAB cavities. This new technology offers the widest leveling range and the possibility of compensating for the geometric luminosity reduction factor. But while the technology has been successfully been used in KEKB, it has not yet been demonstrated to be a viable option for operation in hadron storage rings.

- Luminosity leveling via transverse offsets of the beams at the IPs. First operation experience in the LHC has shown that the operation with beam offsets at the IP is in principle possible and offers a huge leveling range. However, contrary to the CRAB cavity option, this leveling method can only reduce the luminosity and the feasibility of the procedure has not yet 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.

- Dynamic squeeze of the optic functions at the IP during luminosity operation. Feasibility of such a procedure has never been demonstrated during operation in an existing machine, not to mention for a machine 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. However, this leveling method will not allow to recuperate the loss in luminosity due to the geometric reduction factor and, therefore, offers a much smaller leveling range as compared to the CRAB cavities.

- The use of wire compensators for compensating the long-range beam-beam interaction. Compensating part of the long-range beam-beam interaction could open the door for operating the HL-LHC with less than 10 σ beam separation and thus with a larger geometric reduction factor. However, 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 and thus allow crossing angles with less than 10 σ beam separation. In any case, this leveling method can not reduce the luminosity during a run and will never allow an operation with zero crossing angle (head-on collisions at the parasitic beam-beam encounters). It therefore offers a much smaller leveling range as compared to the CRAB cavities.

INTEGRATED LUMINOSITY

The run length at constant luminosity with leveling depends on the maximum virtual luminosity reach. Assuming a virtual peak luminosity of

$$L_{virtual-peak} = k \cdot L_{level} \tag{34}$$

one obtains for the maximum operation time at constant leveled luminosity:

$$T_{level} = \left(1 - 1/\sqrt{k}\right) \cdot \tau_{eff}, \tag{35}$$

where τ_{eff} is the beam lifetime with luminosity leveling (18).

Inserting the expected beam lifetimes [(19) and (20)], peak (32) and leveled luminosity values [(3) and (4)] one gets for the cases of 25 ns bunch spacing:

$$k(25\ ns) = 1.8; T_{Level-nom}(25\ ns) = 4.3\ h; \tag{36}$$

and for the case of 50 ns bunch spacing

$$k(50\ ns) = 3.6; T_{Level-nom}(50\ ns) = 12.9\ h. \tag{37}$$

Inserting for the virtual peak performance (33) one gets for the cases of 25 ns bunch spacing:

$$k(25\ ns) = 5; T_{Level-max}(25\ ns) = 9.4\ h; \tag{38}$$

and for the case of 50 ns bunch spacing

$$k(50\ ns) = 10; T_{Level-max}(50\ ns) = 18.8\ h. \tag{39}$$

The integrated luminosity of a fill is then simply given by the product of the leveled luminosity and the maximum leveling time. Letting the luminosity decay at the end of a fill below the target leveling value one can accumulate an additional

$$\Delta\hat{L}_{end}(25ns) = 0.4\ fb^{-1} \tag{40}$$

$$\Delta\hat{L}_{end}(50ns) = 0.2\ fb^{-1} \tag{41}$$

over approximately 3 hours [21] for the cases of 25 ns an 50 ns bunch spacing respectively. After that point the luminosity has decayed to half of its leveling target value. However, the optimum machine performance will be reached if a new fill is prepared as soon as the machine reached the maximum leveling time. The maximum integrated luminosity per fill can thus be estimated as:

$$\hat{L} = \left(1 - 1/\sqrt{k}\right) \cdot L_{lev} \cdot \tau_{eff}. \tag{42}$$

Inserting the parameters for the 25 ns operation, one gets:

$$k = 1.8 \quad \rightarrow \quad \hat{L} = 0.78\ fb^{-1} \text{ over 4.3 h.} \tag{43}$$

$$k = 5 \quad \rightarrow \quad \hat{L} = 1.69\ fb^{-1} \text{ over 9.4 h.} \tag{44}$$

For the case of 50 ns operation one gets:

$$k = 3.6 \quad \rightarrow \quad \hat{L} = 1.17\ fb^{-1} \text{ over 12.9 h.} \tag{45}$$

$$k = 10 \quad \rightarrow \quad \hat{L} = 1.69\ fb^{-1} \text{ over 18.8 h.} \tag{46}$$

REQUIRED MACHINE EFFICIENCY

In order to reach the target luminosity of $\hat{L} = 250\ fb^{-1}$ per year one requires the following number of physics fills per year:

$$\begin{aligned} \text{25 ns; no CRAB:} &\approx \text{321 fills per year;} \quad (47)\\ \text{25 ns; with CRAB:} &\approx \text{148 fills per year;} \quad (48)\\ \text{50 ns; no CRAB:} &\approx \text{214 fills per year;} \quad (49)\\ \text{50 ns; with CRAB:} &\approx \text{148 fills per year.} \quad (50) \end{aligned}$$

Assuming a similar time allocation for physics fills as during the 2011 run period of the LHC one can expect to have approximately 150 days per year for physics runs [22]. Combining this estimate with the above required fills per year, one obtains for the average number of fills per day:

$$\begin{aligned} \text{25 ns; no CRAB:} &\approx \text{2.14 fills; } T_{fill} = 4.3\ h; \quad (51)\\ \text{25 ns; with CRAB:} &\approx \text{0.99 fills; } T_{fill} = 9.4\ h; \quad (52)\\ \text{50 ns; no CRAB:} &\approx \text{1.4 fills; } T_{fill} = 12.9\ h; \quad (53)\\ \text{50 ns; with CRAB:} &\approx \text{0.99 fills; } T_{fill} = 18.8\ h (54) \end{aligned}$$

The cases with CRAB cavity leveling imply approximately one physics fill per day which seems to be reasonable. But the optimum fill length for the 50 ns cas is quite long. The cases without CRAB cavity compensation of the geometric luminosity reduction factor imply between 1.4 and 2.1 fills per day with significantly reduced fill length as compared to the cases with CRAB cavity compensation. If one defines the machine efficiency as time spend in physics divided by the total number of time planned for physics, one obtains:

$$\begin{aligned} \text{25 ns; no CRAB:} &\approx 38\ \% \quad (55)\\ \text{25 ns; with CRAB:} &\approx 39\ \% \quad (56)\\ \text{50 ns; no CRAB:} &\approx 75\ \% \quad (57)\\ \text{50 ns; with CRAB:} &\approx 78\ \%. \quad (58) \end{aligned}$$

which do not yet include the impact of involuntary beam dumps and the average machine Turnaround time. The above efficiency values can be compared to the LHC operational experience which achieved an average efficiency of 23 % to 33 % (using the above definition for the machine efficiency). The HL-LHC efficiencies are therefore challenging, but within reach for the 25 ns bunch spacing case. But they seem to be virtually impossible for the 50 ns bunch spacing case.

Past machine operation experience in LEP has shown that the integrated annual luminosity can be reasonably well estimated by

$$\hat{L}_{year} \approx h \cdot L_{peak} \cdot \text{number of days of operation,} \quad (59)$$

where h is referred to as the Hübner factor. The Hübner factor includes effects from the overall machine availability and efficiency and the luminosity decay over a given fill. The LEP performance well could be estimated with a Hübner factor of h ≈ 0.2. Attempting to write the luminosity performance for the HL-LHC in a similar fashion using the leveled peak luminosity value, one obtains 'Hübner factors of

$$\begin{aligned} h(25\,ns) &= 0.38 \quad (60)\\ h(50\,ns) &= 0.76. \quad (61) \end{aligned}$$

Again, the performance requirements for the 25 ns bunch spacing configuration seem to be challenging, but not necessarily out of reach (thanks to luminosity leveling the HL-LHC has no luminosity decay over a given fill). However, the performance requirements for the 50 ns bunch spacing configuration seem to be out of reach. If one uses the virtual peak luminosity value rather then the leveled luminosity, one obtains for the required 'Hübner factor $h(25\ ns) = 0.076$, which is clearly smaller than the LEP value.

PARAMETER VARIATION FOR 25 NS OPERATION

In the following we want to estimate the loss in performance in case the beam parameters in Table (1) can not be reached. To this end we assume for the 25 ns bunch spacing parameters a transverse normalized emittance of $\epsilon_n = 3\ \mu m$ instead of the target value of $\epsilon_n = 2.5\ \mu m$. In this case one needs to increase the crossing angle from 480 μrad to 550 μrad and obtains for the maximum luminosity reach

$$\begin{aligned} L_{nom} &= 7.1\ 10^{34}\ cm^{-2} sec^{-1} \quad (62)\\ L_{virt} &= 20.4\ 10^{34}\ cm^{-2} sec^{-1} \quad (63) \end{aligned}$$

and for the maximum fill length

$$\begin{aligned} T_{Fill}(noCRAB) &= 2.8\ h \quad (64)\\ T_{Fill}(withCRAB) &= 8.6\ h. \quad (65) \end{aligned}$$

For the integrated luminosity per fill one obtains

$$\begin{aligned} k = 1.4 &\rightarrow \hat{L} = 0.51\ fb^{-1} \text{ over 2.8 h} \quad (66)\\ k = 4.1 &\rightarrow \hat{L} = 1.56\ fb^{-1} \text{ over 8.6 h.} \quad (67) \end{aligned}$$

In order to reach the target luminosity of $\hat{L} = 250\ fb^{-1}$ per year one requires now the following number of physics fills per year:

$$\begin{aligned} \text{25 ns; no CRAB:} &\approx \text{490 fills per year;} \quad (68)\\ \text{25 ns; with CRAB:} &\approx \text{160 fills per year.} \quad (69) \end{aligned}$$

Compared to the optimum parameters given in Table (1) one thus observes an overall performance reduction between 10 % and 35 % in terms of maximum integrated luminosity per fill and a reduction of the maximum fill length between 10 % and 20 %. In order to reach the HL-LHC goal of 250 fb^{-1} per year this implies only a slightly better average machine efficiency: 39 % instead of 38 % for the parameter of Table (1) but with a significantly larger number of fills per year (between 15 % and 50 % more fills). The above machine efficiency estimate does not include any contributions due to equipment failures during machine cycles and the average Fill-to-Fill length. The impact of these factors on the overall machine performance is difficult to estimate at this stage (no experience on the average Fill-to-Fill length with high beam intensity and high luminosity operation at 7 TeV). But there is clearly a preference for a scenario that minimizes the number of required physics fills per year.

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 β^* values close to 0.15 m. Significant margins for leveling can be achieved for β^* values close to 0.15 m. However, these margins can only be harvested during the HL-LHC operation if the required leveling techniques have been demonstrated in operation. In addition to the validation of the indicated 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 currents 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.

- Need for identifying the maximum acceptable event pileup per bunch crossing for the HL-LHC operation.

- Validation of operating the LHC with a large Piwinski parameter.

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

- What is the maximum attainable cooling power in the LHC arcs with a potential upgrade of the cryogenic system (higher bunch intensities for the 25 ns scenario)?

- Are there other limitations then the LHC arc cryogenic system for the maximum bunch intensity for the 25 ns bunch spacing scenario (e.g. e-cloud related instabilities, RF heating etc.)

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. However, as long as the maximum bunch luminosity is limited by the maximum acceptable event pile-up per bunch crossing, the 50 ns bunch spacing scenario can offer only half of the leveled luminosity. This translates into longer fill length with respect to the 25 ns scenarios and implies rather high machine efficiencies for attaining the desired annual integrated luminosity of 250 fb^{-1}. The later illustrates that the 50 ns bunch spacing scenario is only interesting as a backup scenario in case of serious performance limitations for the 25 ns bunch spacing (e.g. due to electron cloud effects).

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