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Parameter Space for the LHC High-Luminosity Upgrade

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PARAMETER SPACE FOR THE LHC LUMINOSITY UPGRADE *

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We review the parameter space for the high-luminosity upgrade of the LHC (HL-LHC). Starting from the luminosity targets and the primary limitations, e.g., event pile up, turnaround time, injector limits, and intrabeam scattering, we determine compatible beam parameters such as the beam intensity, bunch spacing, transverse and longitudinal emittances, bunch length, and IP beta functions required to meet the HL-LHC goals. Possible HL-LHC parameter sets together with their expected performance reach are presented for comparison and discussion.

TARGET PERFORMANCE

The High-Luminosity Large Hadron Collider (HL-LHC) represents an extensive upgrade of the LHC accelerator and detectors which is planned to be implemented in stages, with the final installations foreseen during a 2-year shutdown in 2022/23. The HL-LHC project aims at a total integrated luminosity of approximately 3000 fb^{-1} over the entire lifetime of the HL-LHC, including about 400 fb^{-1} accumulated in the lower-luminosity running period through 2021. Assuming an exploitation period of ca. 10 years for the HL-LHC alone, this goal implies an annual integrated HL-LHC luminosity of approximately 200 fb^{-1} to 300 fb^{-1} per year, e.g. from 2024 to 2033. In the following we assume an annual target luminosity of $250\ \mathrm{fb}^{-1}$.

BEAM PARAMETERS

The LHC can be operated with bunch spacings of either 25 ns (nominal) or 50 ns (2011/12 running mode). No additional options are considered. Other bunch spacings would imply substantial changes to the RF systems of the injectors and/or the LHC, and to the detector electronics.

For the HL-LHC the peak luminosity will be increased by reducing the beam spot size at the interaction point, by introducing crab cavities to compensate for the otherwise large geometric loss due to the crossing angle, and by increasing the beam current.

The IP spot size can be reduced by further squeezing the IP β^* from a nominal value of 0.55 m at 7 TeV down to 0.15 m by installing new final-focusing triplets comprising larger-aperture quadrupoles (the heartpiece of the upgrade) and by accomplishing the associated chromatic correction and the matching to the arcs through a novel optics – called the achromatic telescopic squeeze (ATS) [1].

The β^* of 15 cm is still large compared with the design rms bunch length of 7.55 cm, so that the hourglass effect results in less than 10% luminosity loss and is neglected in the following. Without additional measures the geometric luminosity loss due the crossing angle is given by

$$F = \left(1 + \left(\frac{\sigma_z \theta_c}{2\sigma_\perp}\right)^2\right)^{-1/2} , \qquad (1)$$

where σ_z denotes the rms bunch length, $\sigma_\perp$ the rms beam size in the plane of the crossing and θ_c the total crossing angle. This reduction factor F is noticeable already for nominal LHC parameters ($F \approx 0.84$). It would be much decreased for the smaller β^*, which must be accompanied by larger crossing angles in order to keep the effect of ‘parasitic’ long-range beam-beam collisions under control. For this reason, crab cavities have become part of the HL-LHC baseline in 2010[2]. By changing the orientation of colliding bunches these crab cavities can restore a complete overlap of the colliding bunches ($F = 1$) while maintaining a large crossing angle for beam separation at the locations of the long-range encounters.

The beam current strongly impacts the maximum potential peak luminosity and the length of the physics stores. The HL-LHC project includes two new separate cryogenics plants for the two high-luminosity insertions, which provide additional cooling margin for the LHC arcs (for heat load from electron cloud, synchrotron radiation and image currents). However, even with this upgrade, the cryogenics as well as several other important systems – such as RF, vacuum, beam dump, machine protection – have only been designed for operation up to the ‘ultimate’ beam current of 0.86 A.

The LHC injector upgrade (LIU) project aims at a major improvement of the injector performance in terms of beam intensity and brightness [3], for the time of the HL-LHC, using a variety of ingredients. The (improved) beam brightness will still be limited by space charge in the various (upgraded) LHC injectors (PS booster, PS, and SPS), with different bounds for the 25-ns and 50-ns beams (due to the different production schemes of these beams). Another limit comes from intrabeam scattering (IBS) in the LHC, where we require that at LHC injection (lasting for 30 minutes or more) the IBS emittance rise times be significantly larger than 5 h. No limitations from head-on beam-beam effects have yet been observed, inculding in several dedicated LHC machine experiments with a beam-beam tune shift exceeding the LHC design value by more than a factor of three. Therefore, head-on beam-beam effects are not expected to limit the beam brightness of the HL-LHC, except for possible harmful effects of a large Piwinski angle, which have not yet been explored in operation.

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The longitudinal parameters (longitudinal emittances and bunch length) at injection and top energy are kept equal to their respective nominal values. Attempts in 2011 to operate the LHC with shorter bunches have revealed heating effects and instabilities. On the other hand, for longer bunches more particles leak out of the rf bucket, populating the beam-abort gap. The HL-LHC is likely to include a higher-harmonic rf system, ensuring beam stability for nominal bunch length at the higher bunch intensity.

Table 1 summarizes the main HL-LHC parameters. The values quoted for the total beam-beam tune shift $\Delta Q_{\rm tot}$ refer to the end of the leveling period where $\Delta Q_{\rm tot}$ is maximum. The IBS growth rates were computed with the latest version of MAD-X [4] considering either the design optics, for the nominal LHC, or the ATS optics with $\beta^*_{x,y} = 15$ cm, for the HL-LHC scenarios.

PILE UP AND LEVELING

Along with the accelerator, the two high-luminosity experiments, ATLAS and CMS, will be upgraded to be compatible with on average 140 events per crossing (pile up), and pile-up tails extending up to 200 events [5].

Assuming that the event pile-up number relates to an inelastic cross section of 60 mbarn [6], the limit of 140 on the event pile up corresponds to a bunch luminosity of $L_{\rm bunch} = 2.6 \times 10^{31}$ cm^{-2}s^{-1}.

For operation with 25 ns bunch spacing there are about 2808 bunches per beam, and an event pile up of 140 then correponds to a maximum average luminosity of $\hat{L}(25\,{\rm ns}) = 7.4 \times 10^{34}$ cm^{-2}s^{-1}. When operating with 50 ns bunch spacing (1404 bunches per beam), the maximum average luminosity is half this value, $\hat{L}(50\,{\rm ns}) = 3.7 \times 10^{34}$ cm^{-2}s^{-1}.

The HL-LHC upgrade project aims at achieving a 'virtual' peak luminosity that is higher than the maximum value imposed by the acceptable event pile up and to deploy a controlled reduction of the peak luminosity during operation ('luminosity leveling') so that the operational luminosity can be sustained over a significant length of time.

Leveling by varying the crab-cavity voltage has been adopted as the HL-LHC baseline but other additional leveling options are being studied (e.g. beam offset at the IP, dynamic β^* squeeze, crossing angle adjustments and compensation for long-range parasite beam-beam interactions during operation).

INTEGRATED LUMINOSITY

Due to proton consumption in the collisions, the total beam intensity, $N_{\rm tot}$, decays as $dN_{\rm tot}/dt = -n_{\rm IP}\sigma_{\rm tot}L$, where $n_{\rm IP}$ denotes the number of high-luminosity IPs ($n_{\rm IP} = 2$ for HL-LHC), $\sigma_{\rm tot}$ the total cross section ($\sigma_{\rm tot} \approx$ 100 mbarn), and L the luminosity. Setting L equal to the leveled luminosity, $L_{\rm lev}$, the effective beam lifetime is

$$\tau_{\rm eff} = \frac{N_{\rm tot}}{n_{\rm IP}\sigma_{\rm tot}L_{\rm lev}} \; . \qquad (2)$$

Table 1: HL-LHC beam parameters and performance reach for the configurations with 25 ns and 50 ns bunch spacing together with the nominal LHC parameters. For all cases we consider 2.5 eVs ($4\pi\sigma_E\sigma_z/c$), an rms bunch length of 7.55 cm, an average tunaround time $t_{\rm ta}$ of 5 h, and 150 days of *pp* physics per year. For the event pileup we assume an inelastic cross section of 60 mbarn. For the crossing angle we aim at a normalized separation between 11 and 13 sigma to reproduce the foot print of the nominal LHC case. The crossing angle during HL-LHC operation might be smaller if other compensation measures become operational (e.g. wire compensators) or larger diffusion coefficients become desirable for halo particles (e.g. for halo cleaning).

Parameter	**nominal**	**25 ns**	**50 ns**
energy E_b [TeV]	7	7	7
$N_b[10^{11}]$	1.15	2.2	3.5
n_b	2808	2808	1404
$I_{\rm beam}$ [A]	0.58	1.12	0.89
$N_{\rm tot}$ [10^{14}]	3.2	6.2	4.9
θ_c [μrad]	285	590	590
b-b sep. [σ]	9.5	12.5	11.4
$\beta^*_{x,y}$ [m]	0.55	0.15	0.15
$\gamma\epsilon_{x.y}$ [μm]	3.75	2.5	3.0
$\tau_{{\rm IBS},x}$ [h]	103	15.4	14.3
$\tau_{{\rm IBS},z}$ [h]	57	21.0	16.4
F	0.84	0.30	0.33
max. $\Delta Q_{\rm bb,tot}$ [10^{-3}]]	11	15	19
$\hat{L}$ [10^{34} cm^{-2}s^{-1}]	1.0	24	25
$L_{\rm lev}$ [10^{34} cm^{-2}s^{-1}]	1.0	7.4	3.7
ratio k	-	3.3	6.9
pile up	19	140	140
lum. region $\sigma_{\rm lum}$ [mm]	45	≥20	≥20
$\tau_{\rm eff}$ [h]	44.9	11.6	18.4
$t_{\rm lev}$ [h]	-	5.2	11.4
$t_{\rm dec,opt}$ [h]	-	3.7	2.9
$t_{\rm run}$ [h]	15.0	8.9	14.3
$L_{\rm ave,opt}$ [10^{34} cm^{-2}s^{-1}]	0.56	4.3	2.7
availability A [%]	(50)	45	72
efficiency E [%]	(38)	29	53
$L_{\rm int}$/year [fb^{-1}]	(37)	250	250

Next, introducing the ratio of virtual peak luminosity and leveled luminsosity, $k = \hat{L}/L_{\rm lev}$, we can express the maximum leveling time as

$$t_{\rm lev} = \tau_{\rm eff}\left(1 - \frac{1}{\sqrt{k}}\right) \equiv \tau_{\rm eff}K \; , \qquad (3)$$

where $K \equiv (1 - 1/\sqrt{k})$ designates the ratio of leveling time and effective lifetime. For the general case, where the physics run is extended beyond the end of the leveling period by a certain decay time $t_{\rm dec}$ (see Fig. 1), the time-averaged luminosity becomes

$$L_{\rm ave} = L_{\rm lev}\frac{t_{\rm lev} + t_{\rm dec}\tau_{\rm eff}/(t_{\rm dec} + \tau_{\rm eff})}{t_{\rm dec} + t_{\rm lev} + t_{\rm ta}} \; , \qquad (4)$$

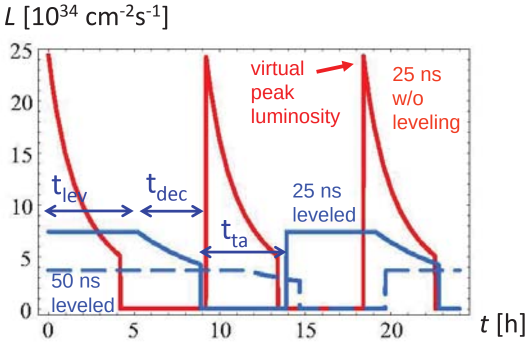

Figure 1: HL-LHC luminosity evolution as a function of time without (red), and with leveling at a pile up of 140 for 25 ns (solid blue) and 50 ns bunch spacing (dashed blue).

with $t_{\rm ta}$ denoting the average turnaround time. i.e. the time between the end of one physics run and the start of the next. The average luminosity assumes a maximum value, $L_{\rm ave.opt}$, for $t_{\rm dec}$ equal to the 'optimum decay time'

$$t_{\rm dec,opt} = \frac{\tau_{\rm eff}}{1+K}\left(-K + \sqrt{(K^2 + (1+K)t_{\rm ta}/\tau_{\rm eff}}\right) \ . \tag{5}$$

The larger the turnaround time is compared with the effective lifetime, the longer a decay time should be included. The optimum total length of a physics run is $t_{\rm run,opt} = (t_{\rm lev} + t_{\rm dec,opt})$.

For the nominal LHC, without leveling the optimum run time is $t_{\rm run,nol} = \sqrt{t_{\rm ta}\tau_{\rm eff}}$ yielding the average luminosity of $L_{\rm ave,nol} = \hat{L}\tau_{\rm eff}/\sqrt{\tau_{\rm eff}^2 + t_{\rm ta}^2}$.

The integrated annual luminosity for LHC and HL-LHC is estimated by multiplying the total time scheduled for physics production T, the machine availability A (time w/o hardware failures divided by total time scheduled), and the average luminosity, as

$$L_{\rm int} \equiv \int_{\rm year} L(t)dt = T_{\rm tot} A L_{\rm ave} \ . \tag{6}$$

For our numerical estimates for HL-LHC in Table 1 we require $L_{\rm int}$ to be 250 fb^{-1}, consider $T_{\rm tot} = 150$ days (per year), and we use the above equation to deduce the minimum availability required. Defining the machine efficiency, E, as the time spent in physics divided by the total allocated calendar time, we can also estimate the miminum needed efficiency, as

$$E \approx A\ t_{\rm run}/(t_{\rm run} + t_{\rm ta}) \ . \tag{7}$$

Refined estimates of integrated luminosities or necessary efficiencies might be obtained considering a realistic run-time distribution of (prematurely aborted) physics stores.

VARIATIONS

Table 2 illustrates that a higher limit on the acceptable pile up strongly reduces the required machine availability and the efficiency, and vice versa. Table 3 shows the effect of a beam current limit.

Table 2: Scenarios with pile-up limits of 100 and 200.

parameter	25 ns		50 ns	
$L_{\rm lev}$ [10^{34} cm^{-2}s^{-1}]	5.3	10.6	2.6	5.3
ratio k	4.6	2.3	9.7	4.8
pile up	100	200	100	200
$t_{\rm run}$ [h]	12.2	6.5	20.4	9.9
availability A [%]	54	30	*92*	48
efficiency E [%]	34	17	*73*	32
$L_{\rm int}$/year [fb^{-1}]	250	250	250	250

Table 3: Scenarios with total current limit equal to ultimate and two different pile-up limits.

parameter	25 ns		50 ns	
N_b[10^{11}]	1.7	1.7	3.4	3.4
$L_{\rm lev}$ [10^{34} cm^{-2}s^{-1}]	7.4	10.6	3.7	5.3
ratio k	2.0	1.4	6.5	4.6
pile up	140	200	140	200
$t_{\rm run}$ [h]	6.8	5.4	10.9	9.5
availability A [%]	57	54	73	59
efficiency E [%]	33	28	50	39
$L_{\rm int}$/year [fb^{-1}]	250	250	250	250

CONCLUSIONS

HL-LHC parameters have been derived for bunch spacings of 50 ns and 25 ns, and the implied requirements on availability and efficiency have been computed, using analytical formulae for optimized performance. The efficiencies required to meet the HL-LHC luminosity goals are challenging, but they appear within reach for all 25 ns cases and for the 50 ns cases with event pile up of 140 or higher. On the other hand, they seem to be nearly impossible for the 50 ns case if the maximum pile up is limited to 100 events. The 25 ns bunch spacing has, therefore, been adopted as the HL-LHC baseline scenario while the 50 ns bunch spacing parameters are maintained as a backup option in case of serious beam current limitations for the 25 ns bunch spacing (e.g. due to electron cloud effects).

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