NEW HIGH LUMINOSITY LHC BASELINE AND PERFORMANCE AT ULTIMATE ENERGY*

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Abstract

The LHC machine is envisioned to operate eventually at an ultimate beam energy of 7.5 TeV at the end of LHC Run 4, i.e. after commissioning of the HL-LHC systems, a stage falling into the High Luminosity LHC (HL-LHC) era. In this paper we review the latest baseline parameters and performance, and study the potential reach of the HL-LHC with pushed optics at the ultimate beam energy. Results in terms of integrated luminosity and effective pile-up density of both the nominal (5.0×10^{34} cm^{-2} s^{-1}) and ultimate (7.5×10^{34} cm^{-2} s^{-1}) levelling operations are discussed.

INTRODUCTION

The HL-LHC [1, 2] parameters have recently gone under review, resulting in a new baseline [3–5], with the aim to meet the original goals on performance with only two crab cavities (CCs) per beam per interaction point (IP) side. For the scope of this work –the assessment of the machine performance–, some of these changes include: shorter turnaround times (TaT), a slight increase of the number of colliding bunches at the IPs, and a reduced β^* and crossing angle at ATLAS and CMS.

Operation at the *ultimate* beam energy of 7.5 TeV [6], corresponding to a magnetic field of 8.93 T in the main arc dipoles and a current of 12 748 A, is a project's goal in order to fully exploit the machine capabilities [7]. This beam energy provides an operational margin with respect to the original definition of 7.56 TeV in the LHC Technical Design Report [8], which corresponds to a dipole magnetic field of 9.0 T and an operational current of 12 850 A. The ultimate energy is not expected, however, to be implemented in the machine before the HL-LHC upgrade, thus falling in the high-luminosity era.

In the first section of this paper, the performance of HL-LHC baseline is reviewed at the *nominal* energy of 7.0 TeV in terms of yearly integrated luminosity ($\mathcal{L}_{\text{int}}$) and effective pile-up density ($\bar{\rho}$), the latter being a parameter that quantifies the expected detector efficiency [9, 10]. The following section addresses the performance estimation for the machine with baseline optics and beam parameters, at the ultimate beam energy of 7.5 TeV, and compares it with that at nominal energy. A brief study on the impact on performance from the absence of CCs for both cases is briefly discussed too. Simulations for both nominal (5.0×10^{34} cm^{-2} s^{-1}) and ultimate (7.5×10^{34} cm^{-2} s^{-1}) levelling are considered (not to be confused with nominal and ultimate in the context of beam energy) for all cases. The effects of different cross sections for burn-off and reduced TaT (availability) [11] are also discussed, illustrating the performance reach under more optimistic conditions.

Table 1: HL-LHC Baseline Parameters [4]

Parameter	Unit	Value
Nominal beam energy	TeV	7.0
Number of bunches	1	2760
Number of collisions at IP1 or IP5	1	2748
Bunch population	10^{11}	2.2
Total beam current	A	1.10
Longitudinal profile	–	q-Gaussian [13]
RMS bunch length	cm	7.6
Full width at half maximum	cm	21.2
Minimum $\beta^*_{\times}$, $\beta^*_{\parallel}$	cm	15, 15
Half crossing angle	µrad	250
Norm. transversal emittance	µm	2.5

NEW BASELINE

The current HL-LHC baseline, with the nominal beam energy of 7.0 TeV, features the parameters shown in Table 1 [4,12]. Levelled luminosites of 5.0×10^{34} cm^{-2} s^{-1} and 7.5×10^{34} cm^{-2} s^{-1} define two operation scenarios: nominal and ultimate, corresponding to pile-up (PU) levels of 131 and 197 events per bunch crossing[1], respectively, for an inelastic cross section of 81 mb. The minimum β^*, reached at the end of the levelling stage, is 15 cm; the normalized beam-beam long-range (BBLR) separation at minimum β^* is $d_{\text{BBLR}} = 10.5\sigma$ (assuming a constant normalized emittance of 2.5 µm).

Simulations are conducted assuming a pessimistic 111 mb total cross section for burn-off ($\sigma_{\text{b.o.}}$). Computation of the intrabeam scattering (IBS) and its impact on emittance growth has been revised, as well as the value of the relative energy spread (1.074×10^{-4} q-Gaussian RMS). Results on the evolution of a series of parameters of interest along an optimum fill for the nominal and ultimate baseline are shown in Fig. 1. At the beginning of the fill, $\beta^* = 64$ cm (41 cm) with $d_{\text{BBLR}} = 21.8\sigma$ (17.3σ) for the nominal (ultimate) operation; the normalized BBLR separation d_{BBLR} once the

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[1] In order to provide 140 and 200 events per bunch crossing, previous simulations were conducted with slightly higher levelled luminosities [14], and/or higher estimates of the cross-section for pile-up [15]; the number of colliding bunches at IP1 and IP5 has also slightly increased.

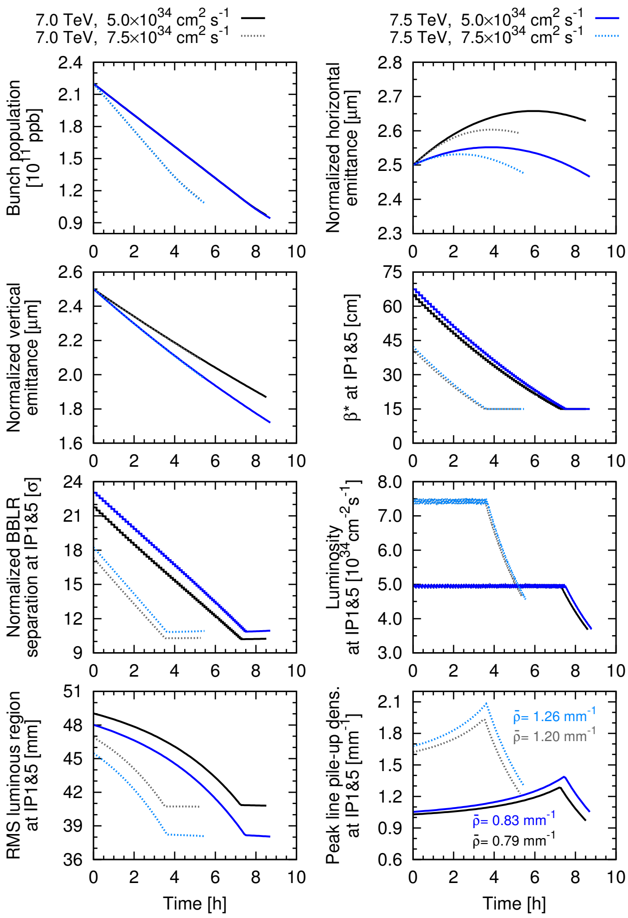

Figure 1: Fill evolution of the HL-LHC baseline for the nominal (5.0×10^{34} cm^{-2} s^{-1}) and ultimate (7.5×10^{34} cm^{-2} s^{-1}) levelling operation, at both the nominal (7.0 TeV) and ultimate (7.5 TeV) beam energies.

minimum β^* is reached deviates slightly from its virtual value of 10.5σ due to emittance evolution. The largest RMS luminous region is found at the beginning of the fill, while the largest peak line pile-up density (1.28 mm^{-1} for nominal and 1.93 mm^{-1} for ultimate) is reached at the end of the levelling. The effective pile-up, an integrated quantity based on the average of the pile-up density along the fill that reflects the expected detector efficiency (defined in [9, 10]), is found to be 0.79 mm^{-1} for the current nominal baseline, increasing by around 50 % at the ultimate operation.

Estimations for $\mathcal{L}_{\text{int}}$ assume 160 days of operation, an efficiency –as defined in [2]– of 50 %, and turn-around times –defined as the time taken to go from the dump of a stable beam back to stable mode– of 145 min and 150 min for nominal and ultimate[2] levelling, respectively. Reduction of TaT from 3 h to the current estimates is a result from a combined ramp and squeeze, shortening of the squeeze time, and the reduction of the ramp-down time after a physics fill [12]. With these assumptions, the HL-LHC baseline is found to deliver around 262 fb^{-1} at nominal levelling, and up to 325 fb^{-1} at ultimate, see Table 2. It was found that the reduction of β^* from 20 cm (assumed in [1]) to 15 cm resulted in a gain of roughly 3 % on $\mathcal{L}_{\text{int}}$ for nominal, and more than 6 % for ultimate operation. Reduction of the TaT to the current values for the nominal and ultimate, led to increments of around 6 % and 7 % with respect to their counterparts with the previous baseline parameters.

Studies on machine availability have shown that, for the nominal levelling, an increase of $\mathcal{L}_{\text{int}}$ between 3 % and up to 23 % can be expected, for conservative and relaxed configurations, respectively [11].

With the more optimistic value of $\sigma_{\text{b.o.}} = 81$ mb –i.e. the inelastic part exclusively– the HL-LHC performance increases by 7 % for the nominal operation, and up to 10 % for ultimate levelling, with respect to the corresponding cases described above. Further reduction of the TaT by 15 min (due to a potential upgrade of the triplet power converters at IP2 and IP8 [12]) also pushes the performance, with gains of 2 % and 3 % for the nominal and ultimate, respectively.

BASELINE AT ULTIMATE ENERGY

The HL-LHC baseline at the ultimate beam energy operates with identical parameters[3] to those found in Table 1, but with a beam energy of 7.5 TeV, and a relative energy spread of 1.038×10^{-4}. Regarding optics considerations, a slightly larger minimum d_{BBLR} (10.9σ) is obtained by keeping the same half crossing angle of 250 µrad, due to the increased beam energy and the scaling of the real beam size. Since the BBLR effects depend on the normalized separation, a scheme with the same d_{BBLR}, instead of the geometrical separation, could be implemented at ultimate energy; moreover, the BBLR kicks also scale inversely with energy. By keeping the same geometrical crossing angle as for the case at nominal energy, an operational margin is thus left.

As in the previous section, the cases of levelling at both 5×10^{34} cm^{-2} s^{-1} and 7.5×10^{34} cm^{-2} s^{-1} are studied. The minimum TaT is expected to increase by five minutes for both nominal and ultimate levelling, as a result of the longer time required for the energy ramp, and for ramping down the magnets at the end of a physics fill. Additionally, the same inelastic and total cross sections assumed for the 7 TeV case are used for the performance estimates at ultimate energy, as their variation is expected to be at the percent level. Performance estimations are conducted assuming the same number of days of operation and efficiency than those for the current baseline.

Simulations show that the potential increment of $\mathcal{L}_{\text{int}}$ due to operation at higher energy is, however, outweighed by the increase in the TaT with respect to the 7.0 TeV scenarios. As seen in Table 2, $\mathcal{L}_{\text{int}}$ in fact decreases, although such reduction is almost negligible. At 7.5 TeV, the levelling time is longer by around 14 min and 8 min for the nominal and ultimate operations, respectively, due mainly to the larger virtual luminosity (a product, in turn from the smaller emit-

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[2] Five more minutes are needed for additional squeeze at ultimate levelling with respect to nominal.

[3] The total number of bunches for operation at ultimate energy has yet to be confirmed due to a possible increase of the rise time of the MKD, as found from first estimates.

Table 2: Performance of the HL-LHC Baseline at the Nominal and Ultimate Beam Energies

Parameter	**Unit**	**7.0 TeV**		**7.5 TeV**	
		Nom.	**Ult.**	**Nom.**	**Ult.**
Turn-around time	min	145	150	150	155
Fill duration	h	8.5	5.3	8.7	5.5
Levelling time	h	7.3	3.5	7.5	3.7
Effective line PU density	mm^{-1}	0.79	1.20	0.83	1.26
Yearly integrated lumi.	fb^{-1}/160 days	261.5	325.3	261.1	324.4

tances at higher energy); the fill duration increases by around 11 min in both cases. Conservative and relaxed scenarios of machine availability yield to a reduction of $\mathcal{L}_{\text{int}}$ by up to 25 %, or its increase by around 13 %, respectively.

Regarding RMS luminous regions at 7.5 TeV, their magnitudes at both nominal and ultimate levelling shrink by 1 mm as a result of the reduction of the crabbing angle ($\theta_{\text{CC}} \approx 354\,\mu\text{rad}$ instead of 380 µrad) provided by the CCs at a higher energy. As a result, the peak pile-up densities increase in turn, reaching around $1.4\,\text{mm}^{-1}$ at the end of the levelling for the nominal case, and almost $2.1\,\text{mm}^{-1}$ for the ultimate operation. Similarly, $\bar{\rho}$ rises as well, with an increment of about 5 % for both levelling operations at the ultimate energy. Figure 1 shows the evolution of several parameters along the fill for the two different levelling scenarios at 7.0 TeV and 7.5 TeV for their comparison. The reduction of the RMS luminous regions, and in consequence the increase of $\bar{\rho}$, could be mitigated by considering a lower geometrical crossing angle, as previously discussed.

A possible optimization can be made by profiting of the smaller physical beam emittance at higher energy –that can allow a reduction of the aperture of the collimators (in mm)–, and a reduction of the crossing angle with the corresponding reduction of the minimum β^* [6]. The increase in performance –expected to be limited due to the operation in levelling mode– has yet to be evaluated. Another option is to increase β^* at the start of the levelling process. Similarly, $\mathcal{L}_{\text{int}}$ at ultimate energy is found to be pushed by the same ratios for both nominal and ultimate than those experienced by the corresponding cases at 7.0 TeV as a result of a potential reduction of 15 min of the TaT, as discussed at the end of the previous section. Performance estimates for the baseline at 7.5 TeV are almost identical to those at the nominal beam energy when $\sigma_{\text{b.o.}} = 81$ mb is assumed.

Absence of crab cavities

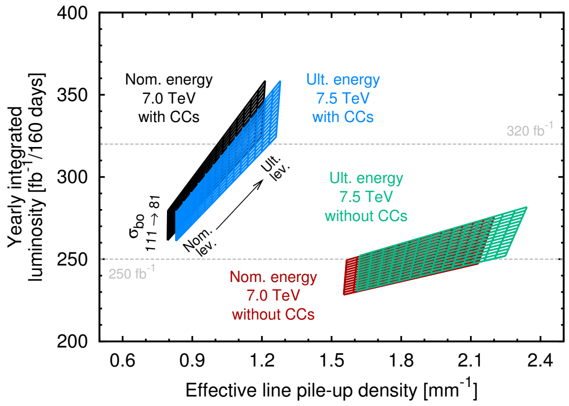

Figure 2: $\mathcal{L}_{\text{int}}$ and $\bar{\rho}$ for the HL-LHC baseline at nominal and ultimate beam energies. The corresponding cases without crab cavities (CCs) are also shown.

In the absence of crab cavities, $\mathcal{L}_{\text{int}}$ at 7.5 TeV is reduced by 12 % for the nominal levelling, and by 23 % for the ultimate case. These values are 1 % lower than those found for the two cases at 7.0 TeV when CCs are not present. Regarding $\bar{\rho}$, it goes from $1.55\,\text{mm}^{-1}$ to $1.61\,\text{mm}^{-1}$ for nominal levelling, and from $2.13\,\text{mm}^{-1}$ to $2.25\,\text{mm}^{-1}$ for ultimate operations, when CCs are absent. These figures represent a more challenging environment for the detectors, but do not necessarily constitute a serious impact. Therefore, the use of flat optics is mandatory in the event of CCs not being available (either due to delays in their installation, or proving not being operational for protons), in order to mitigate performance loss [16]. In this case, however, the implementation of compensation techniques of BBLR effects might be mandatory [17–19]. Operation with flat optics has not been demonstrated yet, and further studies are needed.

Figure 2 shows the performance in terms of $\mathcal{L}_{\text{int}}$ and $\bar{\rho}$ for the different cases discussed, as a function of the operational configuration (nominal or ultimate levelling) and $\sigma_{\text{b.o.}}$.

CONCLUSION

At the nominal beam energy of 7.0 TeV, the current HL-LHC baseline parameters allow the machine to reach and surpass the goals on $\mathcal{L}_{\text{int}}$ of $250\,\text{fb}^{-1}$ and $320\,\text{fb}^{-1}$, with levelling at $5.0 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ and $7.5 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$, respectively. Running the machine at the ultimate energy of 7.5 TeV provides a minimal gain of performance when the present TaT estimates of 145 min and 150 min are assumed. Taking into account the additional 5 min of TaT necessary for energy ramp, and ramp down of the magnets in the ultimate energy operation, leads in fact to a decrease –although almost negligible– of $\mathcal{L}_{\text{int}}$. It has to be noted that the same parameters without further optimization are assumed, but doing this is, in theory, possible. Turn-around times play a prominent role on the machine performance. In terms of $\bar{\rho}$, a small degradation is expected at 7.5 TeV due to reduced θ_{CC}.

Thanks to the higher energy –and therefore smaller physical emittance–, as well as the reduction of the beam-beam effects, the geometrical crossing angle could be reduced, leading to an increase of $\mathcal{L}_{\text{int}}$ and a reduction of $\bar{\rho}$. Optimization also can be performed from the point of view of the collimators. Studies on the feasibility of operation of machine components at 7.5 TeV, and their possible required upgrades are ongoing.

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