

PERFORMANCE AND OPERATIONAL ASPECTS OF HL-LHC SCENARIOS*

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Abstract

Several alternatives to the present HL-LHC baseline configuration have been proposed, aiming either to improve the potential performance, reduce its risks, or to provide options for addressing possible limitations or changes in its parameters. In this paper we review and compare the performance of the HL-LHC baseline and the main alternatives with the latest parameters set. The results are obtained using refined simulations of the evolution of the luminosity with β^* -levelling, for which new criteria have been introduced, such as improved calculation of the intrabeam scattering and the addition of penalty steps to take into account the necessary time to move between consecutive optics during the process. The features of the set of optics are discussed for the nominal baseline.

INTRODUCTION

The High Luminosity LHC (HL-LHC) is an approved upgrade of the LHC, aiming at the increase of the integrated luminosity to 250 fb^{-1} per year, enabling 3000 fb^{-1} over twelve years after the upgrade [1]. Reduction of β^* , increase of the bunch population, crab collisions, larger triplet aperture, and the implementation of additional radiation shielding, are some of the means to achieve this goal. In this paper we study, along the three configurations of the HL-LHC baseline, the main alternative scenarios: the 8b+4e filling scheme and the 200 MHz RF system –proposed for electron cloud suppression–, and two scenarios foreseeing the inability to use crab cavities.

The HL-LHC baseline assumes operation with β^* -levelling, which has been demonstrated at low intensity [2]. The simulations of the performance for a typical fill with a step-based β^* -levelling, allows the comparison among the alternatives in terms of integrated luminosity L_{int} . The levelled luminosity is taken such that the average number of events per bunch crossing (or pile-up μ) remains constant to 140. The beam intensity evolves taking into account the burn-off due to luminosity with a total cross-section of 111 mb, and the emittance evolution includes intrabeam scattering. The bunch length σ_z is kept constant for all scenarios (assuming longitudinal emittance blow-up), except for the 200 MHz scenario, for which σ_z is reduced by letting synchrotron radiation damp the longitudinal emittance. The peak pile-up density μ_{peak} is evaluated as the maximum density of events exactly at the interaction point (IP). The yearly integrated performance is computed assuming 160 days of operation

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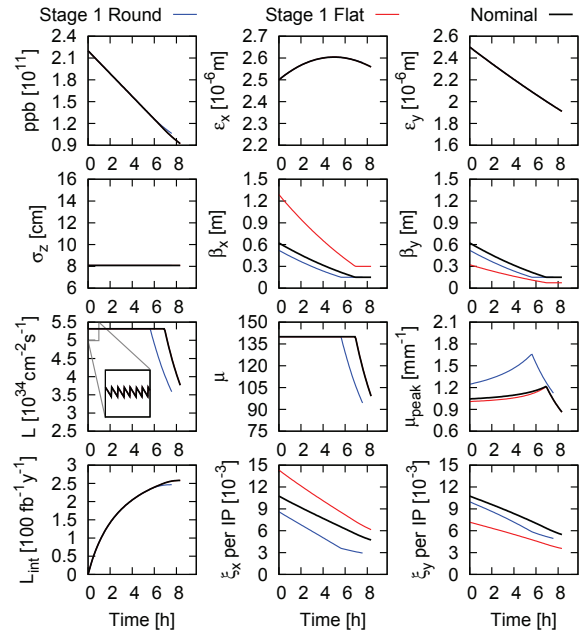


Figure 1: Performance of baseline scenarios. Both luminosity and pile-up exhibit a sawtooth-behavior, but only the peak values at each step have been plotted for clarity.

with a turn-around time of 3 h, 50 % efficiency¹, and all the fills are assumed to have the same length. This corresponds to the optimum fill length. [3, 4].

In the following section we present the results corresponding to a luminosity levelling with 2 %-steps, that is, a change to a new optics with reduced β^* is performed once the instantaneous luminosity has decayed to 98 % of the initial levelled luminosity. Results for different luminosity levelling values and the effect of penalty steps are presented in the subsequent sections.

LUMINOSITY LEVELLING WITH 2%-STEPS

Baseline Scenarios

In the first stage of the HL-LHC baseline (round optics with $\beta^* = 15 \text{ cm}$), we assume the number of crab cavities (CCs) to be limited to two per IP side and per beam, each with a voltage of 3.4 MV (for a maximum total voltage of 6.8 MV per IP side). The uncompensated crossing angle, together with the decrease of the vertical emittance due to synchrotron radiation damping along the fill, introduces an

¹ Defined as the fraction of time the machine spends in stable physics condition [1].

Table 1: Luminosity, Pile-up and Levelling Time of the HL-LHC Baseline and Selected Alternative Scenarios

Parameter	Unit	Baseline			8b+4e	200 MHz	No CC	
		Stage 1 Round	Stage 1 Flat	Nominal			No Wire	Wire
Virtual luminosity w/ CC	$10^{35} \text{cm}^{-2} \text{s}^{-1}$	1.37	1.89	1.89	1.68	1.09	-	-
Peak luminosity w/o CC	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	6.73	11.3	6.73	5.99	3.74	11.7	11.8
Integrated luminosity ^a	$\text{fb}^{-1} \text{y}^{-1}$	246.4	258.2	258.1	190.4	258.1	239.2	239.4
Pile-up w/o levelling w/o CC	events/crossing	177	309	177	220	99	309	311
Peak pile-up density	events/mm	1.66	1.21	1.21	1.21	1.23	1.92	1.44
Levelling time	h	5.64	6.97	6.97	7.87	6.97	4.94	4.94
Optimum fill length	h	7.57	8.35	8.35	9.10	8.35	7.25	7.24

^a For the optimum fill length.

asymmetry between IP1 and IP5 in the VH and HV crossing angle configurations, which yields lower L_{int} and larger μ_{peak} [5], with respect to the nominal baseline (round optics, crossing angle fully compensated by the CCs), as shown in Fig. 1. The ultimate HL-LHC configuration with levelled luminosity at $7.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ has not been studied.

An alternative scenario for the first stage is to use flat optics with β^* equal to 7.5 cm and 30 cm in the separation and crossing planes, respectively. Under certain conditions [6], a crossing angle of $400 \mu\text{rad}$ could be reached at the end of the fill, however this might require the implementation of a long-range beam-beam (LR-BB) compensation scheme. For flat optics, the levelling is performed keeping β_y^*/β_x^* constant. As shown in Fig. 1, the flat configuration (assuming a LR-BB compensation technique) improves the performance and approaches to the nominal in terms of L_{int} and μ_{peak} .

Scenarios for Electron Cloud Suppression

Electron cloud (e-cloud) effects could limit the performance of the machine [7]. In order to minimize these, two

configurations have been proposed, proving to highly suppress the formation of the e-clouds [3]. The 8b+4e filling scheme provides 30 % fewer bunches with larger bunch population (2.3×10^{11} particles per bunch or ppb) and lower emittance ($2.2 \mu\text{m}$) [8]. This yields to a lower peak luminosity at the same pile-up per crossing, and the yearly integrated luminosity is reduced by about 26 % as shown in Fig. 2.

The suppression of e-cloud effects in the dipoles can be also done with longer bunch length (20 cm) with a 200 MHz RF system [4]. This phenomenon is most critical at injection and energy ramp; once at flattop, levelling luminosity can be conducted with bunch length during the filling, finding a balance between e-cloud effects and luminosity production [5]. Longer bunches could be used if limitations in the SPS are overcome. The potential of the 200 MHz option can be increased further, but more research has to be done.

Figure 2 compares the nominal HL-LHC fill evolution to the 200 MHz alternative assuming 15 cm bunch length, which was found to mitigate the heat load for a secondary emission yield of 1.4. The reduction of the bunch length

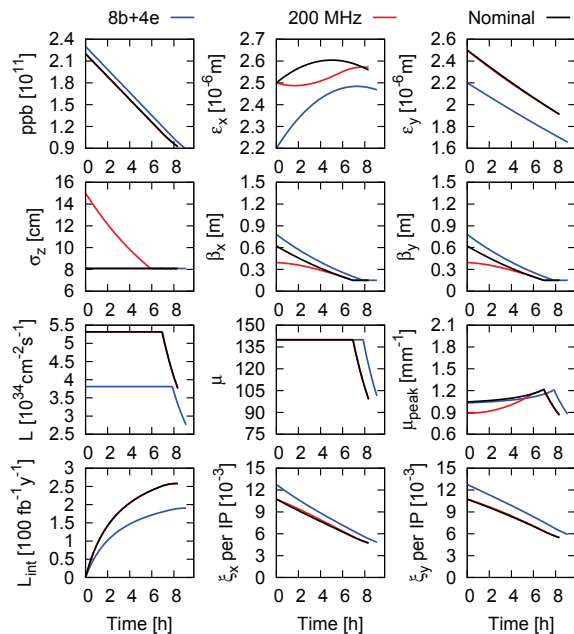


Figure 2: Performance of 8b+4e and 200 MHz scenarios.

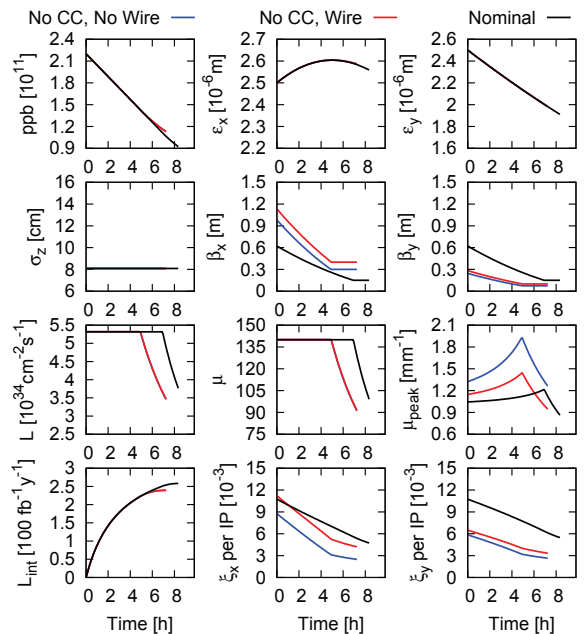


Figure 3: Performance of scenarios without crab cavities.

Table 2: Optics for Selected Luminosity Levelling Values

Parameter	Unit	1 %	2 %	5 %	10 %
Number of optics	-	136	68	27	14
Last levelling step	min	4.0	4.3	11.1	22.7

along the fill requires recapturing into the 400 MHz-system. For this scheme, the nominal performance is recovered; nevertheless, in the case that e-cloud effects do not allow the reduction of bunch length, an 8 %-loss of L_{int} is observed. Simulations at zero chromaticity have shown a decrease of the TMCI threshold to 2.6×10^{11} ppb. This value is above the foreseen operational bunch charge, however it is possible that multi-bunch effects slightly decrease this threshold bringing the operational bunch charge below the target [5].

Scenarios Without Crab Cavities

Crab cavities might prove not operational in the HL-LHC during SPS tests, or due to machine protection issues, crab cavity impedance, or emittance growth induced by RF phase noise. In this case, flat optics at the IP have to be used and current-bearing wires or electron beams for LR-BB compensation can reduce the crossing angle and therefore increase the luminous region. The configuration for the cases without [6] and with [9] wire compensation have been derived from simulations for a crossing angle of $400 \mu\text{rad}$ with $\beta^* = 30 \text{ cm}/7.5 \text{ cm}$, and for $280 \mu\text{rad}$ crossing angle with $\beta^* = 40 \text{ cm}/10 \text{ cm}$, respectively. Figure 3 shows the results in performance of these two scenarios. The absence of crab cavities reduces the nominal baseline performance by about 8 % with a considerably larger peak pile-up density of 1.92 events/mm. Reduction of the crossing angle by the LR-BB compensation mitigates the large peak pile-up to 1.44 events/mm but with a low impact on L_{int} .

Table 1 summarizes the luminosities, pile-up and levelling times for each of the scenarios afore described.

VARIATION OF LUMINOSITY LEVELLING AND PENALTY STEPS

So far we have only considered simulations for a luminosity levelling at 2 %. Table 2 shows the fast increase in the number of required optics as the luminosity levelling is reduced from 10 % to 1 % for the case of the nominal HL-LHC baseline. The length of the final levelling step² increases as the levelling step is increased. The number of optics and duration of the last optics are similar for all cases.

An additional effect that has to be taken into account is the necessary time to move from one optics to another throughout the levelling process, during which the instantaneous luminosity drops. This has been modelled as a penalty step with instantaneous luminosity equal to zero and with a duration of 3 s, a pessimistic assumption in view of results in [2].

² That is, the minimum time interval during which the optics is kept constant; it corresponds to the shortest optics just before the luminosity is left to freely decay until the filling time is reached.

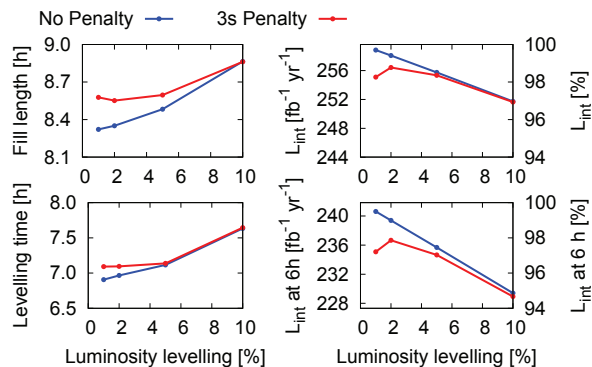


Figure 4: Effect of penalty on fill length, levelling time and integrated luminosity for different values of levelling.

The effect on the fill length, levelling time and integrated luminosities are compared in Fig. 4 for the nominal baseline. The luminosities are expressed in terms of the fraction with respect to the extrapolated value of L_{int} for a 0 %-step and without penalty. From these results, a luminosity levelling at 5 % seems to find a balance between a reduced number of optics (27, compared to 8 during the machine development in 2015), and a negligible reduction in integrated luminosity.

CONCLUSION

Studies of the performance of HL-LHC baseline and the main alternative scenarios have been reviewed with the latest parameters. New criteria, such as step-based luminosity levelling and lost time during the change in optics along the fill (in the form of penalties), have been introduced, allowing more realistic simulations. For the baseline in its first stage, the flat alternative restores the nominal performance lost with round optics and partial compensation of the crossing angle. The 200 MHz option not only provide a similar performance to the nominal, but has the advantage of reducing the effect of e-clouds too. The scenarios without crab cavities can be regarded as a backup for operation; they result in an 8 % performance drop provided one can accept 20 % or 60 % higher pile-up density, for the cases with and without wire compensation, respectively. For a configuration with equal pile-up density, the performance loss is of the order of 20 %. It has been realized that β^* -levelling will require a large number of optics for the HL-LHC. A 5%-step seems to be reasonable due to affordable number of optics, and with negligible reduction in the integrated luminosity. Simulations at pile-up of 200 events/mm, for which the effect of CCs on the performance is more pronounced, are ongoing.

Studies on beta-beating due to head-on and long-range beam-beam as function of bunch intensity, and for different optics for β^* -levelling, have been started for the LHC and will be extended to the HL-LHC. Exploration of means for the correction of this perturbation are in progress.

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