Latest Results on the Performance of HL-LHC Scenarios*

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What? *Review and comparison of the performance of the High Luminosity LHC (HL-LHC) baseline [1] and its main alternative scenarios: 8b+4e, 200MHz, and flat optics with and without crab cavities (CCs). This work is part of an update to the Technical Design Report.*

How? *Refined simulations of the evolution of the corresponding optimum fill, assuming a step-based β^*-levelling of the luminosity, demonstrated at low intensity [2].*

Introduction

The **HL-LHC** is an approved upgrade of the LHC aiming at the **increase** of the **integrated luminosity** (L_{int}) [1]. The simulation of an optimum fill follows a step-based **β^*-levelling**: a squeeze of β^* is performed whenever the luminosity drops below a given percentage of its original value. The **levelled luminosity** is taken such that the average number of events per bunch crossing or **pile-up (PU)** μ remains constant and equal to **140** (200 in the ultimate scenario). The **peak PU density** μ_{peak} is defined as the maximum density of events at the interaction point (IP); a limit of 1.3 events/mm is imposed to this parameter. The evolution of emittance takes into account **intrabeam scattering** (IBS) and a vertical growth of 40 h (observed in the LHC). The beam **intensity** is reduced due to burn-off with a total cross-section of 111 mb (81 mb inelastic, for PU). The estimation of the yearly L_{int} assumes 160 days of operation, a **turn-around** time of 3 h, and a 50% **efficiency** [3].

Luminosity levelling with 2%-steps

Baseline and flat scenario

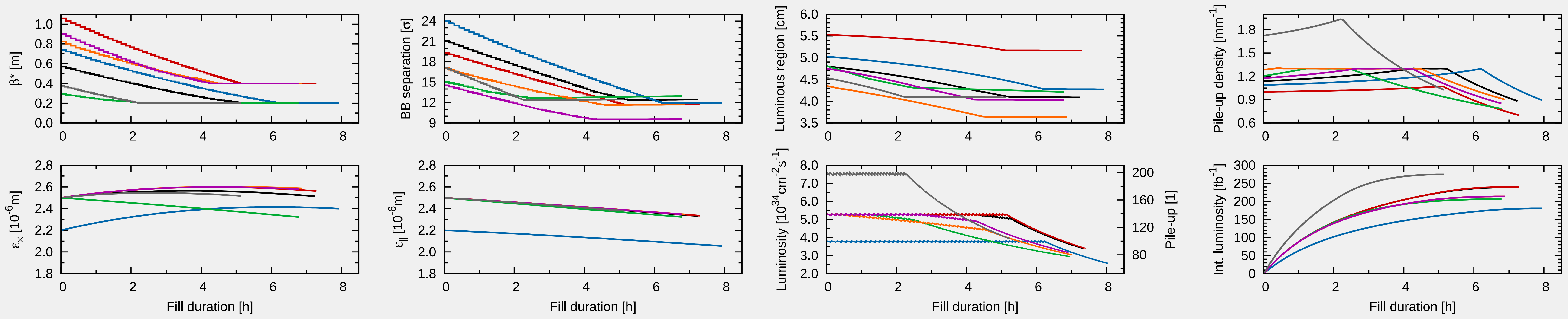
- **Baseline**: Round optics ($\beta^* = 20$ cm), 12.5σ beam separation.
- **Two CCs** per IP side per beam (2×3.4 MV), resulting in the partial compensation of the crossing angle.
- IBS growth times (at start of the fill): 18.8 h (horizontal), and 20.6 h (longitudinal).
- Integrated luminosity: **240 fb^{-1}**; optimum fill of 7.3 h.
- **Flat**: $\beta^* = 40$ cm/15 cm and 11.9σ –assuming a long-range beam-beam (LR-BB) compensation technique–; same performance with lower peak PU density.
- **Ultimate**: baseline optics with a levelling at 7.6×10^{34} cm^{-2}s^{-1} reaching **275 fb^{-1}** of integrated luminosity.

Scenarios for e-cloud suppression

- Two alternatives for **electron-cloud suppression** [4], with reduced performance.
- **8b+4e** filling scheme: fewer bunches with more particles per bunch and lower emittance [5], yields to lower peak luminosity at the same μ.
- 8b+4e reduces the integrated luminosity by 25%, but does not require limiting μ_{peak}.
- **200MHz:** Longer bunch length ($\sigma_z = 15$ cm) in a 200 MHz main RF system. Loss of performance is reduced to only 14%.
- Full potential of 200MHz to be explored.

Scenarios without CCs

- SPS tests, machine protection concerns, etc., might prove **CCs not being operational**; **flat** optics with $\beta^* = 40$ cm/15 cm) has to be used.
- Possibility to use current-bearing **wires** for LR-BB compensation.
- Beam separation: 11.9σ (without) [6] and 9.7σ (with) [7].
- The use of wires with **lower separation** leads to increased luminous region and higher integrated luminosity.



Effect of different levelling steps and penalties

Results on luminosity and pile-up for a levelling at 2% are summarized in **Table 1**. Every step performed during the levelling process represents a new optics. The necessary **time** to realign the beams after changing between consecutive optics has been modelled as **penalty steps** with a constant duration, during which the **instantaneous luminosity** drops to **zero**. The effect of such penalties on L_{int} is illustrated for the baseline in **Table 2** for different durations. In **Table 3**, different luminosity steps (between 1% and 10%) have been explored for the baseline; the **number of optics** increases rapidly as the luminosity steps are shorter, and the length of the shortest step (the last optics) decreases accordingly.

Parameter	**Unit**	**Baseline**	**Flat**	**8b+4e**	**200 MHz**	**No Wire**	**Wire**	**Ultimate**
Integrated luminosity	fb^{-1}	240	240	181	206	214	225	275
Peak pile-up density	evt./mm	1.30	1.07	1.30	1.30	1.31	1.30	1.94
Duration								
Optimum fill	h	7.3	7.3	7.9	6.8	6.9	6.8	5.1
In levelling	h	5.2	5.1	6.3	2.5	4.6	4.3	2.3
At peak PU limit	h	1.0	-	-	1.2	4.2	1.6	-^{a}
Without CCs								
Virtual luminosity	10^{34}cm^{-2}s^{-1}	6.5	9.0	5.8	3.7	9.0	10.0	6.5
Virtual pile-up	evt./cross.	172	237	213	98	237	263	172
With CCs								
Virtual luminosity	10^{34}cm^{-2}s^{-1}	12.6	13.1	11.6	6.8	-	-	12.6
Virtual pile-up	evt./cross.	333	345	428	178	-	-	333

Table 1

^{a} Unconstrained.

Penalty	**Int. lumi. [fb^{-1}]**	**Opt. fill [h]**
0 s	240	7.25
1 s	238	7.26
10 s	232	7.37
30 s	221	7.72

Table 2

Parameter	**Unit**	**Luminosity step**			
		1%	**2%**	**5%**	**10%**
Number of optics	-	94	47	20	10
Duration of last step	min	2.8	5.6	14.2	30.3
Int. luminosity	fb^{-1}	240	240	237	234

Table 3

Conclusion

Studies on the **performance** of the **HL-LHC baseline** and main **alternative scenarios** have been reviewed with the latest parameters. New criteria, such as a **step-based luminosity levelling** and **penalty** steps, have been introduced, allowing more **realistic simulations**. The baseline delivers a yearly integrated luminosity of 240 fb^{-1} with a peak PU density of 1.3 events/mm, a limit imposed by the main experiments. Alternatively, this performance can be reproduced with **flat optics** provided the same two CCs per IP side per beam are available. The **8b+4e** and **200 MHz** configurations result in a reduction of performance by 25% and 14%, respectively, although they have the significant advantage of **reducing** the effect of **electron-clouds**. The scenarios without CCs provide a backup for operation with little loss on performance at the same limit of μ_{peak}. The ultimate operation of the HL-LHC envisions an increase of 15% of integrated luminosity with respect to the baseline, at a challenging peak PU density. Operation with **β^*-levelling** will require a large number of optics; therefore a **5%**-step luminosity levelling seems **reasonable** in terms of their number, and the **negligible reduction** of L_{int}.

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[1] *"High-luminosity Large Hadron Collider (HL-LHC) Technical Design Report"*, edited by G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamot, and L. Rossi, CERN-2015-005. [2] **A. Gorzawski, D. Mirarchi, B. Salvachua, and J. Wenninger**, "MD 239 on collide and squeeze (part 2)", CERN-ACC-NOTE-2016-018. [3] **R. Tomás et al.**, "HL-LHC alternative scenarios", in *Proc. of Chamonix 2014 Workshop on LHC Performance*, CERN-2015-002. [4] **A. Axford, G. Iadarola, A. Romano, and G. Rumolo**, "Progress on electron cloud studies for HL-LHC", HL-LHC WP2 Task Leader Meeting, CERN, Geneva, Switzerland, Apr. 2015. [5] **H. Damerau et al.**, "LIU: Exploring alternative ideas", in *Proc. of RLIUP: Review of LHC and Injector Upgrade Plans*, CERN-2014-006. [6] **D. Banfi, J. Barranco, T. Pieloni, and A. Valishev**, "Beam-beam effects for round and flat optics: DA simulations", 4th Joint HiLumi LHC-LARP Annual Meeting, KEK, Japan, Nov. 2014. [7] **S. Fartoukh, A. Valishev, and D. Shatilov**, "An alternative High Luminosity LHC with flat optics and long-range beam-beam compensation", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, USA, May 2015.

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