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HL-LHC Status and operational scenarios

R. De Maria[a,*] **and R. Tomás**[a]

[a] *CERN,*
Geneva, Switzerland

E-mail: `riccardo.de.maria@cern.ch`, `rogelio.tomas@cern.ch`

This contribution presents the status of the HL-LHC project, the draft schedule and the associated operational scenarios. The contribution will focus on expected beam parameters, machine optics and cycles, and performance estimates. The research is supported by the HL-LHC project.

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[*] Speaker

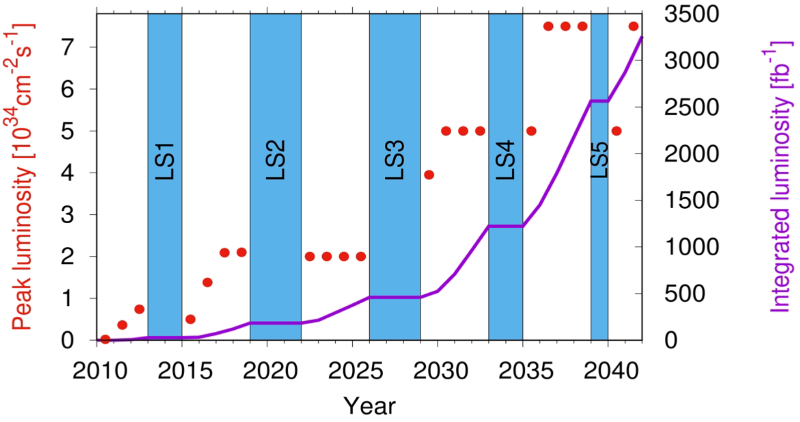

Figure 1: Potential HL-LHC schedule and proton performance for ATLAS and CMS. Heavy ion runs considered at the end of each year.

1. Schedule and performance reach

The High Luminosity LHC project (HL-LHC [1]) aims at increasing the peak luminosity (L_{peak}) of the ATLAS and CMS experiments to $5 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and at being able to level it for several hours (about 7) per fill. This allows to integrate about 250 fb^{-1} per year, enabling the goal of integrated luminosity ($L_{\text{integrated}}$) of 3000 fb^{-1} twelve years after the upgrade. This luminosity is more than ten times the integrated luminosity reach of the first 10 years of the LHC.

The HL-LHC engineering margins could allow the ultimate goal of $L_{\text{peak}} = 7.5 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and a total of $L_{\text{integrated}}$= 4000 fb^{-1}. The objective is to make sure that the accelerator will not limit the physics program. Figure 1 shows the LHC peak and integrated luminosities since 2010 and a potential schedule that could realize this goal.

The main means to obtain the integrated luminosity goals consists in increasing the maximum luminosity that the experiment and the machine can cope with, and increasing the levelling duration. This can be achieved by increasing the so-called virtual luminosity (L_{virtual}, that is, the theoretical maximum luminosity that could be delivered for an instant) and the number of protons per bunch (N_{ppb}).

Figure 2 shows the yearly integrated luminosity expected as a function of the peak luminosity that can be levelled and the total ideal duration of a physics fill for different scenarios [2]. The main assumptions are 80 days continuous successful fills to account for a realistic availability and 2.5 hours of turn-around time to account for the time to dump, ramp-down, inject and accelerate. Increasing L_{peak} gives a steeper increase in luminosity compared to the virtual luminosity, limited by the fact that levelled luminosity cannot exceed $5 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and the events per crossing cannot exceed 200 [3]. Table 1 shows the target HL-LHC parameters to obtain nominal performance [4] and a back-up scenario called 8b+4e that could be implemented if there are bunch current or energy consumption limitations [5]. Note that the minimum β^* in Run 4 is still limited to 0.2 m [4], while efforts are being made to allow reaching 0.15 m or even lower in flat optics configurations.

In addition to ATLAS and CMS, also LHCb plans an upgrade during HL-LHC to increase L_{peak} from $0.2 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ to $1.5 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$. Figure 3 shows the limited impact of the

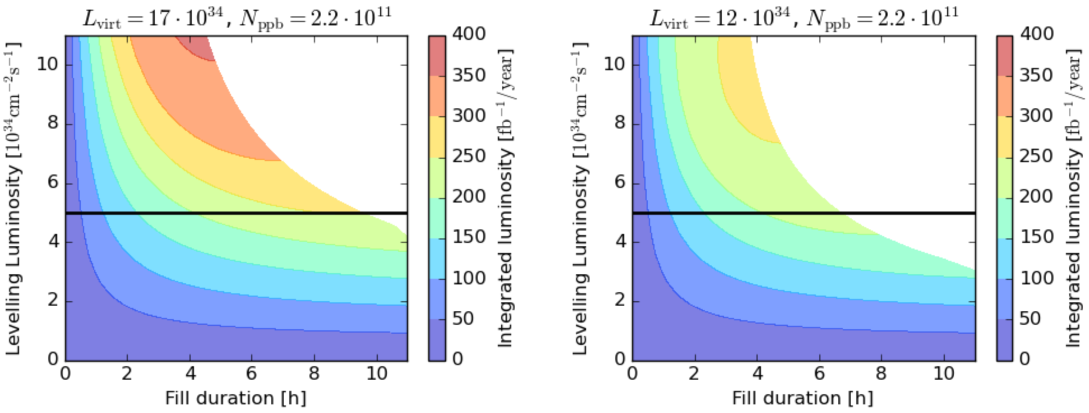

Figure 2: Potential performance reach as a function of levelled L_{peak} and levelling duration under different assumptions of virtual luminosity (L_{virtual}) and number of bunches N_{ppb} . The left plot shows the performance for the nominal HL-LHC parameters (left) and for the 8b+4e scenario (right). In the latter, an increase of the pile-up within the acceptable limit, together with a smaller $\beta^*$and flat optics, could increase $L_{\text{peak}}$and partially restore the luminosity of the nominal scenario.

Parameter	LHC Nominal	HL-LHC Nominal	HL-LHC 8b+4e
Beam energy in collision [TeV]	7	7	7
Particles per bunch, N_{ppb} [10^{11}]	1.15	2.2	2.2
Number of bunches per beam	2808	2760	1968
Number of collisions in IP1 and IP5	2808	2748	1960
Half-crossing angle in IP1 and IP5 [μrad]	142.5	250	250
Minimum β^*[m]	0.55	0.15	0.15
Normalized emittance ε_n[μm]	3.75	2.50	2.50
Beam–beam tune shift/IP [10^{-3}]	3.1	8.6	8.6
Virtual luminosity L_{virtual} [10^{34}cm^{-2}s^{-1}]	-	17.0	12.1
Levelled luminosity [10^{34}cm^{-2}s^{-1}]	-	5.0	5.0
Maximum events per crossing	27	131	182

Table 1: Main beam parameters for the present LHC, nominal HL-LHC and a n HL-LHC back-up scenario in case of electron cloud and/or the energy consumption could limit the beam current.

LHCb upgrade on ATLAS and CMS integrated luminosity, neglecting possible drawbacks from the increased beam-beam interaction in IP8 or from larger bunch-by-bunch variations [6].

2. Operational aspects

The main levelling technique for HL-LHC operation will be β^*-levelling. Crossing angle levelling may be needed to optimize beam lifetime and as a mean to reduce pile-up density. Separation levelling will be used in ALICE and LHCb and for fine adjustments in ATLAS and

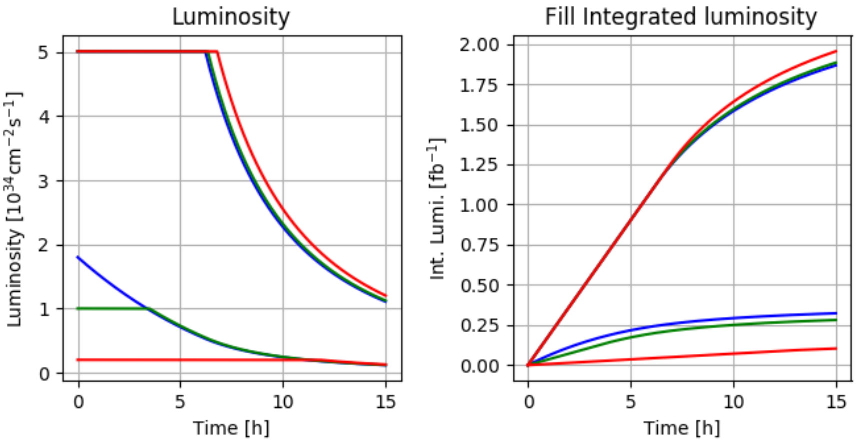

Figure 3: Impact of an upgrade of LHCb for Atlas and CMS. The lines represent different scenarios of LHCb acceptable peak luminosity $0.2 \cdot 10^{34}$cm^{-2}s^{-1} (red, present), $1 \cdot 10^{34}$cm^{-2}s^{-1} (green) $2 \cdot 10^{34}$cm^{-2}s^{-1} (blue).

CMS. Those techniques are already used successfully in LHC operation. Figure 4 shows an example of the HL-LHC cycle in the first operational run [4], with minimum β^*=0.2 m.

The layout of Point 1 and Point 5 allows establishing the beams' crossing plane either horizontally or vertically. The crab cavity type, deflecting horizontally (RFD) or vertically (DQW), has to be installed according to the crossing plane. A potential swap during the HL-LHC cycle is considered to reduce the dose damage from luminosity debris and increase the lifetime of the triplet. Luminosity performance with horizontal and vertical crossing angle planes is not necessarily equal. The nominal layout is built for vertical crossing in Point 5 because the forward physics CMS group prefers vertical crossing in Point 5 to increase acceptance. The dump kicker (MKD) introduces an aperture restriction in the horizontal plane, in particular in Point 5, and phase advance constraints between MKD and the triplets. Vertical crossing in Point 5 is also favorable for the so-called round optics, for which $\beta^*_{\text{crossing}} = \beta^*_{\text{non-crossing}}$ because the aperture bottleneck is in the crossing plane, but this is not the case for the flat optics.

Flat optics, for which $\beta^*_{\text{crossing}} > \beta^*_{\text{non-crossing}}$, is indeed considered as a means to increase the virtual luminosity. Flat optics have larger aperture margins in the crossing angle plane compared to round optics, therefore horizontal crossing would be the best choice in Point 5. However, it would conflict with the forward physics request. Long range beam-beam perturbations are comparably larger with flat optics than for round optics with the same crossing angle in units of beam divergence. Flat optics could be more sensitive to field imperfections in the triplet and the arc, and may be potentially limited by dynamic aperture rather than by physical aperture, to be confirmed by further studies. Flat optics, however, feature smaller beta function at the crab cavities in the crossing plane. This has the advantage to reduce the impedance of the crab cavity main mode, which has recently been found to be a concern for the nominal performance [8]. Flat optics, in addition, is very appealing in the case the crab cavities would not be operational because of the larger beam overlap at the interaction point compared to round optics without crab cavities. For all these reasons, flat optics will be further studied for its deployment in Run 4.

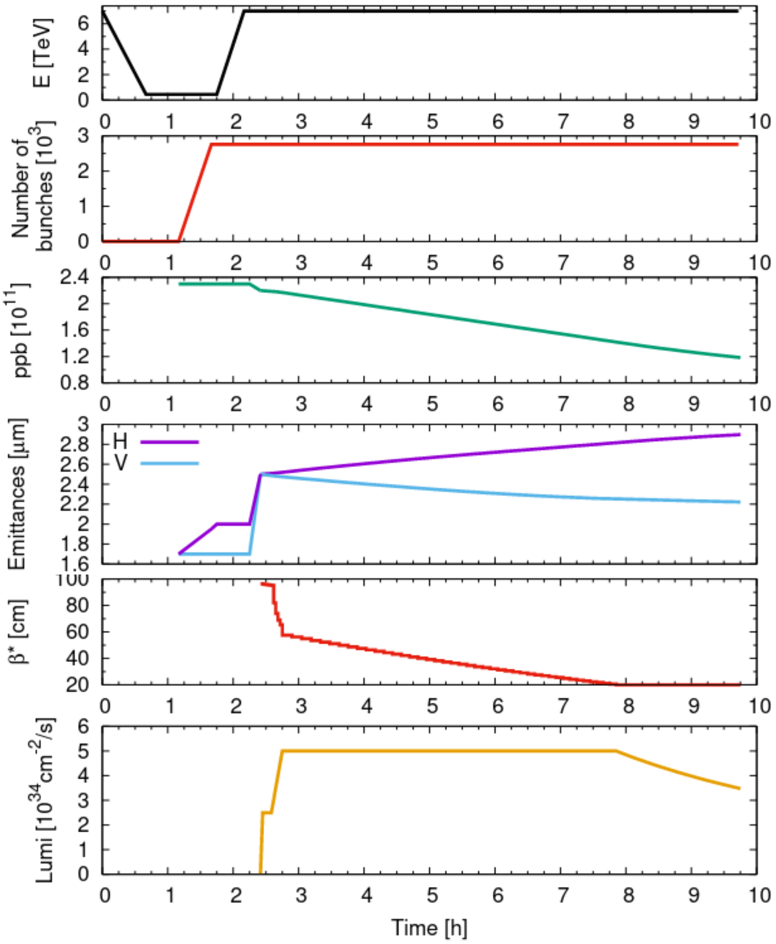

Figure 4: Evolution of key beam and machine parameters during a physics fill in the first HL-LHC Run. The first step in luminosity is due to the need to stabilize cryogenic conditions after the abrupt change of heat load due to collision debris [7].

Alignment in the long straight section around the interaction points is critically important for the HL-LHC. The inner tracker needs to be transversely centred to the interaction point (IP) within 0.5 mm for reducing radiation damage and improve tracks reconstruction. In addition, quadrupoles need to be centred around the reference orbit within 0.5 mm to remain within orbit corrector strength budget and reduce orbit distortions. Furthermore, crab cavities need to be transversely centred around the beam orbit within 1 mm to keep RF power within operational limits. Non-magnetic elements are also needed to preserve stay clear regions for the beam at low $\beta^*$and maintain effective shielding of protecting masks for superconducting magnets. The full remote alignment system (FRAS) [9], introduced in the HL-LHC, will be deployed to keep the straight sections well aligned and, potentially, allow to beam-based alignment to further reduce the impact of magnetic imperfections.

3. Outlook and conclusion

The HL-LHC project is transitioning from design to prototype validation of the new beam line elements. Civil engineering work is well underway. It was decided not to install 11T dipoles in the dispersion suppressor to insert a collimator (TCLD) [10] during LS2. A final assessment of the need was delayed until the middle of Run 3. In addition, the hollow electron lens for active halo control will not be available in Run 4, although the option of installing it after Run 4, which is outside the HL-LHC project, is still being pursued. Uncertainties on the beam intensity ramp-up from potential e-cloud limitations, excessive halo population, RF power limitations and the control of the crab cavity main mode impedance are the main challenges today.

References

[1] Editors: I. Béjar Alonso, O. Brüning, P. Fessia, M. Lamont, L. Rossi, L. Tavian, M. Zerlauth, "High-Luminosity Large Hadron Collider (HL–LHC): Technical design report", CERN Yellow Reports: Monographs, Vol. **10** (2020).

[2] G. Arduini *et al.*, " How to maximize the HL-LHC performance", in RLIUP: Review of LHC and Injector Upgrade Plans, pp.81-94, `https://cds.cern.ch/record/1977361`.

[3] X. Buffat, *et al.*, "HL-LHC Experiment Data Quality Working Group Summary Report", CERN-BE-2022-001.

[4] G. Arduini *et al.*, "HL–LHC Run 4 proton operational scenario", CERN-ACC-2022-0001.

[5] R. Tomás, *et al.*, "HL-LHC Alternative Scenarios", Vol. 2 (2015): Proceedings of the Chamonix 2014 Workshop on LHC Performance. CERN, Geneva. DOI: `https://doi.org/10.5170/CERN-2015-002.217`

[6] R. Tomás, *et al.*, "Burn-off with asymetric interaction points". In Proceedings of 12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil, ISBN: 978-3-95450-214-1 ISSN: 2673-5490. JACoW Publishing, 2021.

[7] S. Claudet, "Request for slow luminosity increase", 160th HiLumi WP2 Meeting, September 2019.

[8] L. Giacomel, *et al.*, "Main Results from Instabilities MDs and Simulation Studies", HL-LHC annual project meeting 2022, Sweden, Uppsala. `https://indico.cern.ch/event/1161569/contributions/4921657/attachments/2513438/4320977/Uppsala_Talk.pdf`

[9] A. Herty, *et al.*, "HL-LHC full remote alignment study", 10th International Particle Accelerator Conference, Melbourne, Australia, 19 - 24 May 2019, pp. THPGW057.

[10] "HL-LHC: Decision Management Non-installation of 11T in LS2", EDMS No. 2441244, 2021-01-10.