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OPERATIONAL SCENARIO OF FIRST HIGH LUMINOSITY LHC RUN

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Abstract

A new scenario for the first operational run of the High Luminoisty LHC (HL–LHC) era (Run 4) has recently been developed to accommodate a period of performance ramp-up to achieve an annual integrated luminosity close to the nominal HL–LHC design target. The operational scenario in terms of beam parameters and machine settings, as well as the different phases to reach optimal performance, are described here along with the impact of potential delays to key hardware components.

PREVIOUS OPERATIONAL SCENARIOS

The HL–LHC operational scenario for Run 4 has been developed in [1], considering changes to the hardware configuration and new findings in beam dynamics with respect to the previous scenario presented in [2]. However, very recent changes to the schedule and potential delays in the installation of key hardware components are motivating its revision. This section presents the operational scenario as in [1] while the potential new scenarios are presented in the second section as reported in [3]. The key changes between [2] and [1] follow:

Postponing the installation of sextupoles (MS10) in the dispersion suppressor to after Run 4[1] It has been verified [4, 5] that beam lifetime due to Dynamic Aperture (DA) without these sextupoles is acceptable for optics with $\beta^* \geq 20$ cm in the two main experimental interaction points, IP1 & IP5, which is the current assumption for Run 4. Figures 1 and 2 show the DA at the start of collisions ($\beta^* = 1$ m) and at the end of the luminosity levelling ($\beta^* = 20$ cm), respectively. Note that at $\beta^* = 15$ cm these sextupoles are mandatory [6].

Reducing the scope of the secondary collimator upgrade, with not all being replaced with low-impedance collimators[1] **[7]** This decision is driven by cost considerations, with the drawback of a small increase of the machine impedance. The low-impedance collimators are Molybdenum coated Molybdenum Carbide-Graphite composite collimators.

Increasing in the primary collimator gap from 6.7 σ to 8.5 σ at top energy To ensure beam stability during the collision adjustment process [8], the impedance of the collimation system is reduced by increasing the collimator gaps. Some key collimator settings are shown in Table 1.

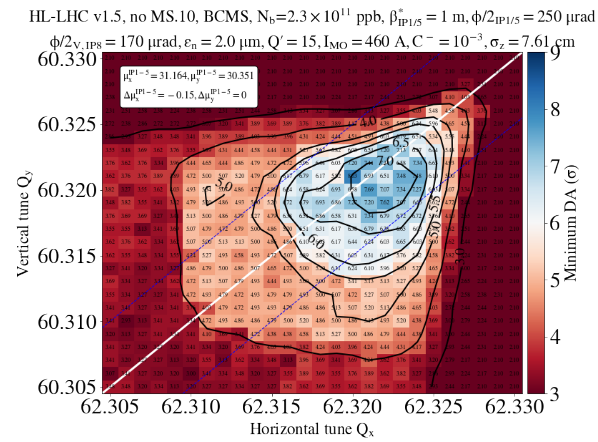

Figure 1: DA including beam-beam interactions at the end of the collision adjustment process versus horizontal and vertical tunes. An optimisation of the betatron phase between IP1 and 5 is applied as $\Delta\phi_x$=−0.15, $\Delta\phi_y$=0. A normalised emittance of 2 μm and bunch intensity of 2.3×10^{11} ppb are pessimistically considered to allow for brighter beams.

The increased gap has the advantage of reducing the halo density at the primary collimator.

Including Hollow Electron Lenses (HEL) in the HL–LHC baseline[1] [12] The HEL is an advanced tool for active control of the diffusion speed of halo particles, which will serve to mitigate losses from fast processes. Due to resources limitations the HEL will not be ready for Run 4.

Cancelling of the installation of 11 T dipoles in LS2 [10] Due to resources limitations Run 4 will happen without 11 T dipoles and associated new collimators in the IR7 dispersion suppressor [11].

The previous plan for the HL–LHC performance ramp-up allowed an integrated luminosity over 550 fb^{-1} at the end of Run 4. With 160 days of physics, the yearly integrated luminosity is expected to reach 240 fb^{-1}. In the first 1.5 years of Run 4, the bunch intensity is assumed to reproduce that of the Run 3, with minimum β^*=30 cm and full crossing angle of 450 μrad.

Figure 3 shows a schematic view of the Run 4 operational cycle including key beam parameters and expected luminosity. The abrupt jumps in bunch intensity and emittances during the collision adjustment process, just before

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[1] System under review for the new Run 4 scenario

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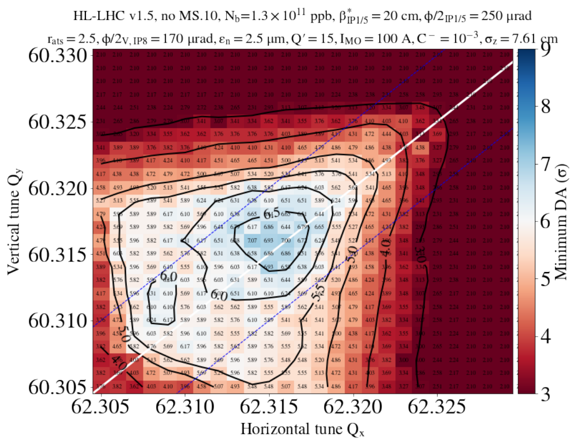

Figure 2: DA at the end of the luminosity levelling versus horizontal and vertical tunes including beam-beam interactions. Target DA is to reach 6σ above the upper blue line [9].

Table 1: Key Collimation Settings at 7 TeV for an Emittance of 2.5 μm and β^*=20 cm

Collimator	Gap [σ]
TCP/TCPM IR7	8.5
TCSPM/TCSG IR7	10.1
TCLA IR7	13.7
TCP IR3	17.7
TCSG IR3	21.3
TCSP IR6	11.1
TCT H4-V4-H6-V6 IR1&5	13.2
TCDQ IR6	11.1
TCL 4-5-6 IR1&5	16.4

2.5 h, correspond to the intensity loss and emittance growth budgets assigned to the interval between injection and the start of collisions. The slow horizontal emittance growth at injection is due to intra-beam scattering (IBS). No emittance growth from electron cloud, as observed in Run 2, is included in the model. The luminosity starts with a step to $2.5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ followed by a linear ramp to meet cryogenic requirements [13, 14]. The bunch intensity and emittance evolution during physics include burn-off, IBS, synchrotron radiation (SR) damping, and emittance growth from Crab Cavity (CC) noise. Emittance growth from luminosity burn-off has a 1% effect on the integrated luminosity of HL–LHC [15], and it is not included in this report.

THE NEW RUN 4 SCENARIO

Recently, it was decided to extend Run 3 by 1 year and the subsequent long shutdown (LS3) by half a year. This implies a delay of Run 4 by 1.5 years, starting in 2029 with a full-year of operation with about 90 days of physics instead of the 30 days in the previous scenario. Furthermore, it is assumed that Run 4 will last 4 full years (instead of the previous 3.5).

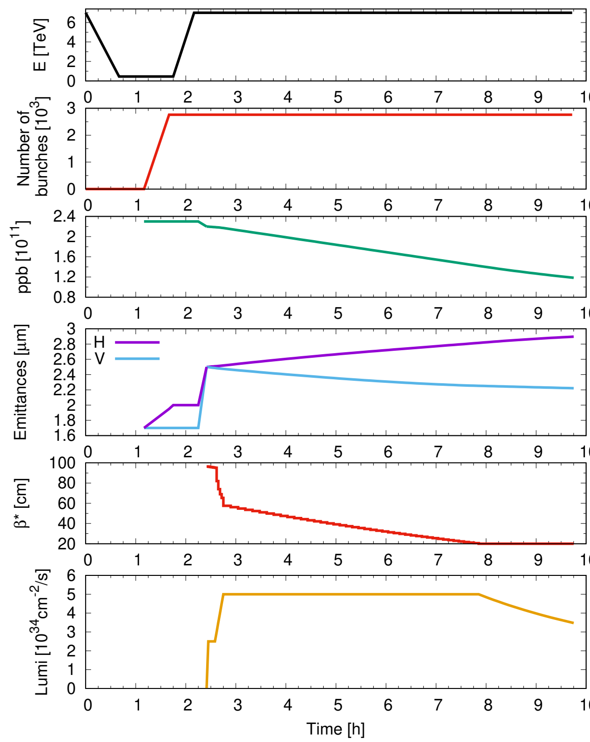

Figure 3: A schematic view of the Run 4 HL–LHC physics cycle showing magnetic cycle, number of bunches, protons per bunch (ppb), transverse emittances (BCMS beam case [9]), and luminosity (top to bottom) versus time until the beam dump.

At the moment of writing this report, the hardware configuration of HL–LHC is still being discussed due to the accumulated delays in some components and current political and economic uncertainties. In particular, the HEL is unlikely to be ready for the start of Run 4. The increase in collimator gaps by 1.8 σ represents an effective mitigation of potential halo issues, since the density of the halo close to the collimator jaws decreases significantly. The potential need for additional mitigation measures in Run 4, for example, to reduce the charge of the bunch, will need to be evaluated using dedicated measurements in Run 3. Beam experiments in Run 3 should also determine if the low impedance collimator upgrade should be carried out in full, or if a reduction in the number of upgraded units would be acceptable.

Assuming no limitations to the beam parameters in Run 4, the potential HL–LHC performance ramp-up is given in Fig. 4, allowing to integrate luminosity over 715 fb^{-1} during Run 4. This increase compared to the previous Run 4 scenario is a result of the 6 months longer run, the faster intensity ramp-up assumed (1 year instead of 1.5 years) and the slightly larger initial bunch intensity to match the updated Run 3 expectation of 1.8×10^{11} ppb [16]. The minimum β^* in Run 4 is tentatively kept to 20 cm but 15 cm is being considered, however requiring the installation of sextupoles in the dispersion suppressor regions.

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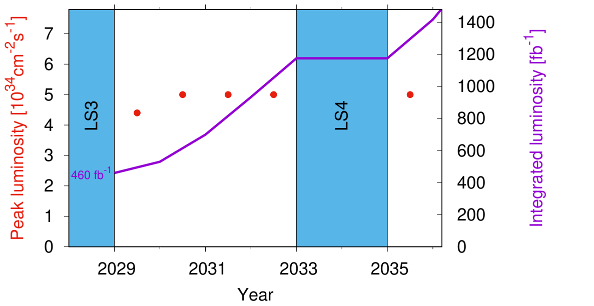

Figure 4: Peak and integrated luminosity during Run 4 (assuming 460 fb^{-1} by the end of Run 3).

THE FIRST YEARS OF OPERATION

The first years of operation of the HL–LHC are expected to take place at a minimum β^*=30 cm, without the use of CCs in physics and with a reduced bunch intensity of 1.8×10^{11} p. This allows reducing the crossing angle to about 450 μrad as validated with the DA simulations shown in Fig. 5. It is foreseen to steadily reduce the crossing angle during the physics fill as the bunch population decays to maximise performance and reduce the radiation dose to the triplet magnets [17].

The beam-based IR non-linear corrections are expected to require considerable commissioning time and iterations between the different magnet types [18, 19]. Therefore, it is assumed that optics commissioning in the first years will only include magnets up to the octupolar order, leaving the commissioning of the decapolar and dodecapolar correctors for the years with lower β^*. Simulations have confirmed that DA is sufficient at β^*=30 cm without decapolar and dodecapolar IR corrections [20]. Moreover, techniques to speed-up the optics commissioning including high-order corrections are being developed [21] and will require dedicated machine experiments in Run 3.

POTENTIAL INTENSITY LIMITATIONS

Bunch intensity could be limited in Run 4 due to the absence of the HEL or if RF voltage limitations are encountered at injection. To accommodate the expected larger longitudinal emittance at SPS extraction with 2.3 × 10^{11} ppb, between 8 and 8.8 MV is required [22], potentially exceeding the RF power capability of the current system with the half-detuning scheme. Acceptable capture losses, injection transients, SPS-LHC energy errors and line-by-line variations of the RF amplifiers may require additional margin. A minimum bunch intensity of 1.8 × 10^{11} ppb is estimated to be easily achievable. Further studies are ongoing to investigate the maximum bunch intensity feasible with the current RF system. If bunch charge is limited to 1.8×10^{11} ppb at injection, the optimal fill shortens by more than 2 hours and the levelling time by more than 3 hours with respect to the baseline shown in Fig. 3, and the β^*_{start} is reduced to 45 cm. Annual integrated luminosity (assuming 160 days) is reduced from 242 to 194 fb^{-1}, reducing the expected

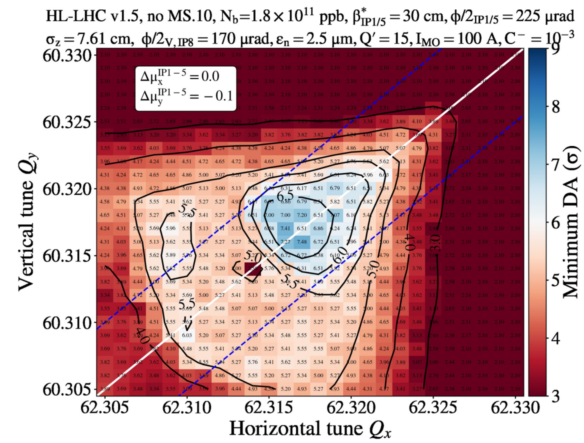

Figure 5: DA after the luminosity ramp-up (β^*=30 cm, full crossing angle of 450 μm and 1.8×10^{11} ppb) in the first years of operation versus horizontal and vertical tunes including beam-beam interactions and for optimised phase advance between IP1 and IP5.

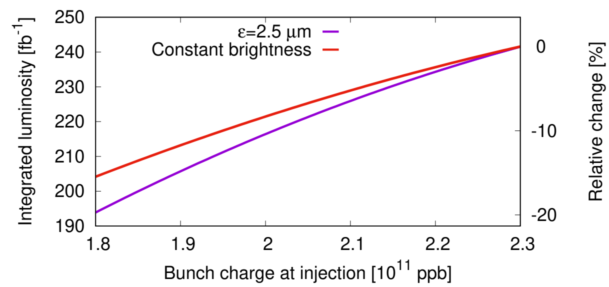

Figure 6: Annual integrated luminosity versus bunch charge at injection in Run 4 (assuming 160 days for physics).

Run 4 integrated luminosity by about 20% for the case with ϵ = 2.5 μm. Figure 6 shows the annual integrated luminosity versus bunch charge at injection in the range between 1.8×10^{11} ppb and 2.3×10^{11} ppb. Mitigation measures imply reducing β^* or the crossing angle. The first requires that the MS10 sextupoles are installed before Run 4 to guarantee sufficient lifetime. The latter requires that long-range beam-beam compensators [23], not yet in the baseline, are installed.

SUMMARY & OUTLOOK

The HL–LHC schedule, hardware configuration and operational scenario are continuously evolving. A new performance ramp-up has been proposed based on the previous scenario to reach the nominal performance of the HL–LHC. Nevertheless, there are important uncertainties in the hardware configuration that need to be clarified before this scenario can be confirmed.

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