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Refining the HL-LHC Operational Settings With Inputs From Dynamic Aperture Simulations: A Progress Report

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Abstract. Recent Dynamic Aperture (DA) simulations aimed at providing guidance for the latest updates of the operational scenario for the High Luminosity upgrade of the LHC. The impact of the increased chromaticity and octupole current has been assessed considering the latest updates of the optics. Additional means to improve the lifetime, such as tune optimization, have been identified and deployed. We also briefly discuss the impact of delivering high luminosity to the LHCb experiment.

1. Introduction

The High Luminosity LHC (HL-LHC) is an approved upgrade of the LHC, aiming at the increase of the integrated luminosity, enabling $3000\,\mathrm{fb}^{-1}$ over its lifetime [1]. To achieve this goal, the commissioning of the Achromatic Telescopic Squeeze (ATS) optics [2], together with the new triplet magnets will be capable to squeeze the beam to 15 cm in β^*. To counteract the reduction of the luminosity due to the larger crossing-angle, necessary to minimize the long range beam-beam effects, two crab-cavities per beam and side will be installed at the two high luminosity insertion regions.

The high beam intensity conditions, require estimations of the DA evolution to define the feasibility of the operational scenario and the achievable performance. In this paper, multi-parametric DA scans are employed to assess the impact of high values of chromaticity, Landau octupole current and the available tune space throughout the β^* leveling, in the presence of beam-beam effects. The scenario of providing LHCb with luminosity increased by a factor 5 will also be assessed.

2. Simulation Framework

The weak-strong approximation is used, tracking a single beam in the potential generated by the other, while the beam-beam lenses are static [3]. This simplification allows for faster tracking times, while still capturing the dynamics relevant for the DA determination of particles with action up to a few beam sizes, σ, without being influenced by the coherent motion of the beam core. The HL-LHC model is implemented in MADX [4], while tracking is done with SixTrack [5] using the SixDesk [6] environment.

Protons with initial amplitudes up to 10 σ are distributed in 5 angles, equally spaced in the positive quadrant of the configuration space and are tracked for 10^6 turns. The minimum DA over all combinations of amplitude-angle, expressed in units of the beam size, is used as the estimator. In the framework of our DA studies, the correlation between beam lifetime and simulated DA has been studied. A clear correlation [7] was observed, which provides the solid baseline for the requirement of 6 σ DA, in the case without magnetic field errors. Previous studies [8] were based on the considerations described in [9], featuring an empirical factor 2 between the simulated and the observed DA.

The 4 σ bunch length is assumed fixed at 1.2 ns, while the transverse emittances round and fixed at 2.5 µm. The momentum deviation is assumed constant at 2.7×10^{-4}. To suppress coherent instabilities, 15 units of chromaticity are provided in the ring, together with negatively powered octupoles, providing Landau damping and partially compensate the effect of the long range beam-beam interactions [10, 11]. The coupling is assumed adequately corrected [12].

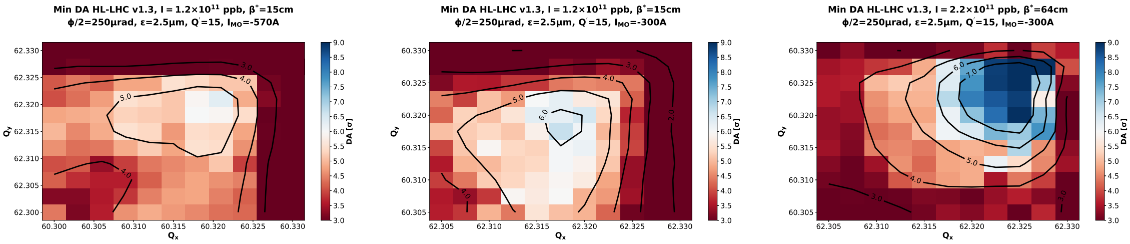
The collisions at the two high luminosity IRs (ATLAS, CMS) are taken as fully head-on. At the ALICE experiment (IR2), the beams are constantly separated by approximately 5 σ to lower the luminosity and keep it constant at $1 \times 10^{31}\,\mathrm{Hz\,cm^{-2}}$. On the other hand, the LHCb experiment (IR8) is leveled by separation to keep a constant luminosity of $0.2 \times 10^{34}\,\mathrm{Hz\,cm^{-2}}$ with a $\beta^* = 3\,\mathrm{m}$. An additional complexity is the dipole spectrometer magnet which is part of the LHCb experimental apparatus. Depending on its polarity, the so-called "internal" half-crossing angle varies by ±135 µrad from the nominal external of 250 µrad. Therefore, the impact of the long range beam-beam interactions, which is reciprocal to the beam-beam separation, varies with the dipole polarity. The results that follow assume the worst case scenario, having always a reduced crossing angle.

3. Beam Dynamics During Leveling

To achieve a constant nominal luminosity of $5 \times 10^{34}\,\mathrm{Hz\,cm^{-2}}$, the HL-LHC operation relies on the progressive squeezing of beams in the two high luminosity interaction points (IP). The leveling process starts with a beam intensity of 2.2×10^{11} protons per bunch (ppb) that decays naturally until $\sim 1.2 \times 10^{11}$ppb, where the target luminosity cannot be maintained further. During the leveling, the β^* is reduced from 64 cm to 15 cm. On the other hand, the half-crossing angle remains constant at 250 µrad.

While the additional magnetic elements (sextupole, octupole) suppress coherent instabilities, the non-linearities they introduce in the lattice reduce the DA. To balance this, a working point (WP) optimization is performed. In Figure 1, we investigate if 6 σ DA is achievable at 15 cm β^*, at the bunch population expected at the end of the leveling process, using different octupole current values. The black lines correspond to iso-DA contours. The option of fully powered octupoles at −570 A ($k_3 = 16.8\,\mathrm{m^{-4}}$) seems forbidden, as no available tune space is found. On the other hand, the option of −300 A ($k_3 = 8.8\,\mathrm{m^{-4}}$), corresponding to the minimum required for coherent stability [13], seems feasible after carefully selecting the WP. Adjusting the WP (62.315, 60.320), the end of leveling is reachable, but only a small margin of DA remains available for further optimizations.

Assuming that the lattice octupoles are kept constantly powered at −300 A during the leveling, we need to assess the available tune space at the start of the process. The results in Figure 1, suggest that the WP found to be optimal at the end of leveling is not the optimal at the start of the process. A new optimal WP is found at (62.320, 62.325). This means that the WP has to be varied during the leveling process to maintain the DA above 6 σ, while the bunch population is decreasing and the strength of the beam-beam kick changes. The start-of-leveling WP is found to be optimal until the bunch population reaches 1.6×10^{11}ppb, corresponding to 30 cm in β^*. From there, the WP corresponding to the end of leveling is more preferable in terms of DA. Therefore, precise tune control is crucial for the operation of HL-LHC, which should be



(a) (b) (c)

Figure 1: Tune scans for different octupole currents: (a) at the end of leveling (1.2×10^{11}ppb) with fully powered octupoles, (b) at the end of leveling with octupoles at -300 A, and (c) at the start of leveling (2.2×10^{11}ppb) with octupoles at -300 A.

feasible as seen at the LHC.

In order to define the beam parameters at the end of leveling, in Figure 2 we study the correlation of the crossing angle with the bunch intensity in terms of DA at the 15 cm β^* case. On top of the iso-DA lines, we overlay in red the iso-luminosity contours in units of 10^{34} Hz cm^{-2}. The 6 σ DA with a constant crossing angle of 250 µrad and target luminosity of 5×10^{34} Hz cm^{-2} can be maintained until the intensity drops to 1.22×10^{11}ppb. This translates into a total leveling time of 7.3 h, assuming a proton cross-section of 111 mb. The integrated luminosity reach is 1.5 fb^{-1} per fill.

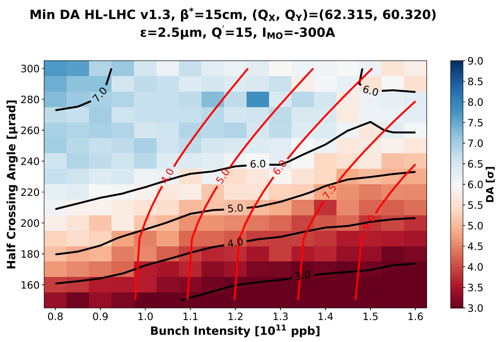


Figure 2: DA correlation of half crossing angle and bunch intensity towards the end of leveling.

The small available DA margin can be spent in reducing the crossing angle to boost performance. We can define a leveling path based on the DA estimations and the luminosity target, as described in [14], by adapting the crossing angle together with the β^*. Two DA scenarios can be assessed; one that requires DA of 6 σ ("adaptive 6 σ"), and one of 5 σ ("adaptive 5 σ") [14]. The leveling time remains almost unchanged for the adaptive 6 σ scenario, and only slightly longer for the 5 σ. The benefit of the adaptive leveling is the reduction of the crossing angle, which results in the elongation of the luminous region at the IP reducing the peak pile-up. Figure 3 compares the evolution of peak pile-up density between the constant crossing and the two adaptive crossing scenarios, including an anti-leveling process similar to the one described in [15] after the end of the leveling. A reduction at the level of 7 % is observed. Moreover, the adaptive scenarios reduce the crossing angle by 40-50 µrad on average. This also benefits the magnets at the IR that are responsible for the final focusing, which receive a reduced radiation dose from the proton debris by ∼10 % [16].

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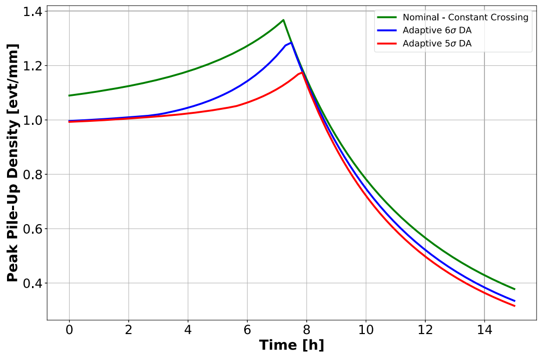

Figure 3: Evolution of peak pile-up density under the constant and the adaptive crossing scenarios.

Finally, the 6 σ DA target has been chosen to accommodate the uncertainty on the impact of magnetic field imperfections. To estimate this, DA simulations are performed assuming 60 different realizations of the machine. A statistical analysis is performed for 4 scenarios at the end of leveling (β^* =15 cm). The baseline and the two adaptive crossing angle scenarios are complemented with the ultimate luminosity HL-LHC scenario, which assumes leveled luminosity at 7.5×10^{34} Hz cm^{-2}. The result is shown in Figure 4. The average DA spread is found to be at the level of 0.3 σ. Therefore, the beam-beam interaction is the main DA degradation mechanism, while the magnetic imperfections only slightly affect the result.

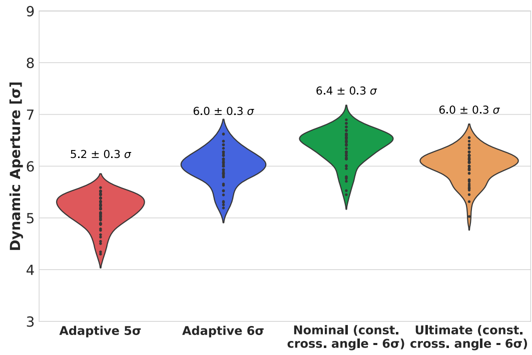

Figure 4: Statistical result of the impact of magnetic field imperfections in DA for four different scenarios at the end of leveling.

4. High-Luminosity LHCb

The collision scheme of the LHCb experiment was discussed in the previous section. The Phase-II upgrade of the detector, will enable the data taking at instantaneous luminosity 10 times higher than the current nominal. A scenario where IP8 is leveled to 1×10^{34} Hz cm^{-2} with a β^* of 1.5 m was studied, although it is not part of the HL-LHC baseline. While this configuration decreases the leveling time at the IP1/IP5 by 7 %, it has no significant impact on the DA, if the external half-crossing angle remains at 250 µrad.

To increase the performance margins, a reduction of the external crossing angle of IR8 can be performed. A reduction to 200 µrad has been found to have a negligible effect in the dynamics at the end of leveling. However, as shown in Figure 5, further reduction of the external crossing angle to 180 µrad and 150 µrad impacts the DA. Therefore, the configuration with half crossing angle of 200 µrad seems acceptable, since it is almost transparent, in terms of DA, to the dynamics of the whole ring. Under this scheme, LHCb can keep a constant luminosity of $1 \times 10^{34}\,\mathrm{Hz\,cm^{-2}}$, by transversely separating the two beams, for 4.7 h, if the internal crossing angle is subtracted from the external one. With the reverse polarity of the spectrometer, the leveling time is reduced to 3.1 h. Therefore, while in terms of DA the polarity which increases the total crossing angle in IR8 is preferred, it also reduces the integrated luminosity delivered to the experiment.

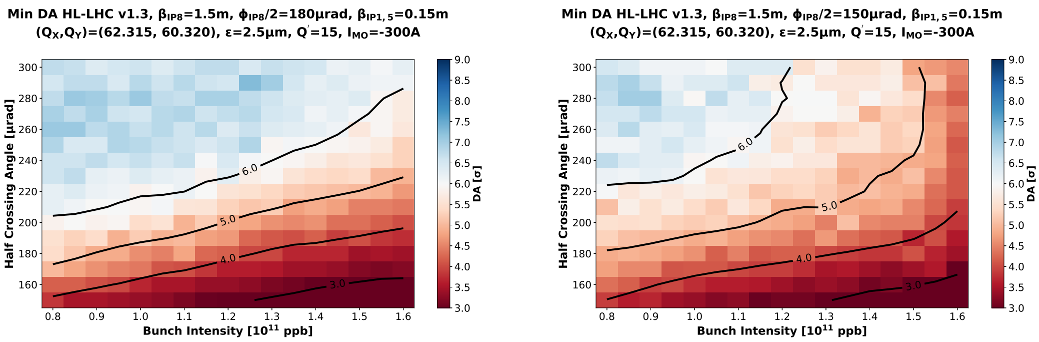

Figure 5: The effect of reduced crossing angle in IR8 for 180 µrad (left) and 150 µrad (right), for the spectrometer polarity that reduces the total crossing angle.

5. Conclusion

The latest operational scenario of HL-LHC was validated in terms of DA, deploying an optimized WP, which partially mitigates the effect of the additional non-linearities. The adaptive crossing angle leveling improves pile-up and triplet irradiation conditions. Finally, preliminary beam-beam studies on a scenario with increased luminosity at IP8, not yet in the HL-LHC baseline, have been conducted and have not evidenced any show-stopper so far in terms of DA.

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