DYNAMIC APERTURE STUDIES FOR THE FIRST RUN OF HIGH LUMINOSITY LHC*

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Abstract

Dynamic Aperture (DA) studies based on single-particle tracking simulations have proven to be a powerful tool for optimizing the performance of the Large Hadron Collider (LHC), as well as its future High-Luminosity upgrade (HL-LHC). The present paper presents the studies performed for the HL-LHC that are essential for its optimal overall operation. The main focus lies on the exploration of new optics scenarios such as flat optics, where the transverse beam sizes at the high-luminosity interactions points are not equal. Multi-parametric DA studies are deployed to derive the best parameters for operation during one of the most critical stages of collisions, the end of the luminosity leveling.

INTRODUCTION

In the so-called flat optics scenario of the High-Luminosity Large Hadron Collider (HL-LHC), the β-functions at the Interaction Points (IPs) of the two high-luminosity experiments, ATLAS and CMS, are optimized to create asymmetric transverse beam sizes. Initially proposed for the LHC [1, 2] and as an alternative HL-LHC scenario without crab cavities [3, 4], reducing the β-function in the non-crossing plane allows the virtual luminosity to be increased, even with crab cavities [5]. In addition to its performance benefits, flat optics can also help to mitigate other issues such as beam instabilities [6]. The flat optics can thus play a critical role in achieving the ambitious performance goals of the High-Luminosity Large Hadron Collider (HL-LHC), which aims to increase the integrated luminosity of the collider by a factor of 10 [7]. As such, the flat optics are being carefully scrutinized for the operational scenarios of the HL-LHC [8].

In addition to the optics, other beam and machine parameters have a crucial impact on the single particle beam dynamics. To optimize the HL-LHC's performance, single particle tracking simulations are employed to select the best configuration for operation. These simulations are performed with Xsuite, a new tracking tool developed at CERN consisting of a collection of Python packages, which includes strong, non-linear fields such as those coming from beam-beam interactions [9]. The main goal of these simulations is to evaluate the Dynamic Aperture (DA), which is a figure of merit that reflects the single particle stability of the beam. Such DA studies have been extensively and successfully used in the past for round optics [10–12] and the DA simulation framework has been described in [13]. In the present paper, the studies focus on flat optics and the DA sensitivity to various parameters. A DA larger than 6 σ has been established as sufficient for maintaining a satisfactory beam lifetime during LHC operation [14]. Additionally, a tune split, namely the difference between the fractional part of the horizontal and vertical tune, of at least 5×10^{-3} is required for good coupling control and to prevent beam instabilities.

During collisions the luminosity is leveled, i.e. the β-functions are gradually reduced in steps to restore the luminosity decrease due to the beam intensity decay from the inelastic scattering of protons. The studies focus on one of the most critical phases of beam collisions, the end of the luminosity leveling, when the β-functions reach their minimum values of 7.5 cm and 18 cm. The sensitivity of the DA at this stage of collisions to various parameters such as the working point, bunch intensity, chromaticity, crossing angle in ATLAS/CMS and octupole current are presented. The DA variations for the different bunches in the filling scheme are also discussed.

DA SENSITIVITY STUDIES

The dependence of the DA on different parameters is studied for the flat optics configuration. In the HL-LHC era, increased bunch intensities will be available from the injectors thanks to the LHC injectors upgrade project [15]. However, the higher bunch intensity combined with the degradation of the beam screen surface observed during the long shut downs will result in excessive heat load due to electron cloud build-up, which inhibits the use of the nominal 25 ns filling scheme [16]. Instead, alternative filling schemes such as the so-called 8b4e scheme may be employed, which consists of a sequence of 8 bunches and 4 empty slots. The filling scheme determines the number of long-range beam-beam encounters that affect each bunch, making it a critical parameter in the study. To ensure a realistic representation of the beam-beam effects, the 8b4e filling scheme is used in the simulations, an approach that is feasible thanks to the newly developed tracking tools [9]. Specifically, a bunch colliding head-on in all experiments and with the maximum number of long-range encounters is selected for analysis.

A set of simulations is performed for different working points (Q_x, Q_y) as shown in Fig. 1, where the resulting DA is indicated by the color code. The white diagonal line and the blue lines at a distance of 5×10^{-3} from the diagonal are also illustrated, along with the target DA limit of 6 σ represented in green. For a chromaticity of 5 (top), the DA target is easily reached for several working points. However, for a chromaticity of 15 (bottom), which may be necessary

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to stabilize the beam from coherent instabilities, the DA target is achieved for only a few working points. This comparison demonstrates the important sensitivity of the DA to chromaticity.

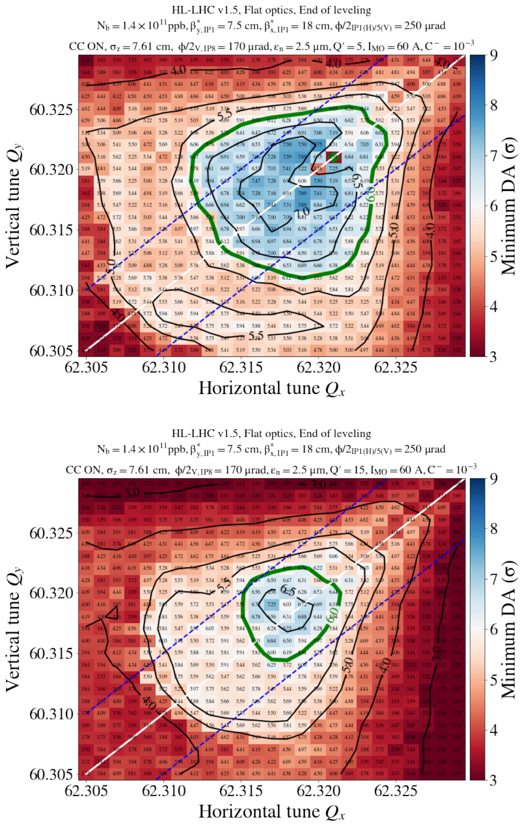

Figure 1: The color coded DA for a chromaticity of 5 (top) and 15 (bottom) as a function of the horizontal tune Q_x and vertical tune Q_y. The diagonal (white line) and the distance of 5×10^{-3} from the diagonal (blue lines) are also illustrated as well as the 6 σ DA target (green).

The bunch intensity at the end of the luminosity leveling stage is another crucial factor as it determines the strength of beam-beam interactions. Figure 2 shows the DA sensitivity to the bunch intensity for a series of working points, with a chromaticity of 5 and 15. It is estimated that at this stage of collisions, the bunch intensity will be around 1.4×10^{11} protons [17], which results in an acceptable DA for a chromaticity of 5. However, when operating with a chromaticity of 15, the same bunch intensity leads to an unacceptable DA.

In addition to chromaticity control, Landau octupoles are used to stabilize the beam by introducing amplitude detuning. These octupoles can also be used to compensate for long-range beam-beam tune spread when powered with negative current polarity [18]. Figure 3 shows the DA evolution as a function of the octupole current for a scan in working points and for a chromaticity of 5 and 15. The blue vertical lines represent a current of 0 A and 60 A, which is the value currently considered for the HL-LHC operational scenario, as it introduces the required detuning to stabilize the beam for the flat optics under consideration. The results indicate that there is a significant improvement in the DA when moving to negative octupole polarity thanks to the compensation of the long-range beam-beam effects. Even with a chromaticity of 15, the DA target can be easily reached with octupole currents down to −250 A. This observation suggests that switching the octupole polarity is a powerful tool that is beneficial for the beam lifetime in operation.

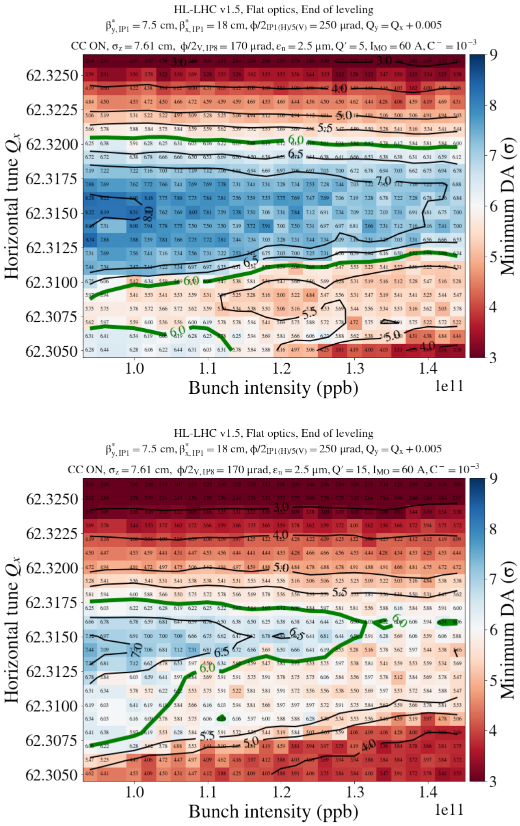

Figure 2: Sensitivity of DA on the bunch intensity for various values of the horizontal tune Q_x with $Q_y = Q_x + 5 \times 10^{-3}$, with a chromaticity of 5 (top) and 15 (bottom).

An alternative approach to reduce the impact from beam-beam effects is to increase the crossing angle between the beams. It must be noted, however, that the maximum crossing angle is limited by the collider's aperture and the strength of the orbit correctors. In the HL-LHC case, it is possible to increase the crossing angle from 500 μrad to a maximum of 590 μrad. However, as shown in Fig. 4, this limited range of crossing angle flexibility did not result in any significant improvement in the DA. These findings suggest that increasing the crossing angle within the constraints imposed by the collider's limitations may not be sufficient to optimize the beam performance. Instead, approaches such as optimizing the working points, reducing chromaticity, and reversing octupole polarity may be more promising for flat optics and the feasibility of such approaches will be explored experimentally in future studies.

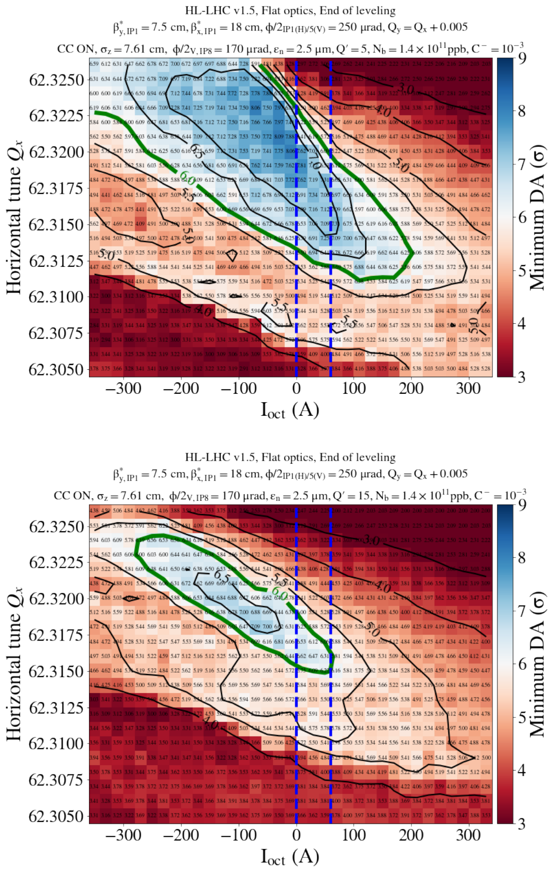

Figure 3: The color coded DA for a chromaticity of 5 (top) and 15 (bottom) as a function of the Landau octupole current and horizontal tune Q_x (with $Q_y = Q_x + 5 \times 10^{-3}$).

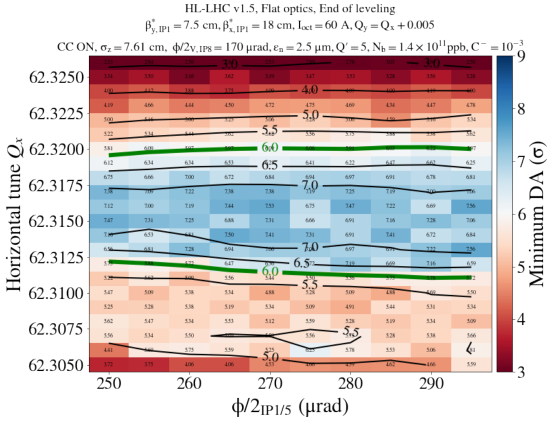

Figure 4: The color coded DA for a chromaticity of 5 (top) and 15 (bottom) as a function of the half crossing angle in ATLAS/CMS and the horizontal tune Q_x (with $Q_y = Q_x + 5 \times 10^{-3}$).

BUNCH-BY-BUNCH DA VARIATIONS

The previous simulations were performed considering the beam-beam encounters of a specific bunch. However, the impact of beam-beam effects varies depending on the number of long-range interactions and the previous conclusions cannot be generalized for all bunches in the filling scheme. On the contrary, bunch-by-bunch DA variations are expected. Their effect has also been observed experimentally through the measurement of proton losses in the LHC. Figure 5 (top) shows the DA for the first 3000 bunch slots, with the selected bunch for DA analysis of the previous section highlighted in green. A specific optimized working point is selected for the analysis (Q_x, Q_y=62.316, 60.321). In each study, the exact number of beam-beam encounters is considered for each bunch. The number of long-range encounters (bottom) in ATLAS/CMS (red) and LHCb (blue) are also illustrated. The results of the analysis indicate that the selected bunch does not result in the worst DA among all the bunches. Nevertheless, it is important to note that the spread of the bunch-by-bunch DA variations is limited to 0.5 σ, compatible with the statistical noise of the analysis.

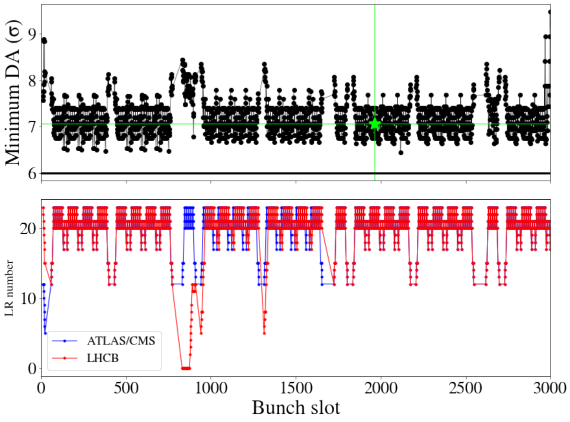

Figure 5: Bunch-by-bunch DA variations (top) and the number of long range interactions (bottom) in ATLAS/CMS (blue) and LHCb (red). The bunch selected for the DA sensitivity studies is marked in green.

CONCLUSIONS

In the present paper, a DA framework using the new tracking tool, Xsuite, was employed to provide insights into the selection of the best beam and machine parameters for for flat optics in the HL-LHC era. Operating with optimized working points, reducing chromaticity and reversing octupole polarity at the end of the luminosity leveling have been found to be the most promising approaches to enhance the collider's performance, while increasing the crossing angle in the limited range imposed by the accelerator's constraints has little effect. Overall, the findings from this study provide valuable insights into the impact of beam-beam effects on the DA, and thus the beam lifetime, and illustrate methods to improve performance through DA scans. This approach that can be generalized to other accelerators. Further research in these areas will be critical to ensure optimal performance for the experiments in the HL-LHC era.

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