MULTIPARAMETRIC RESPONSE OF THE HL-LHC DYNAMIC APERTURE IN PRESENCE OF BEAM-BEAM EFFECTS

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Abstract

We performed extended simulations of HL-LHC dynamic aperture in the presence of beam-beam effects in the weak-strong approximation, evaluating the contributions of parameters such as: bunch intensity, crossing angle, chromaticity, current in the Landau octupoles and multipole errors.

From the beam dynamics point of view, the main difference between the LHC (until 2017) and the HL-LHC is the deployment of the achromatic telescopic squeezing (ATS) optics, allowing not only for a smaller β^* reach, but also modifying the phase advances between the lattice correctors (sextupoles, octupoles) and the main IPs, and increasing the peak β functions in the arcs [1]. These correctors become therefore more efficient for the chromatic correction, but also a mitigation of the beam-beam long range interactions using the Landau octupoles is enabled, resulting in a possible reduction of the normalised crossing angle.

The limits have been investigated in a tracking simulation campaign aimed at exploring the operational space for the HL-LHC and two possible options for luminosity levelling.

INTRODUCTION

The High Luminosity LHC (HL-LHC) is an approved upgrade of the LHC, aiming at the increase of the integrated luminosity to 250 fb^{-1} per year, enabling 3000 fb^{-1} over its lifetime [2]. This goal will be achieved through an upgrade of the high luminosity insertion regions allowing to reduce β^* and to implement crab crossing to counteract the reduction of the luminosity due to the large crossing angle, required to minimize long range beam-beam effects. In addition, the brightness of the beams delivered by the injectors will be increased by almost a factor of 3. The β^* levelling will be used to maintain the instantaneous luminosity at 5×10^{34} Hz cm^{-2}, so to keep the event pile-up to acceptable levels for the experiments.

Precise indications of the dynamic aperture (DA) evolution can be used to define the operational scenarios and the achievable performance. Multi-parametric DA scans have been proven to be a valuable technique for the prediction of the LHC margins for performance tuning [3]. The studies have therefore been extended to the HL-LHC in an exploratory campaign aimed at qualifying better margins and the potential performance reach of the machine. These estimations follow from our current knowledge of the LHC, extrapolated to the HL-LHC, and aim at identifying possible means to improve the performance of the baseline scenario, whose latest review can be found in [4].

In this paper, we present the impact of the settings of chromaticity and Landau octupoles, a detailed proposal for the simultaneous evolution of β^* and crossing angle during the luminosity levelling and the first estimate of the impact of magnetic errors in presence of beam-beam effects.

SIMULATION FRAMEWORK AND SETTINGS

The simulations are performed in a weak-strong approximation in which only a single beam is tracked and the beam-beam lenses (both for the head-on and long-range interactions) are static. This simplification allows for a relevant speed up and applies well to the particles with an action of some sigmas, whose dynamics is relevant for the determination of the DA and is not much influenced by the coherent motion of the beam core. We rely on the MADX [5], SixTrack [6], SixDesk [7] environment commonly used at CERN.

We consider the minimum value of DA determined over 1×10^6 turns for 5 angles equally spaced in the positive quadrant of the configuration space. Although the statistics may appear limited, the fine granularity of the parametric scans compensate for it, proving to be adequate in most of the cases. The studies are performed with the HL-LHC optics v1.2 [8] and are focussed on Beam1.

In order to perform the estimations of the intensity decay, we adopt an inelastic cross section of 81 mb at 7 TeV, in contrast with the total cross section of 111 mb used in [4]. Indeed, the current observations in the LHC indicate that this could be achieved [9], provided that other sources of beam losses are understood and controlled in HL-LHC. The 4 σ bunch-length is fixed at 1.2 ns. Concerning the emittance we consider a "round-beam" scenario with constant normalised emittances of 2.5 μrad, and a second scenario in which synchrotron radiation, intra-beam scattering and elastic scattering at the IPs, result in a reduction of emittance mainly in the vertical plane [9]. As additional sources of emittance blowup are observed in the LHC, we consider the "round-beam" scenario as more realistic.

CHROMATICITY-OCTUPOLE SCANS

The settings of chromaticity and Landau octupoles play a crucial role in guaranteeing the stability of the beam in presence of collective effects such as e-cloud and wakefields. However these settings have also a severe impact on the DA, potentially reducing the beam lifetime.

Chromaticity-octupole scans allow to identify sharp DA transitions and help in the selection of the working point. Figure 1 presents an example for the beam parameters at the end of levelling, including all the interaction regions. The divergent colour scale is used to mark the areas of good DA (blue) and of potentially unacceptable DA (red), with the transition taking place at the target DA of 6 σ. It can be noted

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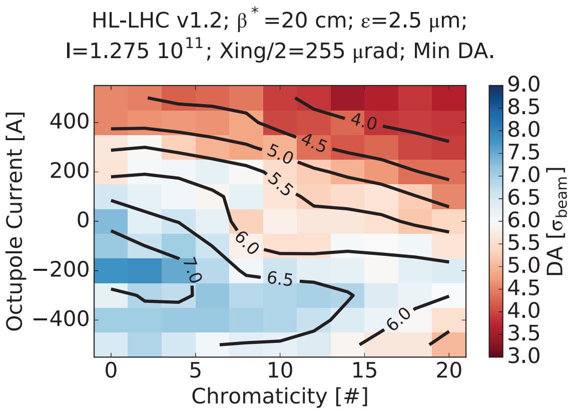

Figure 1: DA response to octupoles and chromaticity for the nominal crossing angle of 510 µrad and end-of-levelling settings with head-on collisions in LHCb and 5 σ separated beams in Alice. The negative setting for octupoles improves the DA, allowing for a larger chromaticity and/or reduced crossing angle.

that negative octupoles are much more favourable for the HL-LHC. In addition the detrimental effect of chromaticity is highlighted: in case it will be possible to reduce it (by means of enhanced feedback systems or suppression of the e-cloud), some additional margin can be obtained [10].

BEAM DYNAMICS IN THE LEVELLING PROCESS

We have investigated both the nominal levelling scenario, relying on the progressive reduction of β^* in IP1 and IP5, and an alternative based on beam separation. DA-related studies show that both the levelling techniques are possible [11], but we chose to focus here on the levelling with β^* which is the current baseline.

The possibility to adjust the crossing angle during the fill is also considered in order to contain the requirements on the maximum crabbing angle, now limited to ~350 µrad, which is the maximum achievable with two crab cavities per beam per IP side without specific optics optimisations [8].

With two degrees of freedom: β^* and crossing angle; two constraints are needed: the target luminosity and the minimum DA; the first is obtained from numerical integration based on the techniques presented in [12], while the latter is obtained from tracking simulations. The intersections of the iso-luminosity with the iso-DA curves, computed for decreasing beam intensities, allow reconstructing the time evolution of the operational parameters during the levelling process. In addition, other observables such as the peak pile-up density and the length of the luminous region, which benefit from operating with large β^* and small crossing angle, are automatically optimised.

In terms of DA requirements, two scenarios can be formulated: a "relaxed" one, in which the DA is chosen at 6 $\sigma_{\rm beam}$, and an "aggressive" one, which allows for 5 $\sigma_{\rm beam}$ DA. The benefits of pushing for a smaller DA are related to the pileup

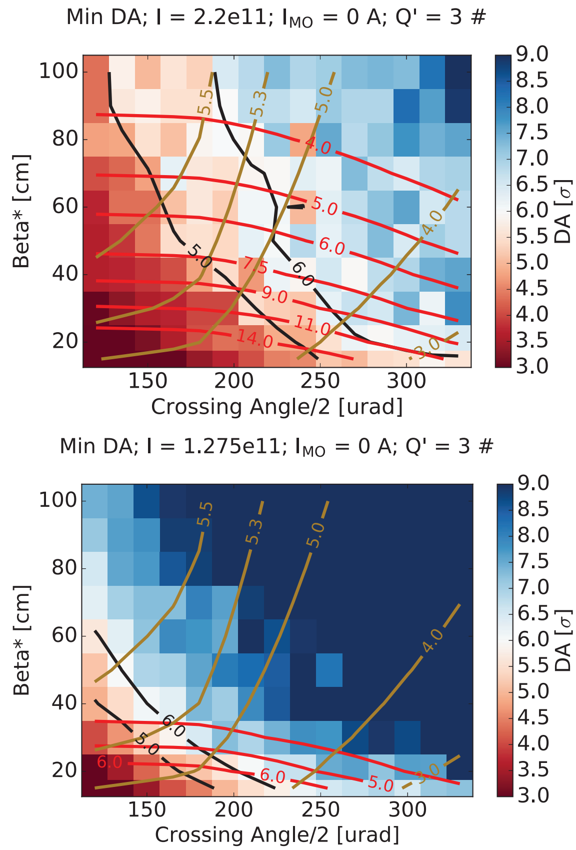

Figure 2: Multi-parametric scans of minimum DA in beam sigma for various values of β^* and half crossing angle for the start (top) and the end (bottom) of the levelling process. The superimposed curves correspond to the various contours of Dynamic Aperture (black), Luminosity (red) and r.m.s. length of the luminous region (gold). The study was performed with 3 units of chromaticity and the octupoles off.

density and the length of the luminous region. Due to the sinusouidal shape of the crabbing voltage, these are still improved even for crossing angles smaller than the maximum crabbing angle. For crossing angles above the maximum crabbing angle, marginal gain in term of the duration of the levelling process can also be achieved.

It should be noted that the aggressive DA settings also limit the tune space available for accommodating the different classes of bunches whose dynamics is especially affected by the missing collision in IP8 and by other coherent effects. Furthermore operation at high chromaticity might be required, although octupole currents in the range of −200 to −300 A are expected to recover some DA.

Figure 2 shows the DA simulation results for the study of the β^* levelling process. The selected plots refer to 2.2×10^{11} protons per bunch (the beginning of the fill) and 1.275×10^{11} protons per bunch (the nominal end of levelling). The black contours represent the DA levels in units of $\sigma_{\rm beam}$ and the red contours are the levels of luminosity over the same range of parameters in units of $1\times10^{34}\,\mathrm{Hz\,cm^{-2}}$.

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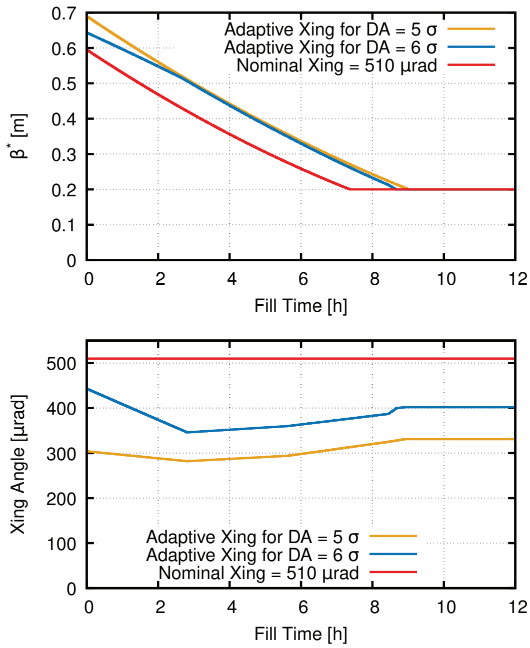

Figure 3: The evolution of β^* (top) and crossing angle (bottom) as a function of time for the relaxed and the aggressive scenarios, with round emittance. The nominal case with the crossing angle fixed at 510 μrad is also shown.

Finally, the gold contours represent the r.m.s. length of the luminous region in units of cm.

The resulting time evolution of the β^* and the crossing angle is shown in Fig. 3. Both the relaxed and the aggressive scenarios are shown, for the more conservative round emittance case. The RF curvature of the crab cavities and the hourglass effect are taken into account according to [12]. It is interesting to note that a crabbing angle of 350 μrad still allows to substantially compensate the crossing angle even for the relaxed scenario.

IMPACT OF MAGNETIC FIELD ERRORS

We chose the bunch intensity of 1.275×10^{11} protons, close to the end of the levelling process, to perform a statistical analysis in order to estimate the impact of magnetic errors. In addition to the unperturbed machine, DA simulations for 60 different realisations have been performed with the last version (v5) of the field error table without fringe fields, in an area spanning over ±4 cm in β^* and ±20 μrad in crossing angle around the point resulting in the nominal luminosity.

Overall, the average DA over the full statistical sample is 6.4 σ_{beam}, while the average standard deviation is found to be 0.56 σ_{beam}. The global minimum DA for the statistical population over all configurations is 4.8 σ_{beam}, and, as expected, it is found at the furthest configuration from the nominal point corresponding to a lower iso-DA curve. Furthermore, the dependence of the statistical results on the intensity, and thus time during the levelling process, is found to be well within the simulation uncertainties.

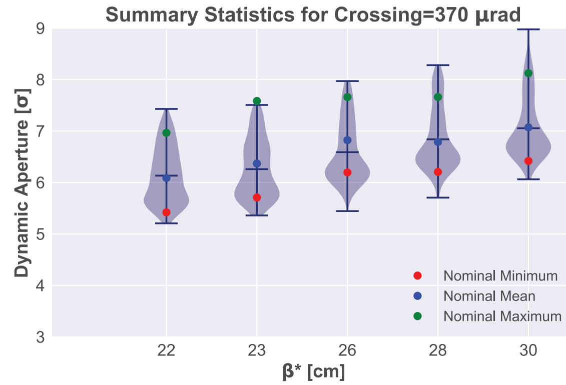

Figure 4: The DA as a function of the β^* is illustrated for 370 μrad crossing angle. The three bar points for each violin correspond to the minimum, average and maximum value of the statistical population. The shaded area represents the density of seeds presenting the same DA. The red bullets on top of each violin correspond to the minimum DA of the case without errors.

Summary results for a selected crossing angle as a function of β^* are collected in the violin plot shown in Fig. 4. For each seed the minimum DA value is determined over the angles in the configureation space. The density of the observed minimum DA values is represented by the shaded areas, while the horizontal bars show the maximum, average and minimum DA value of each configuration. The dots superimposed to each violin show the minimum DA for the case without errors.

These results indicate that the field quality optimised according to the specifications resulting from the DA simulations without beam-beam effect appear adequate also in presence of these effects. Nevertheless, the final determination of the machine performance will require to take into account several additional aspects such as: operation with high chromaticity and octupoles, bunch-by-bunch tune spread, sources of emittance blow-up, noise and effect of fringe fields.

CONCLUSIONS

By applying several multi-parametric DA scans, we started to produce an overview of the parameter space of the HL-LHC. The simultaneous operation of β^* and crossing angle during the levelling process has been determined with a rigorous approach based on DA estimations. In addition, the impact of magnetic imperfections has been evaluated in the presence of beam-beam effects. The current tolerances and correction strategies appear to be adequate in order to guarantee the operation of the machine.

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