CROSSING ANGLE ANTI-LEVELING AT THE LHC IN 2017

N. Karastathis*, K. Fuchsberger, M. Hostettler, Y. Papaphilippou,
D. Pellegrini, CERN, Geneva, Switzerland

Abstract

In 2017, LHC incorporated in operation an anti-leveling procedure of adapting the crossing angle of the colliding beams in steps to increase the integrated luminosity. In this paper, we present the Dynamic Aperture simulations that were employed to identify the operational margins, and therefore define the leveling steps. The results are complemented by observations from nominal operation, as well as projections for the 2018 run. Additional leveling techniques, investigated in dedicated machine studies are also discussed.

INTRODUCTION

LHC started exploring the mechanics of certain leveling scenarios in nominal operation during RunII, with the aim of gaining experience for their application during the High Luminosity upgrade (HL-LHC) [1]. In 2017, the dynamic variation of the crossing angle at the two high luminosity experiments during stable beams was incorporated into proton physics fills. This, "anti-leveling" process, as it was named, was intended to regain some of the luminosity, which is lost naturally from the bunch intensity decay, by increasing the luminosity geometric factor. The dynamics that govern the collision process, have a direct impact on the beam lifetime, and are highly non-linear due to the nature of the beam-beam force. In simulations, the best description of the impact of non-linear effects is given by the estimation of Dynamic Aperture (DA). Such simulations were employed to define the optimal crossing angle at the start of collisions, as well as to identify possible margins for optimization, resulting in a step-wise variation of the crossing angle, and are presented in this paper.

SIMULATION FRAMEWORK

The following simulation results are performed under the weak-strong approximation, tracking a single beam. The lenses for the beam-beam interactions, both the head-on and the long-range) are static. This approach has the advantage of being computationally faster and applies well to the particles with an action of a few beam sizes, σ. In terms of tracking codes, MADX [2], SixTrack [3], and the SixDesk [4] environment are the setup of choice.

Protons with initial amplitudes up to 10 σ are distributed in 5 transverse initial condition ratios (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. A minimum DA of 5 σ corresponds roughly to lifetimes of the order of 100 h [5], and is usually the target for the LHC DA studies. However,

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* nikolaos.karastathis@cern.ch

during the design phase and in the presence of larger uncertainties, a target of 6 σ is preferred.

The 4 σ bunch length is assumed fixed at 1.2 ns, while the transverse emittances are assumed round at 2.5 µm. The $\Delta p/p_0$ is fixed at 2.7×10^{-4}. The bunch intensity delivered to LHC by its injectors is currently at the level of 1.25×10^{11} protons. To suppress coherent instabilities, 15 units of chromaticity are maintained in the ring, together with positively powered lattice octupoles at the maximum current, providing Landau damping.

Finally, for operation at 6.5 TeV, the proton inelastic cross-section is assumed to be 81 mb, while the total cross-section 111 mb.

INITIAL CROSSING ANGLE CHOICE

The maximum protected aperture by the LHC collimation system limits the maximum crossing angle at the high luminosity experiments (ATLAS and CMS) and therefore, the normalized beam-beam long-range separation to approximately 10 σ for β^* values ranging from 30 cm to 40 cm and bunch population of up to 1.25×10^{11} protons. In 2017, the Achromatic Telescopic Squeeze [6] (ATS) scheme was incorporated in terms of optics, also paving the way towards the HL-LHC upgrade. Under this scheme, two values for the β function at the interaction points (IP), β^*, were commissioned; starting at 40 cm, and following aperture measurements and DA simulations, reducing it to 30 cm. With an average normalized emittance at the start of the physics production fills of 2.5 µm, these values suggest a half-crossing angle choice of 150 µrad for the former, and 175 µrad, for the latter case.

The simulated results of these two configurations are shown in Figure 1. The correlation of bunch intensity and half-crossing angle is expressed in terms of the minimum DA. The black lines corresponding to the iso-DA contours, suggest that the requested targets of initial crossing angle, with the delivered bunch intensity, are met with a DA of 6 σ.

Even though the change in β^* was performed within the same year, the initial crossing remained fixed at 150 µrad. Due to the operational experience with the machine, it was proven that LHC can comfortably operate at a DA of 5 σ. Figure 1b, which corresponds to the 30 cm case, shows that for the initial bunch intensity of 1.25×10^{11} protons, the 150 µrad is well above the 5 σ target. Following this recommendation, LHC successfully operated with an initial crossing angle of 150 µrad throughout the year.

CROSSING ANGLE ANTI-LEVELING

During the physics production, the beam lifetime increases due to the weakening of the beam-beam effects,
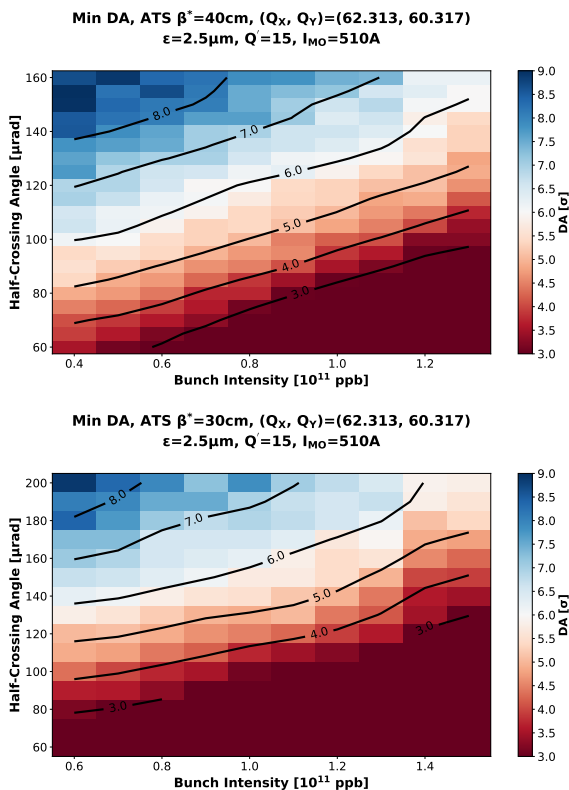
Figure 1: Minimum DA scan of the half crossing angle as a function of the bunch intensity for the ATS 40 cm (a), and 30 cm (b) case. The black lines correspond to the iso-DA contours.

OBSERVATIONS FROM THE PHYSICS RUN

The anti-levelling procedure was incorporated in almost all the physics production fills. The detailed performance analysis for the 2017 run is presented in [7]. While the orchestration of the various systems (power converter, orbit feedback, etc.) required to perform a crossing angle reduction was automatized [8], transients mainly due to orbit and/or working point jitter have been identified to produce a small amount of losses. Operationally, these were mitigated by tune optimization. This effect is shown in Figure 2a for a selected fill. The plot shows the losses normalized to the delivered luminosity, it is therefore an effective cross-section, σ_{eff}, defined as $\sigma_{\text{eff}} = \left(\frac{dN}{dt} \right) / \mathcal{L}$, where N denotes the beam population, $\mathcal{L}$ the instantaneous luminosity summed over all IPs and t the time. σ_{eff} should approach the proton inelastic cross-section if all proton losses are due to luminosity production. The overlayed green curve shows the steps in the crossing angle. While the losses after the first hour in collisions are almost stabilized close to the burn-off limit, a clear correlation is observed between the steps and the increase of the losses in the machine.

To estimate whether the additional losses produced by the crossing angle steps have an impact on the luminosity gain of the anti-leveling process, two effective cross-section evolution scenarios have been investigated. The first follows the evolution of the average effective cross-section throughout the fill, as taken by the data. The second, only follows the

which is a result of the natural proton burn-off. The instantaneous luminosity produced by the colliding beams has a dependence on the angle and the plane of collision. By reducing the crossing angle, the instantaneous luminosity is increased, and consequently the total integrated one.

The almost linear correlation of the bunch intensity and the crossing angle, shown in Figure 1, suggests that during the intensity decay, the crossing angle of the two colliding beams can continuously be reduced to increase performance, while maintaining a certain level of DA.

The ideal strategy for the anti-leveling would be to follow an iso-DA line during the intensity decay. However, due to restrictions from the experiments, similar to the ones discussed in the previous section, fixed steps of 10 μrad of half-crossing angle were adopted. Additionally, the step was not correlated to the beam intensity, but performed in fixed intervals within the physics production. Numerical estimates derived from Figure 1, suggest that the crossing steps should be performed at 2 h, 4 h and 8 h after the start of collisions. The total gain of this procedure would be 5% of integrated luminosity, compared to the fixed angle scenario.
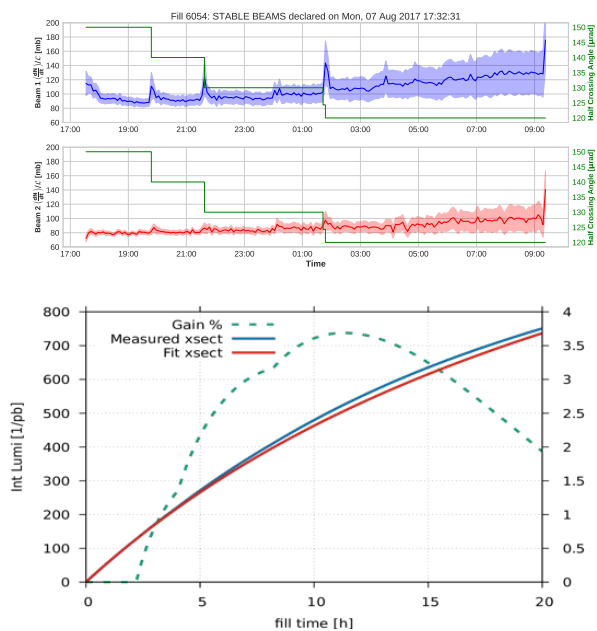

Figure 2: (a) Evolution of the effective cross-section for a representative fill. The crossing angle was reduced in steps of 20 μrad. A small increase of beam losses is correlated with the angle reduction. (b) Comparison of the integrated luminosity gain, for a varying and a fixed effective cross-section scenario, for the same fill.

first two hours of collisions, right before the first reduction of the crossing angle, and assumes a constant cross-section afterwards. The result, shown in terms of integrated luminosity gain in Figure 2b, suggests that despite the losses, the anti-leveling process results in a gain of 3%-5% of integrated luminosity over the typical LHC fill length of 10 h-15 h.

However, this type of losses can be almost completely mitigated by reducing the performed step size. This results in continuously varying the crossing angle, as in following the iso-DA line. This hypothesis was tested in operation for a single physics fill. The aim of the test was to reduce the crossing angle in smaller steps, while still keeping the same relative reduction of 20 μrad at the predefined time instances within the fill, to maintain a good level of DA. The results for both beams are shown in Figure 3, which suggest no significant impact of the crossing angle variation on the beam losses.
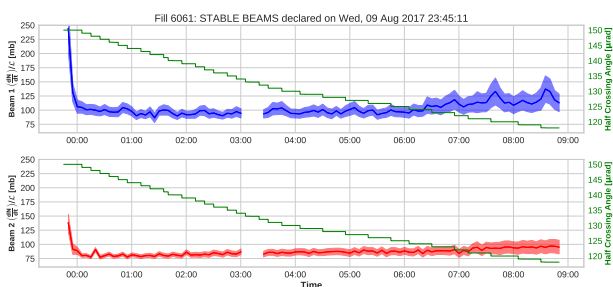

Figure 3: Evolution of the effective cross-section for a fill during which the crossing angle was continuously adapted in small steps.

PROJECTIONS FOR 2018

In 2018, the injectors are expected to deliver brighter beams to the LHC. Preliminary estimates [9] include bunch intensity at the level of 1.3×10^{11} protons, brought at collisions baring round normalized emittances of 2.5 μm. In addition, the experience gained with the 30 cm ATS optics, allows to squeeze even more the beams, down to $\beta^* = 25$ cm at the two high luminosity experiments. In terms of DA, the result for such configuration is shown in Figure 4a. It suggests an initial crossing angle for the collision process at 160 μrad, which is accommodated within $5\,\sigma$ of DA.

The increased peak luminosity creates an ideal situation to test the β^*-leveling mechanics, which are vital for the HL-LHC operation. For the 2018 operation, a variation of the crossing angle could be performed in smaller steps from 160 μrad to 130 μrad, taking into account the correlation of the bunch intensity with the crossing angle shown in Figure 4a. When the bunch population is adequately decreased (~0.95×10^{11} protons or ~8 h in collisions) a reduction of the β^* could be performed in one (down to 25 cm) or two steps (first to 27 cm, then to 25 cm).

The mechanics of the β^* levelling have been studied in dedicated machine studies [10]. Figure 4b, shows the luminosity of the four experiments, when squeezing the β^* from 40 cm to 30 cm and de-squeezing back to 40 cm.
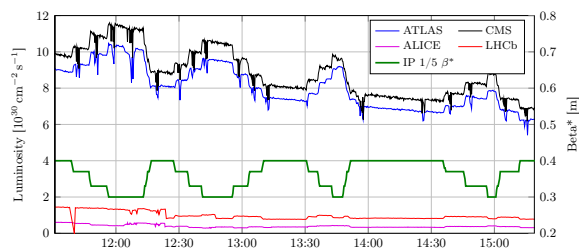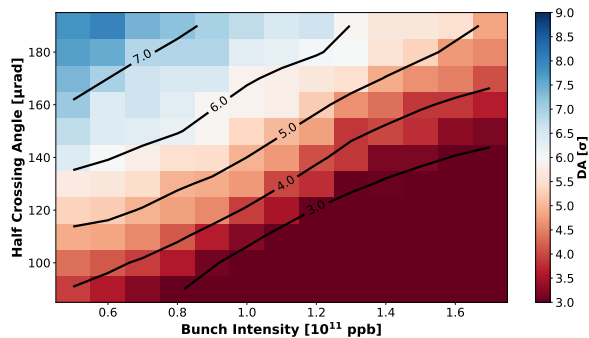

Figure 4: (a) The correlation of crossing angle and bunch intensity in terms of DA for the 2018 estimated beam parameters. (b) Luminosity evolution from the four experiments when squeezing and de-squeezing the β^* during a dedicated experiment.

CONCLUSION

The beam dynamics simulations guided the operation throughout 2017, in terms of crossing angle choice. The available lifetime margin was converted to luminosity via the successful incorporation of the anti-leveling process, contributing to achieve a total delivered integrated luminosity of 50 fb^{-1}. The goal for LHC in 2018 is to exceed this value, and to gain operational experience with new leveling techniques, such as the β^* leveling, towards the HL-LHC upgrade.

ACKNOWLEDGMENTS

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