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

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Abstract

We performed extended simulations of LHC dynamic aperture (DA) in the presence of beam-beam effects in the weak-strong approximation, evaluating the contributions of parameters such as: tunes, optics, bunch intensity, crossing angle, emittance, chromaticity and current in the Landau octupoles. Here we present a summary of these studies, giving an overview of the amplitude of the LHC operational space and pointing out the remaining margins for mitigation of instabilities. These studies supported the actions deployed during the 2016 run of the LHC, which aimed at maximising its performances. Examples of such actions are the switch to lower emittance beams, the reduction of crossing angle and tune trims. More recently, DA scans have been used to help the definition of the operational scenarios for the 2017 run. Additional room for improvements, for instance by deploying crossing angle levelling, will be explained.

INTRODUCTION

The performance optimisation of the Large Hadron Collider (LHC) relies on a careful tuning of a number of operational parameters, balancing many conflicting constraints. Tunes, optics, bunch intensity, crossing angle, emittance, chromaticity and current in the Landau octupoles, they all play a role in the maximisation of the luminosity, the mitigation of non-burnoff losses and the prevention of beam instabilities.

The duration of the LHC cycle, which typically extends up to several hours, together with a number of constraints from machine protection, does not allow to probe such a vast parameter space in an experimental manner. It is therefore essential levering on detailed computer simulations aimed at identifying the possible steps for improvements, to be validated in Machine Development sessions or directly applied to the machine.

The 2016 run of the LHC has been closely followed up by means of dynamic aperture (DA) investigations. These studies helped to steer performance of the collider towards the reach of the design luminosity and beyond. Although the many uncertainties involved and the fact that a precise relation between beam lifetime and DA is not available, the latter has been proven a valuable estimator of margins and boundaries. Excellent response from the machine has been obtained; confidence has been gained in the model and in the technique, allowing for reliable predictions.

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 substantial computational speed up and applies well to the particles with an action of some r.m.s. beam size (σ), whose dynamics is relevant for the determination of the DA and is not much influenced by the coherent motion of the beam core.

The model relies on the MADX [1], SixTrack [2], SixDesk [3] environment and includes all the IPs. The tolerances on alignment and multipolar errors are such that they can be effectively corrected and, on average, no significant impact is observed in presence of beam-beam effect.

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 compensates for it, proving to be adequate in most of the cases. The studies focussed on Beam 1, which has shown the weakest lifetime all along the run.

PREDICTIONS AND FOLLOW UP OF THE 2016 RUN

Emittance reduction

After the start-up with nominal beams, the availability of a new method for production of physics beams (BCMS [4]), resulted in a progressive reduction of the emittance from 3.75 μm to about 2.3 μm during the first part of the 2016 run.

Smaller emittances increase the strength of the head-on beam-beam, but at the same time the sampling of multipolar

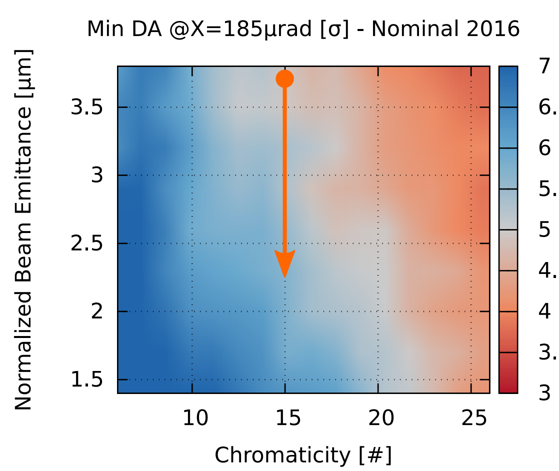

Figure 1: The additional DA gained for small emittances allows to run with higher chromaticity and/or with smaller crossing angle (not shown). The arrow indicates the reduction performed in 2016.

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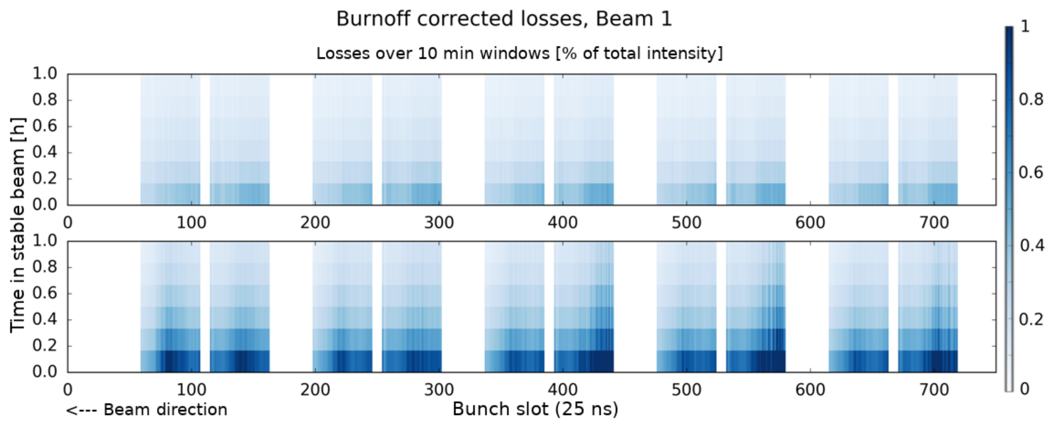

Figure 2: Losses observed for some trains of bunches of Beam 1 during the first hour in stable beam as percent of the total intensity, computed over 10 min windows and averaged over several fills before (top) and after (bottom) the reduction of the crossing angle from 185 to 140 µrad. The progressive increase of the losses along the trains indicates some e-cloud build-up, while the signature of LR interactions is visible as the enhanced losses in the centre of the trains, where bunches suffer more LR interactions. Beam 2 presents a similar behaviour although the losses are milder.

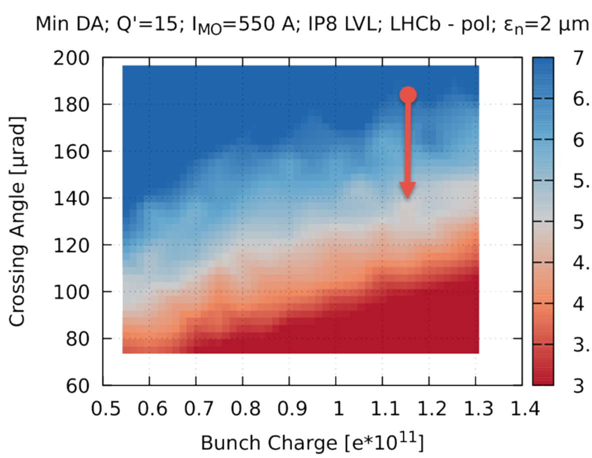

Figure 3: DA response to bunch intensity and crossing angle. The arrow indicates the crossing angle reduction performed during 2016. The DA at the beginning of the fill has been reduced to 5 σ, the intensity decay gives more margin later in the fill.

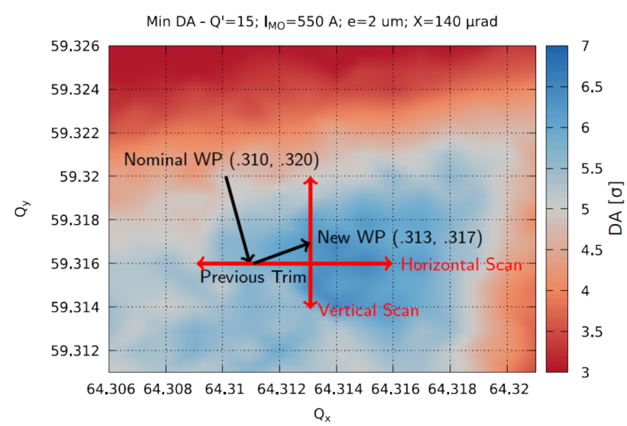

Figure 4: A tune scan showing that the performed adjustment to the tune. The arrows represent the area explored experimentally, carefully monitoring the beam lifetime.

components is reduced. It has been found that although the physical value of DA (measured in mm) decreases for smaller emittances (indicating that the head-on component has a visible impact on DA), in units of beam σ, the DA improves. This is illustrated in Fig. 1 for a region around the emittance change. The divergent colour scale is used to mark the areas of good DA (blue) and of DA leading to potentially unacceptable loss rates (red). The machine, indeed, responded to the smaller emittance with improved beam lifetime [5].

Reduction of Crossing

The bunch intensity along 2016 has been limited by the heating of the injection kicker [6]. This, together with the increased margin from the reduced emittance, allowed for a consistent reduction of the crossing angle. The decision for a switch from 185 µrad to 140 µrad, was based both on previous experience [7] and new simulations [8].

The new crossing angle caused a minor increase of losses during the first hour in Stable Beams (see Fig. 2), whose impact on the luminosity production was superseded by the enhancement of the geometrical reduction factor [9].

Figure 3 shows the prediction from simulations indicating a DA of 5 σ at the beginning of the fill. This justifies the fact that a DA around of 6 σ is going to be used as a starting point also in 2017, with a possible reduction to 5 σ as a second step during the run. More experience will be necessary in order to better qualify these values.

Tune Adjustment

During the 2016 Run the measured lifetime of Beam 1 has consistently been shorter than the one of Beam 2. Variations of this asymmetry were noted for changes of the polarity of the LHCb spectrometer, whose main effect is the intro-

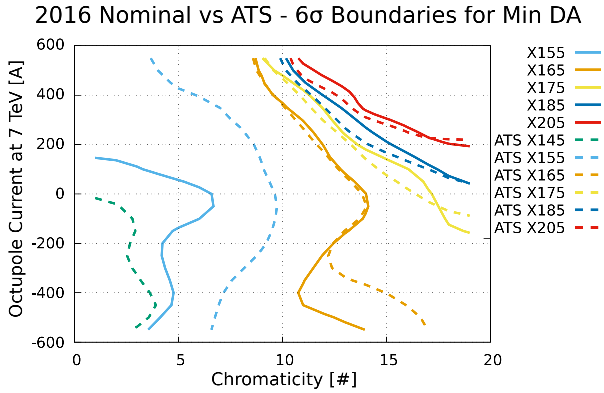

Figure 5: 6 σ DA boundaries in the chromaticity-octupole space, comparing the performances of Nominal and ATS optics for several crossing angles in IP1 and IP5. The legend indicates the half crossing angle values in µrad.

duction of a tune shift of about 1×10^{-3} for the bunches colliding there (the majority) [10].

DA tune scans were performed for Beam 1 (see Fig. 4) and confirmed that the nominal working point (0.31, 0.32) is suboptimal, and, for well corrected linear coupling, areas of better DA are observed closer to the diagonal. The response of Beam 1 lifetime to small tune trims was monitored at the beginning of a fill; the working point selected by this procedure (0.313, 0.317) was in remarkable agreement with the predictions from simulations and resulted in a complete recovery of Beam 1 lifetime in the next fills [10].

ATS OPTICS

The achromatic telescopic squeeze (ATS) is the baseline optics for the HL-LHC, allowing to reach lower values of β^* [11]. During 2016 the ATS concepts have been successfully demonstrated in MDs [12] and it has been chosen to use it already in 2017 with moderate settings.

Figure 5 shows a comparison of the performances of Nominal and ATS optics. It can be noted that ATS is predicted to perform remarkably better with small chromaticity allowing for tighter crossings, in particular with negative octupoles which allow for LR compensation [13].

PREPARATION FOR THE 2017 RUN

Several studies have been performed in order to help the definition of the 2017 settings [14, 15]. Figure 6 summarises the DA sensitivity to the tune. With the 2017 settings, the nominal tune (0.31, 0.32) is particularly suboptimal. We propose an optimised tune of (0.313, 0.317), which was already demonstrated during 2016 and proved to be effective even in presence of small residual coupling. It should also be noted that if the good DA area in the tune-space becomes too small, it might be impossible to accommodate all the different classes bunches, e.g. pacman bunches [16], bunches without collision in IP8...

Figure 7 shows an intensity-crossing scan for the optimised tune. The starting point at 150 µrad and 1.25×10^{11}

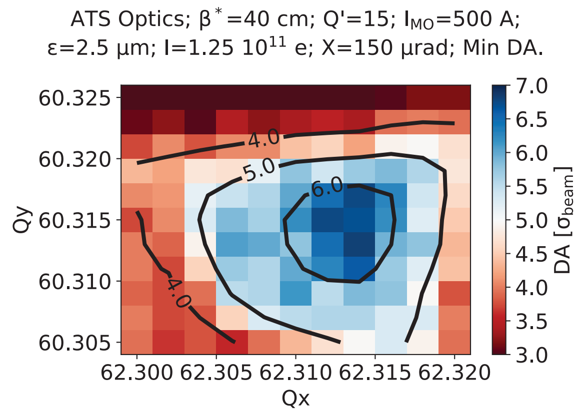

Figure 6: Tune scan for the proposed 2017 settings at collision. Good DA is obtained moving closer to the diagonal, provided that linear coupling is properly corrected.

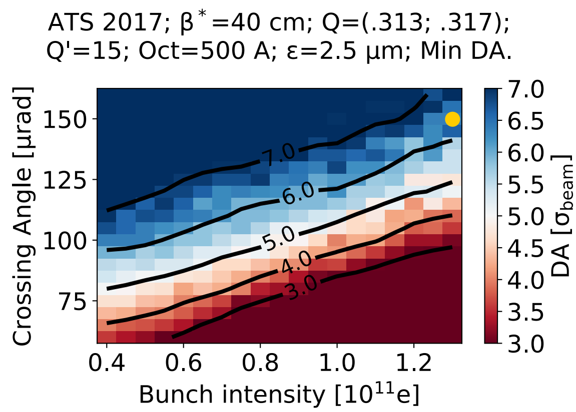

Figure 7: A Crossing-Intensity scan for the 2017 settings and optimised tune. The yellow dot is the proposed starting point for 2017, which is expected to give substantial margin.

proton per bunch presents significant margin for a further crossing reduction and/or crossing anti-levelling, which consists in following the iso-DA curve during the intensity decay. The predicted gain of integrated luminosity with crossing angle anti-levelling reaches up to 3 %, with a continuous adjustment of the crossing angle along the fill [17].

CONCLUSIONS

Multi-parametric DA scans have been applied to the LHC allowing to gain more confidence in the sensitivity of its parameter space. The 2016 Run has been closely followed up. Input has been provided for the main decisions taken along the year and the predictions turned out to be extremely accurate in spite of the many uncertainties present. The studies played a central role also in the definition of the parameters for 2017. Although the start up will be more aggressive, margins have already been identified and they may result in a substantial performance increase along the year. In particular a careful tune control at the level of 1×10^{-3} allows for a substantial gain of DA, which together with a potential reduction of chromaticity and octupoles, may allow to further push the crossing angle and/or β^*.

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