DYNAMIC APERTURE STUDIES OF LONG-RANGE BEAM-BEAM INTERACTIONS AT THE LHC

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Abstract

Long-range beam-beam interactions dictate the choice of operational parameters for the LHC, such as the crossing angle and β^*, and therefore the luminosity reach for the collider. The long-range beam-beam interaction can lead to particle losses, closed orbit effects and emittance growth. Defining how these effects depend on the beam-beam separation will determine the minimum crossing angle and the β^* the LHC can operate. In this article, analysis from a dedicated machine study is presented in which the crossing angle was reduced in steps and the impact on beam intensity and luminosity lifetimes were observed. Based on the observations during the machine study, the intensity decays are compared to expectations from models. Estimates of the luminosity reach in the LHC are also computed.

INTRODUCTION

The long-range (LR) beam-beam interactions are one of the effects that will dictate luminosity performance of the LHC and the choice of parameters for future projects [1]. The strength of the LR beam-beam interactions are dependent on the beam to beam separation, d_{sep} at the first encounters. The d_{sep} in the drift space and can be expressed for small crossing angles, α as

$$d_{sep} \approx \sqrt{\frac{\beta^* \gamma_r}{\epsilon_n}}\alpha, \quad (1)$$

where β^* is the β-function at the interaction point (IP), γ_r is the relativistic factor, ϵ_n is the normalised emittance and α is the crossing angle. During the 2015/6 LHC proton-proton runs, two dedicated machine studies were performed to investigate how the LR beam-beam interaction impacts particle losses and the luminosity lifetimes as the crossing angle is reduced. During these machine studies the minimum operational beam-beam separations were identified for two different β^* in the LHC [2–4].

In this article, `Sixtrack` [5] simulations of the Dynamic Aperture (DA) are compared to measured data with the aim of understanding if the DA model proposed by Giovannozzi et al [6, 7] can predict the intensity evolution of colliding beams.

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DYNAMIC APERTURE FROM MEASURED DATA

In order to directly compare data from the experiment to tracking simulations the measured DA needs to be calculated. The DA can be calculated from measured intensity loss following the method described in [6, 7]. The DA as a function of turn number N, is given by

$$\mathcal{D}(N) = \sqrt{2\log\frac{\Delta I}{I_0}}, \quad (2)$$

where $\frac{\Delta I}{I_0}$ is the fractional intensity loss measured during the 2016 machine study. The DA model presented in [6] was applied to single bunches and hence does not include proton burn-off. Proton burn-off is calculated from the luminosity and is used to compensate the measured intensity from the machine study [8]. Compensating for the proton burn-off allows the measured DA to be directly compared to DA obtained using `Sixtrack` simulations [8]. In addition to proton burn-off, an asymmetry between the horizontal and vertical emittances was present during the machine study. Since the measured DA is calculated in units of bunch σ the measured DA is dependent on the emittance. In order to provide an initial estimate of the impact of the asymmetric emittance on the measured DA, the DA was calculated with respect to three values of the emittance; the vertical, horizontal and averaged values.

SIMULATION SETUP

Particles were tracked over 10^6 turns through the 2016 LHC lattice with collisions taking place at IP1 and IP5 with a $\beta^* = 40$ cm. The crossing angle for each tracking simulation followed the steps taken during the machine study [9]. Particles were distributed over a total of 59 angles in the $x - y$ plane. The beam-beam interactions were implemented in `Sixtrack` using the standard 6-dimensional symplectic mapping in ref [10] for the head-on (HO) colliding bunch. A full comparison can be found in [9].

Unlike the tracking simulations, the real DA in the LHC will be limited by the physical aperture of the machine. The physical aperture in the LHC is defined by the collimator settings and for a bunch emittance of $\epsilon = 2.5\mu$m the DA will be limited at approximately 6.5σ.

Coupling was also included in the tracking simulations with the value for $|C^-| = 4 \times 10^{-3}$.

PRELIMINARY COMPARISONS

In Figure 1 the measured DA for the HO colliding and HO+LR colliding bunches are shown as a function of crossing angle. The measured DA for the HO bunch does not vary

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significantly with crossing angle and the DA remains limited at approximately 3.75 σ. For the nominal colliding bunches, the DA at large crossing angles is comparable to the HO colliding bunch, however the DA reduces with crossing angle as the LR interactions begin to dominate losses. The DA at small crossing angles follows strongly the LR pattern as observed in Figure 2, with bunches in the centre of the train, with the smallest DA corresponding to the highest number of LR interactions.

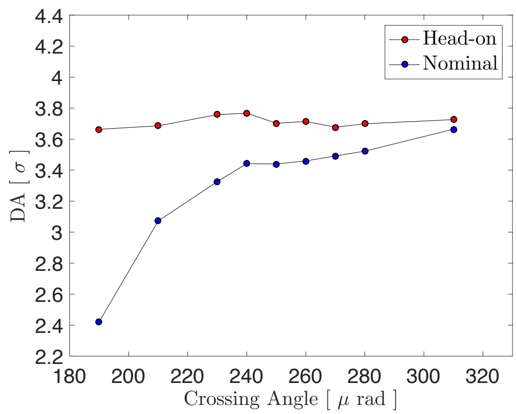

Figure 1: The measured DA from intensity loss normalised to $\epsilon_n = 2.5$ μm for the HO colliding bunch and the mean DA for nominal bunches colliding at IP1 and IP5 with both HO and the maximum number of 34 LR beam-beam interactions.

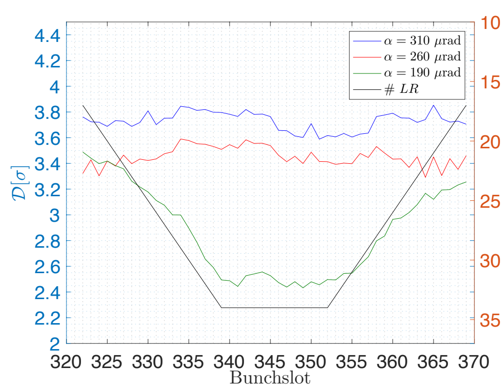

Figure 2: Measured dynamic aperture normalised to ϵ_n = 2.5 μm for the first train in the LR beam-beam machine study.

Long-range and head-on effects

Figure 3 shows a comparison between the measured and simulated DA for the nominal colliding bunches. Towards smaller crossing angles where the beam-beam separation is below 10 σ and the LR beam-beam interaction dominates the losses, there is a good comparison between the two results. However as the beam-beam separation increases the simulated DA continues to improve whereas the measured DA saturates at ~ 3.75 σ. The maximum DA for the nominal colliding bunch at large DA is similar to that of the HO

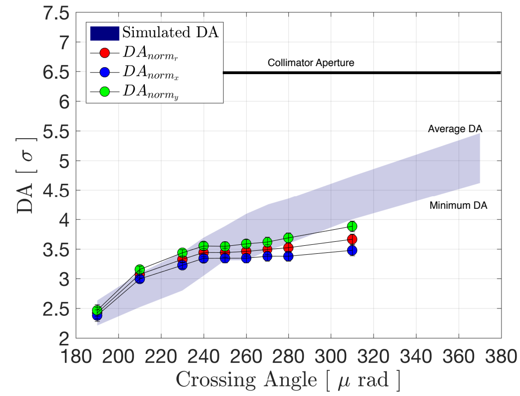

Figure 3: Comparison of tracking simulations to the measured DA for the nominal colliding bunches including measured intensity, emittance and linear coupling from the 2016 LRBB MD.

colliding bunch. An additional effect is limiting the DA towards larger crossing angles. This effect cannot be due to the LR beam-beam interaction as the beam-beam separation is sufficiently large above $\alpha = 260$ μrad. To further investigate the possible limitation of the DA, the HO colliding bunch is investigated.

Head-On Collisions

To determine why the DA does not continue to improve with increasing crossing angle, the simplest beam-beam configuration is investigated with two HO collisions. Figure 4 shows the DA as a function of $x - y$ angle from tracking simulations. The DA from simulations is calculated to be larger than the physical aperture of the LHC. Hence, tracking simulations indicate that the physical aperture of the machine should limit the DA. However comparing the measured DA and simulated DA as a function of crossing angle as seen in Figure 5, a clear discrepancy can be observed. At larger crossing angles the LR interaction has a negligible impact on the DA, this means that the DA for the nominal colliding bunches and the HO bunch should be comparable. The DA from measurement shows that the nominal and HO colliding bunches do indeed compare well, however the DA from simulations is not well representative of the measured DA. To further explain the possible differences between the measured and simulated DA, additional sources were investigated. Including linear coupling reduces the simulated DA by approximately 1σ but is not sufficient to explain the clear discrepancy between measurement and simulation.

Preliminary simulations of a single seed including magnetic lattice errors is shown in figure 6 and both tracking and measured DA compare well. Introducing magnetic errors to the model has a significant impact on the simulated DA. These errors indicate that these non-linearities in conjunction with HO beam-beam collisions may be the cause of the DA saturation at larger crossing angles, outside of the LR beam-beam dominated region below $\alpha = 260$ μrad. Full 60 seed simulations can be found in [9]. Figure 7 shows that

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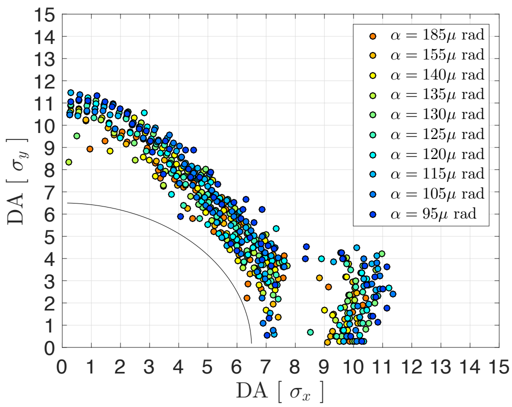

Figure 4: DA from simulations in the $x-y$ plane including linear coupling, measured intensity and emittance for the HO only colliding bunch. The collimator aperture is shown as the black curve.

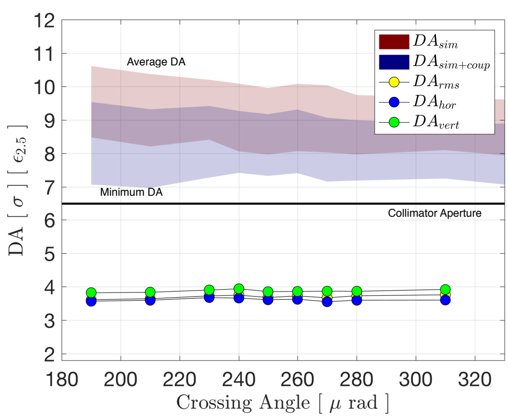

Figure 5: Comparison of simulation and measured DA for the HO only bunch including measured intensity, emittance, and linear coupling.

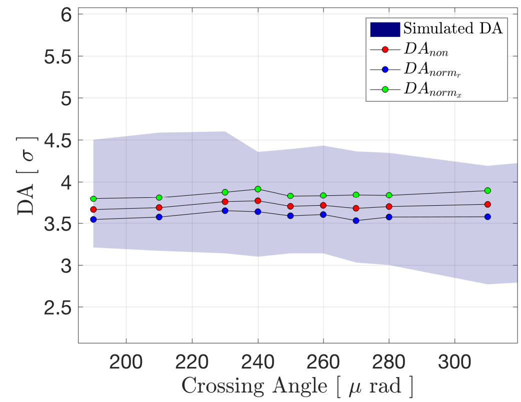

Figure 6: Comparison of tracking simulations to the measured DA for the HO only bunch including measured intensity, emittance and magnetic errors.

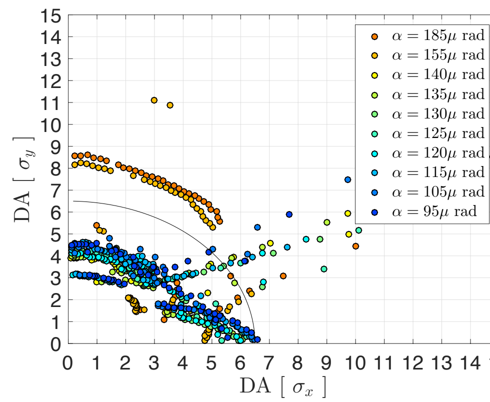

Figure 7: DA from tracking simulations in the $x-y$ plane including lattice errors, measured intensity, and measured emittance for the HO only colliding bunch. The collimator aperture is shown as the black curve.

the simulated DA in the $x-y$ plane is strongly affected by the non-linearities introduced by the lattice errors. This indicates the importance of tracking particles over many angles in the $x-y$ plane.

CONCLUSION

Using data obtained during the 2016 LR beam-beam machine study, the measured DA was calculated from intensity loss and compared to tracking simulations. The nominal colliding bunches, which undergo both HO and LR beam-beam interactions compare well to simulation and measured data at small crossing angles. At small crossing angles the LR beam-beam interaction is strong and hence dominates the particle losses, reducing the DA. For large crossing angles the DA from tracking simulations continues to improve, whereas the measured DA saturates at approximately $3-4\sigma$. This implies that some addition mechanism is limiting the DA that is not caused by the LR beam-beam interaction as the DA is comparable to the HO colliding bunch at large crossing angles. For the HO colliding bunch, tracking simulations show that the source of particle losses is not due to HO beam-beam alone and the additional contribution from linear coupling is not sufficient to describe the limited DA at larger crossing angles. Instead, preliminary simulations suggest that it is the interplay between HO beam-beam and the non-linear magnetic errors of the LHC that limits the DA. Without these errors the simulated DA will be limited by the physical aperture of the machine defined by the collimator settings. Including the magnetic errors in the simulations show that the losses are well represented for the HO colliding bunch in the crossing angle range $\alpha = 260$ μrad to $\alpha = 370$ μrad in the LHC. Complete simulations and discussion of the cases can be found in ref [9].

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