DYNAMIC APERTURE STUDIES DURING COLLISIONS IN THE LHC

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Abstract

The dynamic aperture during collisions in the LHC is mainly determined by the beam-beam interactions and by multipole errors of the high gradient quadrupoles in the interaction regions. The computer code JJIP has been modified to accommodate the LHC lattice configuration and parameters and is employed in this study. Simulations over a range of machine parameters are carried out, and results of preliminary investigation are presented.

1 INTRODUCTION

There has been an extensive study of the dynamic aperture of the LHC at injection, in which field errors of the arc magnets are dominant. However, things are quite different during collisions when field errors of the high gradient quadrupoles (the triplet) in interaction regions (IRs) and the beam-beam interactions play predominating roles. This is because the β-functions in the triplets are large and beam separations in the IRs are small. As a matter of fact, error multipoles in the arcs are small during collisions so that the tracking can be lumped into a few blocks. Thus large numbers of turns can be simulated with relative ease. This is particularly important for the LHC because beams, during experimental luminosity running, should circulate for 10 hours or longer.

The LHC has four interaction points (IPs): IP1 and 5 are high luminosity points, IP2 and 8 low luminosity points. The triplet magnets are identical in the four IRs. So is the head-on beam-beam interactions. However, the long-range beam-beam is important only in the high luminosity IRs, which has small β^* (0.5 m) and large $\beta_{\max}$ (4400 m). In order to minimize the beam-beam effects, there is a crossing angle at the IPs. A large crossing angle would certainly benefit as far as long-range beam-beam is concerned. But it would also reduce the luminosity, jeopardize the triplet field quality and enhance the synchro-betatron resonances. Moreover, larger crossing would require more aperture in the triplets. Therefore, a careful choice of an appropriate range of the crossing angle is a critical issue in the LHC IR design. This paper intends to provide some insights to help with making such a choice by means of a tracking code JJIP.

2 BRIEF DESCRIPTION OF THE CODE

The code JJIP was originally written for the IR studies of the former SSC project. It has been modified for accommodating the LHC lattice configuration and machine parameters. It consists of three basic tracking blocks — Tracking in the arcs is a simplified map with lumped errors; the triplet part is considered as thin-lense, in which each magnet is sliced; the head-on beam-beam is a simple kick and the multiple parasitic crossings are treated equally in the free space as well as in the triplet.[1]

The input data card provides a number of variables in the parameter space: launching positions, beam emittance, β^*, crossing angles, crossing planes, error tables of arc magnets and triplets, coupling strength, position errors in the 6-D phase space at IPs, tune modulations and noises, *etc.* On a single processor SUN Sparc-20 workstation, it takes about 15 minutes to track a million turns, equivalent to the 1.5 minutes required for a particle to travel 10^6 turns in the LHC in real time.

3 RESULTS OF PRELIMINARY INVESTIGATION

3.1 *Bench test:*

As a test case, the triplet error tables in Ref. [2] were adopted in the preliminary tracking study. Under similar conditions, the dynamic aperture obtained from JJIP is 10σ, while Ref. [2] gives 9.9σ. This justifies the use of the short cut in the arcs.

3.2 *Scaling of dynamic aperture* vs. β^**:*

Figure 1 shows the scaling of the dynamic aperture *vs.* β^* in the absence of beam-beam interactions. The beam separation n when expressed in terms of the beam size σ is:

$$\begin{aligned} n &= S(L)/\sigma(L) = L\theta_0/\sqrt{\epsilon\beta(L)} \approx \theta_0/\sqrt{\epsilon/\beta^*} \\ &= \theta_0/\sigma' \end{aligned} \tag{1}$$

in which S is the beam separation in meters, L the distance from the IP, θ_0 the full crossing angle, ϵ the beam emittance and σ' the *rms* beam angular spread. The separation n is kept constant in this scaling, which is 9.5σ that corresponds to θ_0 = 300 μrad and β^* = 0.5 m. When β^* increases, σ' will decrease and so does θ_0. Therefore, one would expect a larger dynamic aperture for a larger β^*. It is seen from Fig. 1 that the scaling is approximately linear. (Similar study for the SSC gave a scaling of ${\beta^*}^{1.5}$, see [3].)

3.3 *Relative weight of various sources limiting dynamic aperture:*

Figure 2 decomposes the different sources that could limit the dynamic aperture (DA) and gives a quantitative comparison of each contribution. The tracking conditions are

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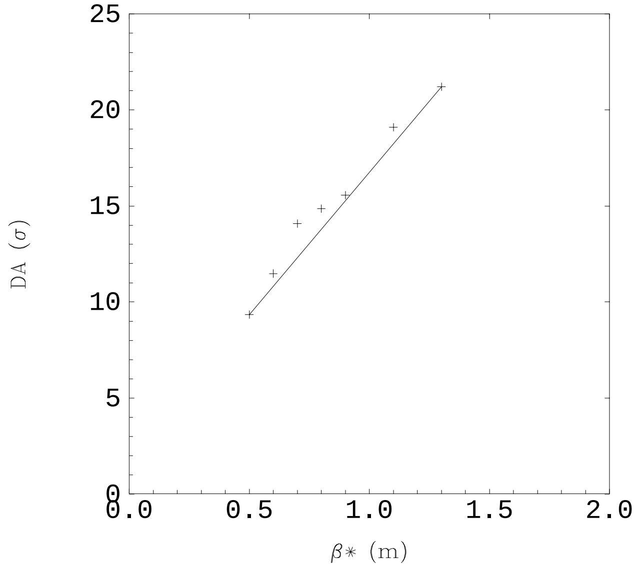

Figure 1: The scaling of dynamic aperture *vs.* β^* when the beam separation is kept constant at 9.5σ. It is approximately linear.

as follows: collision optics, 10^5 turns, 5 seeds, field error tables from Ref. [2], and θ_0 = 300 μrad. The results show that: (a) Arc errors only: DA $\geq 21\sigma$; (b) Arc errors + triplet errors (b_{10} off): DA = 17.3σ; (c) Arc errors + triplet errors (b_{10} on): DA = 11.5σ; (d) Arc errors + triplet errors (b_{10} on) + beam-beam: DA = 8.43σ; (e) Same as (d), but the crossing plane is tilted by 45°: DA = 9.33σ. From these results, the following observations are made:

- The arc magnets only minimally constrain the dynamic aperture during collisions.
- The systematic 20-pole b_{10} plays a major role in limiting the dynamic aperture, which is in agreement with Ref. [2]. However, the value of b_{10} (-0.005 $\times 10^{-4}$) assumed here seems to be greatly exaggerated. In the present triplet design for the LHC at Fermilab, it has been reduced by more than a factor of five (0.0009 $\times 10^{-4}$).[4]
- The beam-beam interactions limit the dynamic aperture even when the crossing angle is as big as 300 μrad.
- A 45°-tilted crossing plane improves the dynamic aperture if the particle oscillates horizontally. This is because for the same crossing angle, the beam distance becomes larger than that with horizontal crossings. However, this improvement disappears if the particle oscillates diagonally (not shown in the figure).

3.4 *Dynamic aperture* vs. *crossing angle:*

On the one hand, larger crossing means the beams are further away from the magnet axis, which leads to poor field qualities. Thus, the dynamic aperture limited by the triplet would become smaller. On the other hand, however, the dynamic aperture limited by beam-beam would become larger due to less beam-beam interactions. Therefore, one would expect that, when the crossing angle increases, the dynamic aperture would at first increase (which is the beam-beam dominated region); after reaching a maximum value, it would decrease (which is the triplet errors dominated region). Figure 3 is an illustration of this process at three crossing angles: 200, 300 and 350 μrad. The solid curve is the case when there are magnet errors but no beam-beam. The dashed one is when both magnet errors and beam-beam interactions are present. It is seen that, below 300 μrad, the beam-beam is dominating, while above that, the triplet errors seem to take over. The maximum dynamic aperture is achieved at about 300 μrad using the above error table.

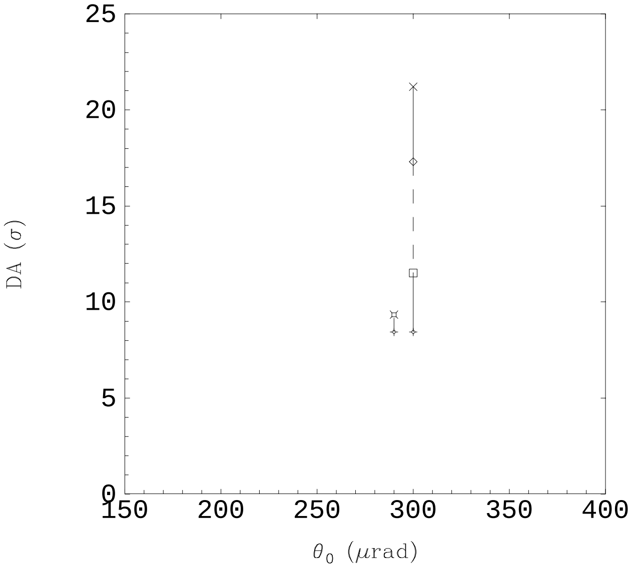

Figure 2: Contribution of various sources limiting the dynamic aperture. Right line from top down: (a) Arc errors only: DA $\geq 21\sigma$; (b) Arc errors + triplet errors (b_{10} off): DA = 17.3σ; (c) Arc errors + triplet errors (b_{10} on): DA = 11.5σ; (d) Arc errors + triplet errors (b_{10} on) + beam-beam: DA = 8.43σ. Left line from bottom up: (d) See above; (e) Same as (d), but the crossing plane is tilted by 45°: DA = 9.33σ.

3.5 *Space budget of the triplet aperture:*

One primary goal of these studies is to determine the required aperture of the triplets, which is 35 mm (radius) in the present design. Figure 4 demonstrates a proposed space budget for the aperture of the quadrupoles Q2 and Q3 (both are in the high-β region) at the high luminosity points IP1 and 5. (a) The radiation shielding takes 6 mm.[5] Another 2 mm is reserved for the helium flow. Thus, the available physical aperture is 27 mm. (b) The mechanical tolerance is 1.6 mm (0.6 mm for cold bore and 1 mm for misalignment).[6] (c) The peak closed orbit error is 4 mm.[7] (d) The β-beat is 10%. (e) The allowed beam oscillation around the equilibrium orbit is 9σ (which

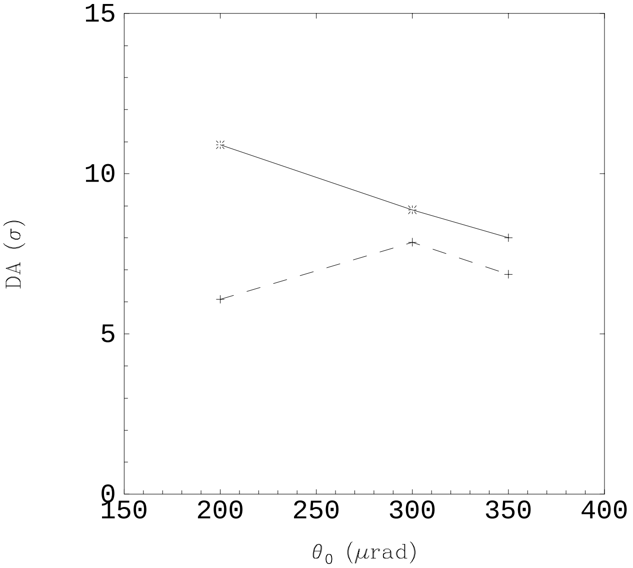

Figure 3: Dynamic aperture *vs.* crossing angle: The solid curve is the case when there are magnet errors but no beam-beam. The dashed one is when both magnet errors and beam-beam interactions are present. Below 300 μrad, the beam-beam is dominating, while above that, the triplet errors seem to take over.

corresponds to 7σ of the primary collimator and 9σ of the secondary halo).[8] Within the 9σ, the dynamic aperture needs to be $\geq 7\ \sigma$. (f) The crossing separation is $n\sigma$/2, where n is defined in Eq. (1). These numbers are still preliminary. The task of the tracking study is to find out how big the crossing angle needs to be (the value of n) in order to achieve a dynamic aperture of 7σ.

4 PLAN OF FUTURE STUDIES

A new iteration of tracking studies will include the following:

1. Use of the updated triplet error tables provided by the magnet builders Fermilab and KEK, respectively;

2. Study of the effects such as tune modulation, noises, x-y coupling, synchro-betatron resonances, particle offset in the 6-D phase space at the IP, closed orbit errors and Pacman, *etc.*

Based on these and other related studies to be made in collaboration with CERN, one should be able to:

- Determine the required triplet aperture;

- Make necessary trade-offs in the space budget;

- Identify the most damaging multipoles of the triplet for correction;

- work out a sorting strategy.

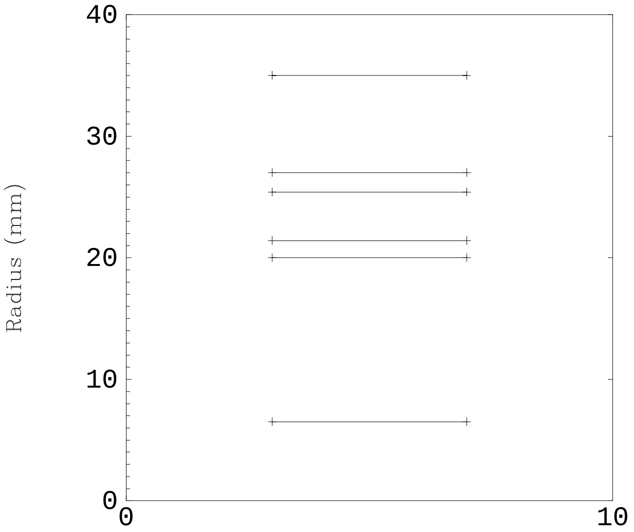

Figure 4: Space budget of the aperture of Q2 and Q3 at IP1 and 5. The quad radius is 35 mm. From that line down: (a) The radiation shielding takes 6 mm. Another 2 mm is reserved for the helium flow. (b) The mechanical tolerance is 1.6 mm (0.6 mm for cold bore and 1 mm for misalignment). (c) The peak closed orbit error is 4 mm. (d) The β-beat is 10%. (e) The allowed beam oscillation around the equilibrium orbit is 9σ (which corresponds to 7σ of the primary collimator and 9σ of the secondary halo). Within the 9σ, the dynamic aperture needs to be $\geq 7\ \sigma$. (f) The crossing separation is $n\sigma$/2, where n is defined in Eq. (1).

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6 REFERENCES

[1] J. Irwin, SSC-233, SSC Laboratory (September 1989).

[2] A. Faus-Golfe and A. Verdier, ‘Dynamic Aperture Limitations of the LHC in Physics Conditions due to Low-Beta Insertions,’ Proc. European Particle Accelerator Conference, June 10-14 1996, Sitges, Spain.

[3] D. Ritson, SLAC-TN-91-2, also SSCL-N-752 (March 1991).

[4] G. Sabbi *et al.*, ‘Magnetic Design of a High Gradient Quadrupole for the LHC Low-β Insertions,’ this conference.

[5] N.V. Mokhov and J.B. Strait, ‘Towards the Optimal LHC Interaction Region: Beam-Induced Energy Deposition,’ this conference.

[6] R. Ostojic, private communication.

[7] J-P. Koutchouk, private communication.

[8] J.B. Jeanneret and T. Risselada, LHC Project Note 66, CERN (September 1996).