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LHC DYNAMIC APERTURE INCLUDING THE BEAM-BEAM FORCE

L.H.A. Leunissen, H. Grote and F. Schmidt

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The LHC dynamic aperture in collision is constrained mainly by the beam-beam encounters, and by the field errors in the low-beta triplet quadrupoles. The nominal field errors were used and have been corrected with a local corrector scheme at each IP. The correction algorithm is explained, and the resulting dynamic aperture is shown. In the calculations, the effect of the crossing angle geometry, the beta-function, the bunch intensity and the pacman bunches on the dynamic aperture are studied. It is, however, also necessary to study how the unavoidable long range beam-beam encounters influence the dynamic aperture.

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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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Abstract

The LHC dynamic aperture in collision is constrained mainly by the beam-beam encounters, and by the field errors in the low-beta triplet quadrupoles. The nominal field errors were used and have been corrected with a local corrector scheme at each IP. The correction algorithm is explained,and the resulting dynamic aperture is shown. In the calculations, the effect of the crossing angle geometry, the beta-function, the bunch intensity and the pacman bunches on the dynamic aperture are studied. It is, however, also necessary to study how the unavoidable long range beam-beam encounters influence the dynamic aperture.

1 INTRODUCTION

The LHC model studied in this note is the new nominal collision machine (ATLAS, CMS, and LHCB with head–on collisions and halo collisions at ALICE) and we present an extension of previous tracking results [1]. The calculations are based on LHC version 6.0, with 15 parasitic crossing points on either side of each IP. The crossing angles are fixed throughout: $\pm 150\mu$rad vertical at IP1 and IP2 (alternating), $\pm 150\mu$rad horizontal at IP5 and IP8 (alternating).

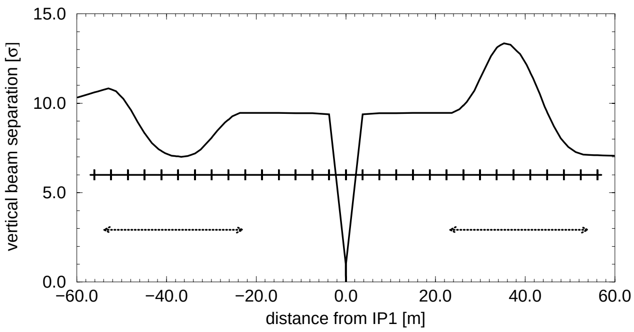

Figure 1: *Full bunch separation at IP1. The scale with the tick marks indicates the beam-beam encounter positions. Arrow head lines mark the ranges with triplet quadrupoles.*

The bunch sizes in the opposite beam appearing in the beam–beam element definition, and the beam separation in Figure 1 were taken from the orbits and beta-functions of the two matched rings including the latest separation bump scheme. The number of beam–beam encounters is somewhat arbitrary. However, 15 parasitic crossings are considered a reasonable choice since number 16 is already inside the beam separation dipole D1.

First, we present the low–beta quadrupole field errors used in the numerical studies. Then we show the correction formalism of the multipole components. Numerical calculations presented in the following paragraphs determine the influence of the crossing angle, β^* and tune modulation on the dynamic aperture.

2 TRIPLET ERRORS

Component		systematic	uncertainty	random
b3		0	0.72	0.36
b4		-0.175	0.83	0.36
b6		0.34	0.91	0.21
a3		0	0.69	0.34
a4		0	0.33	0.34
Component		systematic	uncertainty	random
b3		0	0.63	0.34
b4		0	0.22	0.34
b6		0.21	0.41	0.18
a3		0	0.32	0.34
a4		0	0.26	0.34

Table 1: *Low–beta quadrupole field errors for KEK version 4.x (upper) and FNAL version 3.1 (lower). Values are relative to the main field at $x = 17$ mm in units of* 10^{-4}.

The largest components of the latest triplet errors are given in Table 1. The body and end effects have been combined into one single number for the thin–lens approach used here: each triplet quadrupole is split into four thin–lens quadrupoles at each of IP1, IP2, IP5, and IP8.

3 CORRECTION SCHEME AND FORMALISM

On either side of IP1, IP2, IP5, and IP8 two corrector groups are placed as proposed by J. Strait at a CERN-KEK-US meeting, April 2000. Each corrector group contains several correction spools such that on either side of each IP one corrector exists for b_3, b_4, b_6, a_3, and a_4. The correction formalism follows the one outlined by A. Verdier and A. Faus–Golfe [2]. The principle is rather simple: with one corrector for each multipole component on either side of each IP, we compensate the total kick for purely horizontal, and purely vertical motion simultaneously.

4 DYNAMIC APERTURE CALCULATIONS

We present tracking studies for the LHC with and without the beam–beam interaction. The maximum radius for which the particles are stable for 10^5 turns is defined as the dynamic aperture (DA). The DA is calculated for five different phase space angles, $\phi = \mathrm{atan}(\sqrt{\epsilon_y/\epsilon_x})$ with $\phi =$

15°, 30°, 45°, 60° and 75° and ϵ_x, ϵ_y the horizontal and vertical transverse emittances, respectively. The tracking was performed with SixTrack [3] for 60 different sets of the random multipole distribution, called "seeds" in the following, of the triplet errors at collision energy.

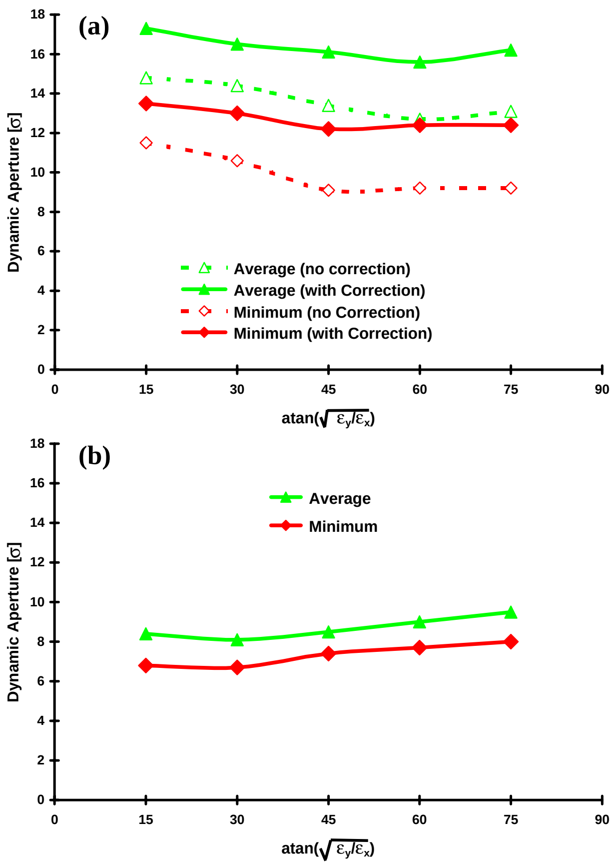

Figure 2: *Dynamic Aperture without (part a) and with (part b) beam–beam interaction (triplet correction included). Tracking performed for* 10^5 *turns.*

Figure 2a shows that the triplet errors reduce the average and minimum dynamic aperture to about 13 σ and 9 σ, respectively. This is mainly due to the b_6 component of the quadrupoles. The correction system, as described above, raises the dynamic aperture to more than 15 σ and 12 σ, respectively. When including the beam–beam interaction (Figure 2b), and the triplet errors and their correction, the dynamic aperture goes down to values around 8.5 σ and 6.8 σ, respectively.

Table 2 holds the data of all previously discussed cases.

The DA is mainly limited by the parasitic beam crossings. This is shown by calculations in which either the head–on or the parasitic collisions are switched off. For example, after the head–on collisions are turned off at IP1, IP2, IP5 and IP8 the DA (for 5 phase space angles) remains the same. However, when only head–on collisions are inserted in the calculations, the minimum DA goes up to more than 13 σ. To increase the dynamic aperture the effect of the parasitic beam crossings should be reduced.

Case	DA	15°	30°	45°	60°	75°
Before	Min.	11.5	10.6	9.1	9.2	9.2
Corr.	Av.	14.8	14.4	13.4	12.7	13.1
After	Min.	13.5	13.0	12.2	12.4	12.4
Corr.	Av.	17.3	16.5	16.1	15.6	16.2
After	Min.	6.8	6.7	7.4	7.7	8.0
Corr.	Av.	8.4	8.1	8.5	9.0	9.5

Table 2: *Computed DA for the LHC with triplet errors at collision energy without (upper) and including beam–beam interactions (lower). Each time the minimum of, and the average over 60 seeds are given. The angle is* $\phi = \mathrm{atan}(\sqrt{\epsilon_y/\epsilon_x})$.

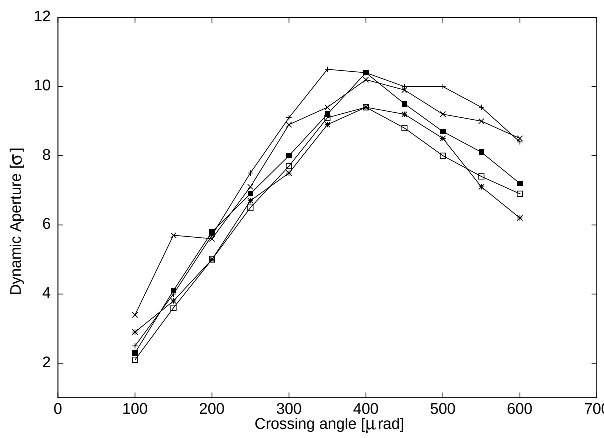

Figure 3: *DA as function of the crossing angle at IP1 and IP5. The symbols are represented by: 15° = +, 30° = ×, 45° = ∗, 60° = white box, 75° = black box.*

Changing the crossing angle results in different bunch separation in the interaction region and changes the strength of the parasitic crossings. For one seed, the crossing angle is varied and the luminosity is kept constant (10^{34} cm^{-2}s^{-1}) by adjusting the bunch intensity accordingly. The crossing angles at IP1 and IP5 are changed simultaneously while keeping the crossings at IP2 and IP8 constant, see Figure 3. In this plot the five lines indicate the different phase space angles (15° = $+$, 30° = $\times$, 45° = $*$, 60° = white box, 75° = black box). This result shows that an increase in crossing angle to 400 μrad would improve the DA by 2 σ. The DA increases from 0 to 400 μrad due to the increase of bunch separation. A further increase of the crossing angle results in a decrease of the DA. This is the effect of the large particle orbit in the low–beta quadrupoles.

The intensity of the bunch influences the beam–beam kick. Figure 4 shows the change of DA as function of the bunch intensity (nominal 10^{11} particles). In this plot $0.7 \cdot 10^{11}$ particles correspond to a luminosity of $0.4 \cdot 10^{34}$ cm^{-2}s^{-1} and $1.4 \cdot 10^{11}$ particles per bunch gives a luminosity of $1.6 \cdot 10^{34}$ cm^{-2}s^{-1}. The increase of the bunch intensity reduces the DA by approximately 2 σ over the indicated luminosity range. The beam–beam parameter changes from 0.0023 to 0.0046.

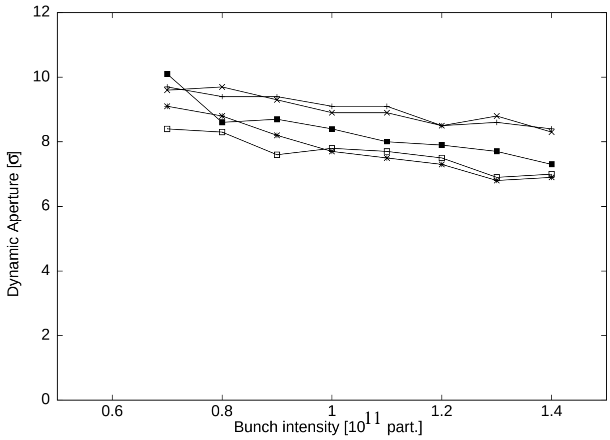

Figure 4: *DA as function of the bunch intensity for a crossing angle of 300 μrad. For the legend, see Figure 3.*

For coherent effects it can be important to have the two rings operating with different tunes [4]. Two working points have been selected [5] for operation of the LHC. They are: Q_x=0.232, Q_y=0.242 (average DA = 7.6 σ) and Q_x=0.285, Q_y=0.295 (average DA = 7.6 σ), respectively. The average is taken over the five different phase space angles and the crossing angle is 300 μrad. Tracking has shown that both working points yield approximately the same dynamic aperture during collision as with the nominal tunes (Q_x=0.310, Q_y=0.320, average DA = 8.1 σ).

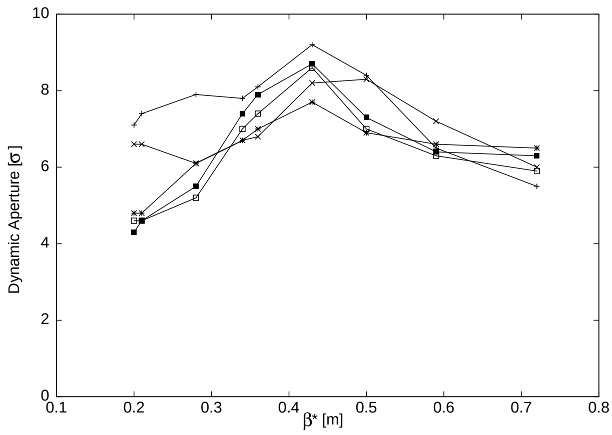

Figure 5: *DA as function of β^* at IP1 and IP5 at constant separation. For the legend, see Figure 3.*

Investigation of another tune Q_x=0.307, Q_y=0.317 is done to shift the footprint away from the third-order resonance. This should result in a larger DA. However, the distance to the 7th-order resonance is decreased resulting in an average DA of 7.7 σ.

Figure 5 shows the dependence of the DA on the β^*–function at the IP. The crossing angle is varied simultaneously with the β^*–function so as to maintain a constant separation at the parasitic collision points. The figure indicates that the DA peaks at a β^* of 0.4 m and reduces to 4 σ at a β^* of 0.2 m.

The dependence of the DA on the relative momentum deviation was also tested. For 60 different seeds the relative momentum deviation δ was reduced by 50 % (the nominal value of the bucket half height is $\delta = 0.00036$). Table 3 shows the result for this calculation.

	ϕ				
Dyn. Aper.	15°	30°	45°	60°	75°
Minimum	6.2	7.4	6.8	6.3	7.2
Average	8.9	8.4	8.2	7.8	8.3

Table 3: *Computed DA for the LHC with triplet errors at collision energy with half the bucket height.*

The DA is not influenced by reducing the amplitude of the synchrotron oscillation.

5 CONCLUSIONS

Tracking has been performed for the LHC lattice version 6.0 at collision energy without and including the beam–beam interaction. Each interaction zone carries the triplet errors of either FNAL or KEK and a correction system has been implemented to counteract mainly the b_6 component. The correction has shown to be very effective for the case without the beam–beam interaction. But there is also a considerable improvement when this interaction is included, resulting in a minimum dynamic aperture of some 6 σ for 10^5 turns. It is therefore advisable to increase the total crossing angle to 400 μrad which results in a net gain of roughly 2 σ. This gain should not lead to a substantial loss in luminosity since the particle intensity can be adjusted without noticeable change in the dynamic aperture.

6 REFERENCES

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