LHC Project Note 310

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Dynamic Aperture Studies for LHC Optics Version 6.2 at Collision

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Summary

This note summarizes the results of dynamic aperture studies for the LHC optics V6.2 at collision energy. The effects of the triplet errors and beam–beam interactions on the dynamic apertures are extensively studied. The dependence of the dynamic apertures on the particle numbers per bunch are calculated. The chaotic bounds are determined for these tracking runs for 10^5 and 10^6 turns tracking respectively.

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1 Introduction

Previous studies have been done for LHC lattice version V6.0 and were reported in Ref. [1]. Although the LHC triplet errors have not changed since then (see Table 1) and although we use the same correction system it became necessary to redo the beam–beam tracking study for the LHC lattice version V6.2 due to the fact that there have been substantial changes in the optics in the IPs, which may have implications for the dynamic aperture in collision.

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* $x = 17mm$ *in units of* 10^{-4}.

The LHC model studied in this note is based on the LHC version 6.2, with ATLAS, CMS, LHCB headon collisions and ALICE halo collisions at collision energy. The lattice is anti–symmetry about four IPs. At the collision energy, the multipolar components of the triplet quadrupole, i.e. b_3, b_4, b_6 and a_3,a_4 play an important role in reducing the dynamic apertures and have to be corrected with local correctors on both sides of the IPs . There are a total 124 beam–beam encounters, including the head–on and long range interactions, around the four IPs. At collision, the separation is about 9.5 σ [1]. The beam–beam interactions have been simulated with a weak–strong tracking model.

Straight Section	Plane	IP1	IP2	IP5	IP8
β^* [m]	both	0.5	10	0.5	10
Total Crossing	horizontal			300	300
Angle [μrad]	vertical	300	300		
Half Separation [mm]	horizontal		1.0		
Triplet Correction	–	on	off	on	off

Table 2: *Lattice parameters at the experimental IPs.*

For the LHC dynamic aperture study the code SixTrack [2] is used. The dynamic aperture (DA) is defined as the maximum radius for which the particles are stable for 10^5 or 10^6 turns. For each phase space angle we take the minimum dynamic aperture of 60 different sets of error distributions, called seeds in the following. The phase space angle is defined as $\phi = \arctan(\sqrt{\epsilon_y/\epsilon_x})$, with ϕ =15°, 30°, 45°, 60° and 75°, where ϵ_y and ϵ_x are vertical and horizontal Courant–Snyder emittances [3] respectively.

In the nominal tracking case the triplet errors are considered with their corrections and the beam–beam interactions are included, both head–on and long range. In order to check the effects of the various triplet error corrections and the beam–beam interactions we have studied the dynamic apertures for a combination of errors with and without the beam–beam force. As expected from earlier studies the beam–beam interactions lead to a dramatic reduction of the dynamic aperture, in particular for longer term tracking (10^6 turns). Among the triplet errors, the b_6 component in the triplet quadrupoles is by far the most important in reducing the dynamic aperture. However, we have found that these findings have no longer valid when the beam–beam interactions have been introduced. Lastly, the dynamic aperture versus bunch intensity has been calculated.

In the Appendix Table 3 is found that holds the results of all tracking runs.

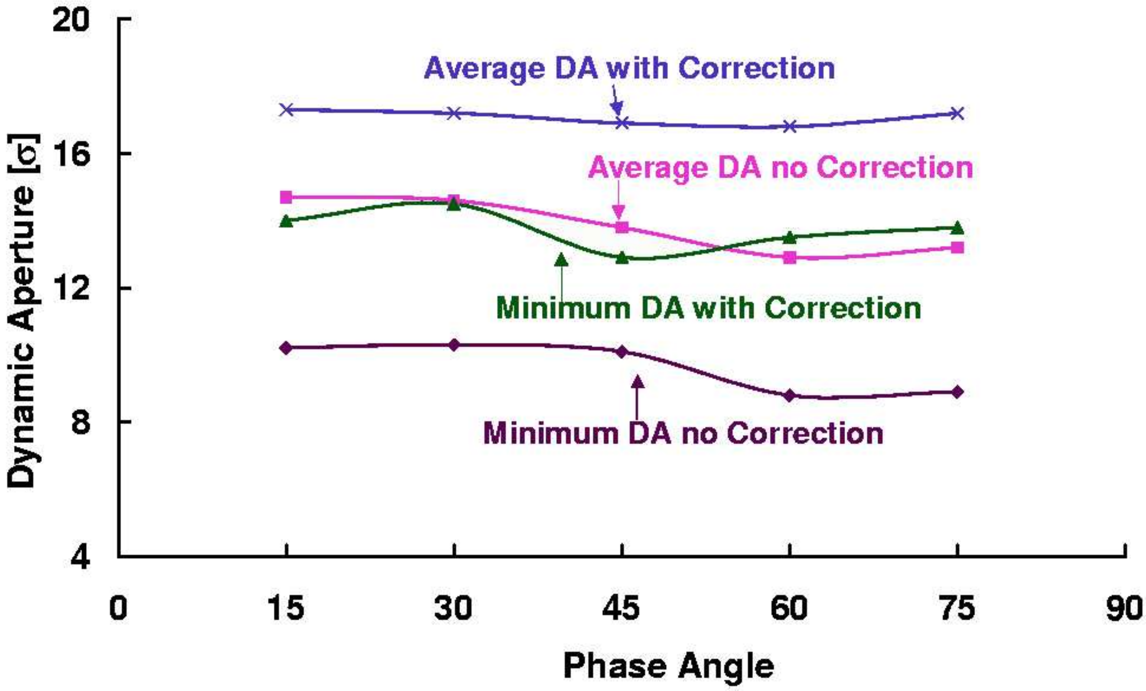

Figure 1: *Average and minimum dynamic apertures without and with the correction of low–beta triplet field errors. The beam–beam interaction is not included and the tracking has been performed for* 10^5 *turns.*

2 Dynamic Aperture at Collision without Beam–Beam

The nominal correction scheme of the low–beta triplet errors has been investigated for the LHC V6.2 in collision but without beam–beam interactions. Figure 1 shows the average and minimum dynamic apertures among the 60 seeds for 10^5 turn tracking. The triplet errors reduce the average and minimum dynamic aperture to 12.9 σ and 8.8 σ respectively. This is mainly due to the large b_6 component of the triplet errors (but see section 4). After applying the local triplet corrections of b_3, b_4, b_6, a_3 and a_4 as described in Ref. [4], the average and minimum dynamic aperture increase to 16.8 σ and 12.9 σ respectively, i.e. larger by some 4 σ. We can therefore conclude that the triplet correction scheme is indeed effective for LHC lattice version V6.2.

3 Dynamic Aperture at Collision including Beam–Beam

With the full triplet error corrections as described above, the tracking is done including the beam–beam interactions. Figure 2 shows the average and minimum dynamic apertures for tracking with 10^5 and 10^6 turns. The 10^5 turn average and minimum dynamic aperture are found to go down to 8.6 σ and 7.7 σ. While for the 10^6 turn tracking, they drop to 7.2 σ and 6.4 σ respectively. As for the earlier LHC lattice versions the beam–beam interaction play an important role in reducing the dynamic aperture at collision energy. In particular, there is a large additional reduction between 10^5 and 10^6 turns which we do not observe without the beam–beam interaction. Our conjecture for this large reduction of the DA is the following: the parasitic crossings make the motion very slightly chaotic at small amplitudes. It therefore takes the particles a very long time until they reach large amplitudes where the magnet nonlinearities lead to a fast particle loss. [1]

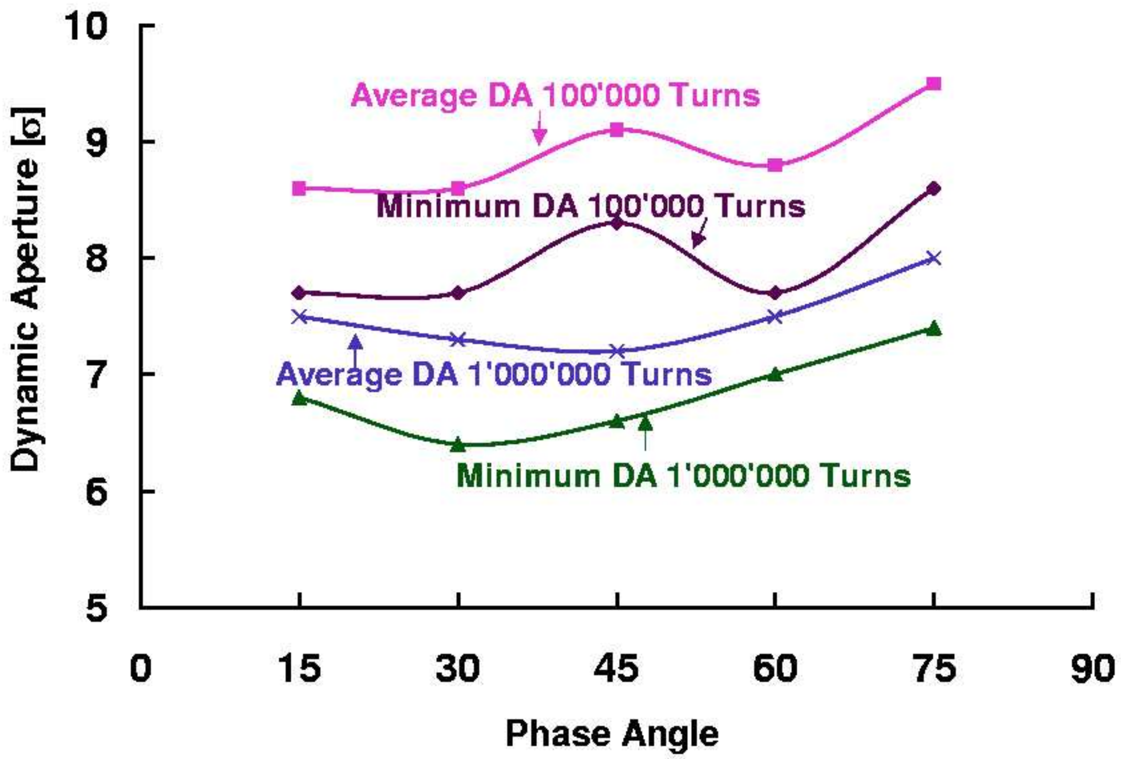

Figure 2: *Average and minimum dynamic apertures at collision including beam–beam interactions. The tracking is performed for* 10^5 *and* 10^6 *turns.*

4 Dynamic Aperture with b_6 Triplet Correction only

In earlier studies it had been found that in absence of the beam–beam interactions the correction of just the b_6 component of the triplet quadrupoles is almost as effective as the full correction package to recover the dynamic aperture. Figure 3 shows the minimum dynamic apertures (beam–beam interaction included) for 10^5 and 10^6 turn tracking for the following cases: without any correction, with the full triplet corrections and with a b_6 correction only.

For 10^5 turns the b_6 correction is still quite effective compared to the full correction for the larger angles, i.e. predominantly vertical motion. However, after 10^6 turns there is no more any improvement of the dynamic aperture due to the b_6 correction. Apparently, the uncorrected multipolar components, which are not dangerous without beam–beam, lead to a very slow particle losses in the presence of the beam–beam interactions. On the other hand after 10^6 turns the gain in the dynamic aperture due to the full correction system is little more than 1 σ and only for predominantly horizontal motion. In essence one can say that the beam–beam force is very dangerous for particle stability even for very weak nonlinearities and that the full triplet correction system will lead, at best, to a 20% increase of the dynamic aperture.

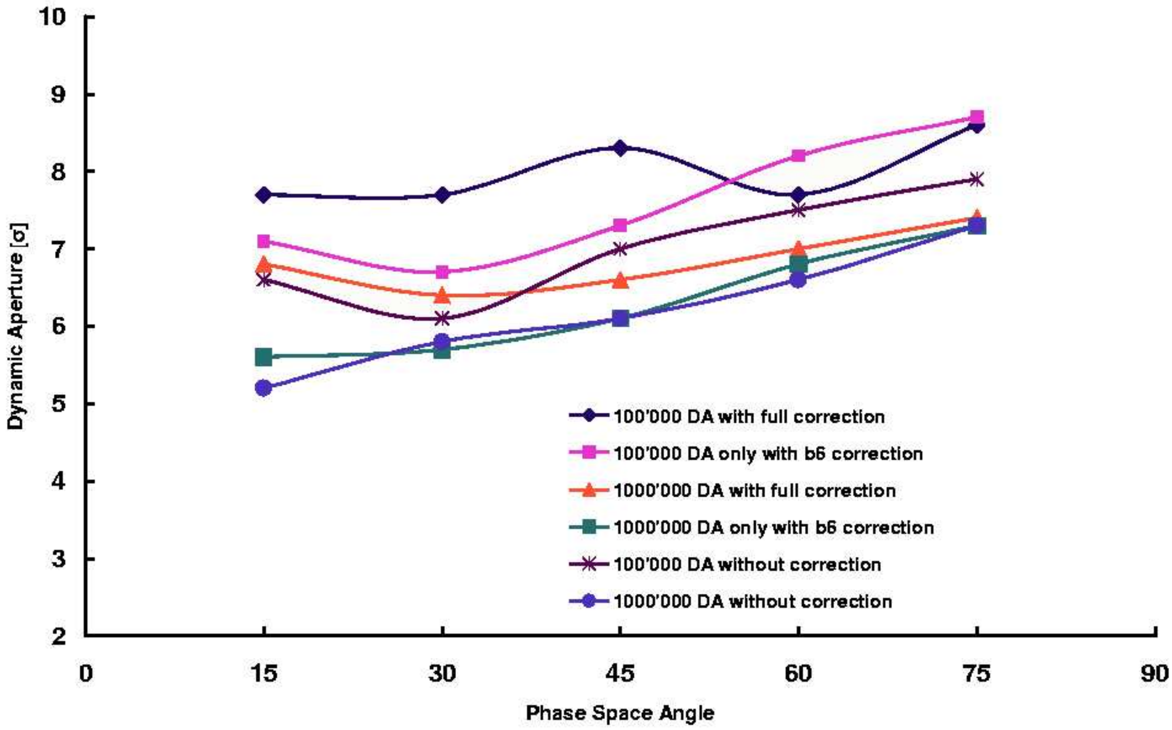

Figure 3: *Minimum dynamic apertures at collision: without correction, for the full triplet error correction and for the correction of just the* b_6 *component. The beam–beam interactions are included and the tracking is performed for* 10^5 *and* 10^6 *turns.*

5 Early Indicator of Particle Loss

Chaos is detected by following the evolution of the distance of phase space of two initially close–by particles [5]. Following the definition "chaotic spikes" in Ref. [1], we have checked the chaotic bounds for LHC lattice version V6.2. Our approach is to choose a certain width of the chaotic spike, in our case 0.3σ, as a criterion for very long–term losses. An example of such a chaotic spike after 10^5 turns can be found in Fig. 4.

Figure 5 shows the spikes found for the 300 individual tracking runs that are made in a typical study case (60 seed and 5 phase space angles). Four different curves can be identified: the upper two curve shows the dynamic aperture for 10^5 and 10^6 turns respectively; the lower

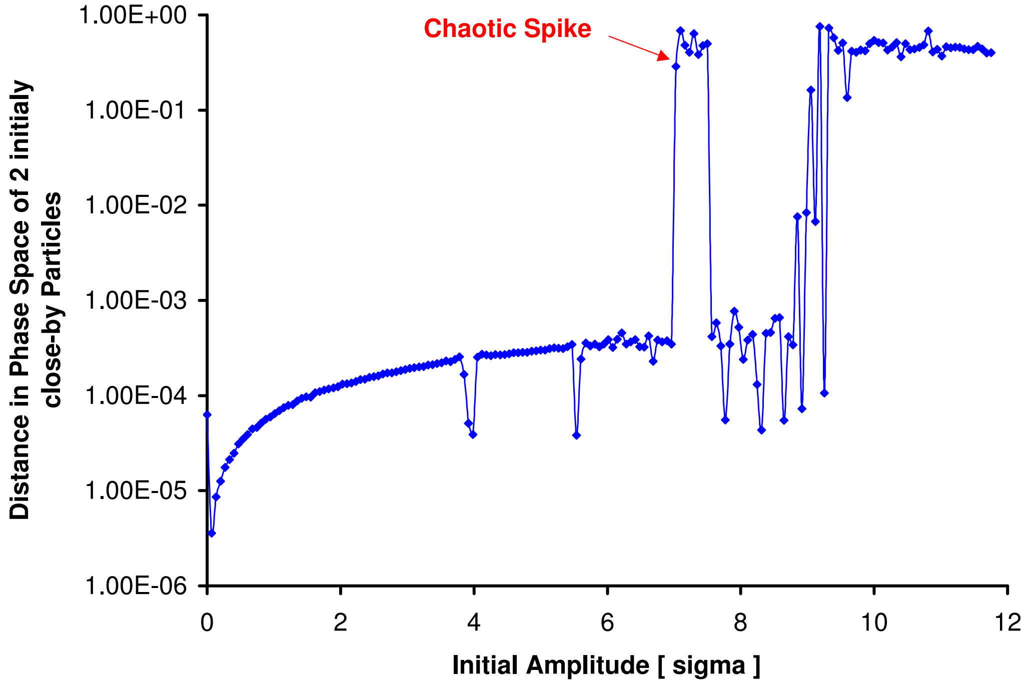

Figure 4: *Example for a chaotic spike. It is defined as a chaotic region of a certain width within otherwise regular and therefore stable motion. This has to be distinguished from the broad onset of chaos where particle loss sets in rather quickly.*

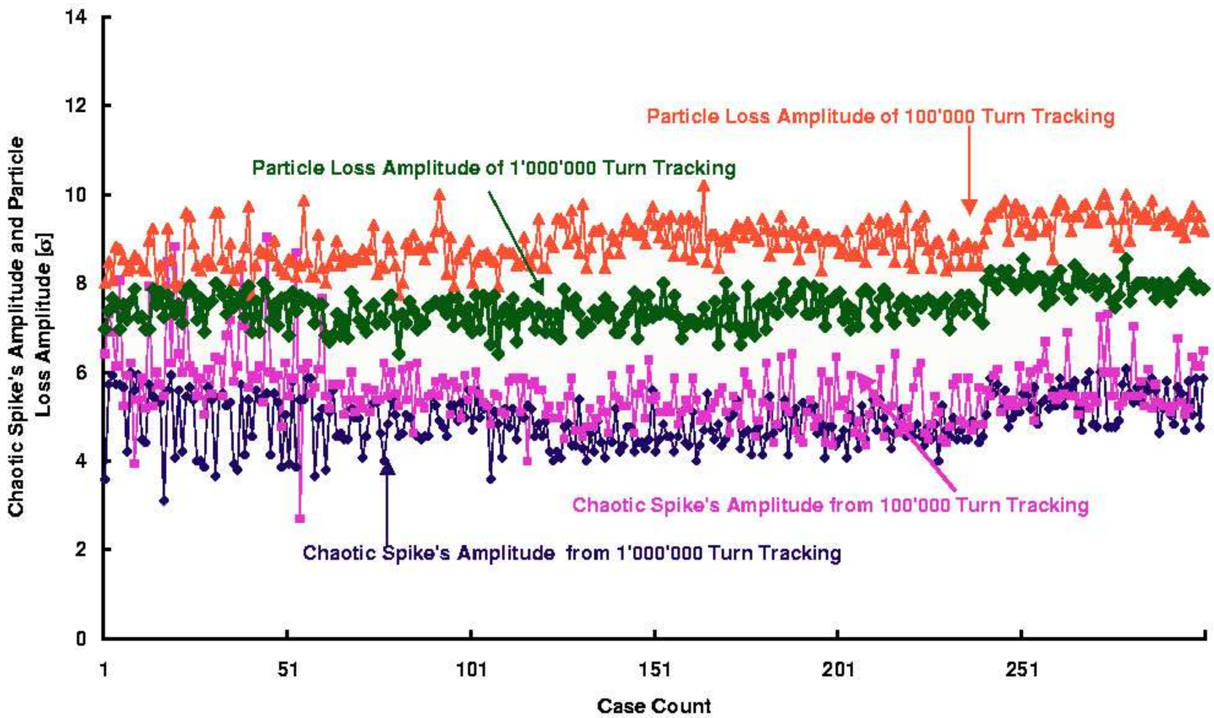

Figure 5: *DA and the chaotic spikes derived from* 10^5 *and* 10^6 *turn tracking, respectively.*

two curves depict the chaotic spikes derived from 10^5 and 10^6 turns respectively. While the dynamic aperture drops by 1–2 σ between 10^5 and 10^6 turns the chaotic boundary, detected via spikes, remains quite stable. This gives us confidence that this method gives a good estimate for the very long–term dynamic aperture. On the other hand this leaves us with an estimate of about 4 σ for the LHC lattice version V6.2 (at 10^6 turns the spread is between $4 - -6$ σ with a few seeds even below 4 σ).

6 Dynamic Apertures versus Particle Numbers

The beam–beam force is directly proportional to number of particles of the other beam, but it remains to be tested how this actually affects the dynamic aperture. The tested number of particles are 0.667, 0.833, 1.2, 1.5 times the nominal particle number per bunch which is 1.0510^{11}. Figure 6 shows how the 10^5 turn minimum dynamic aperture changes with respect to the ratio of the tested particle number with respect to the nominal one. In the studied range of particle numbers one finds, more or less, a linear dependence with changes of ± 1 σ for the dynamic aperture at the extremities of the particle ratios.

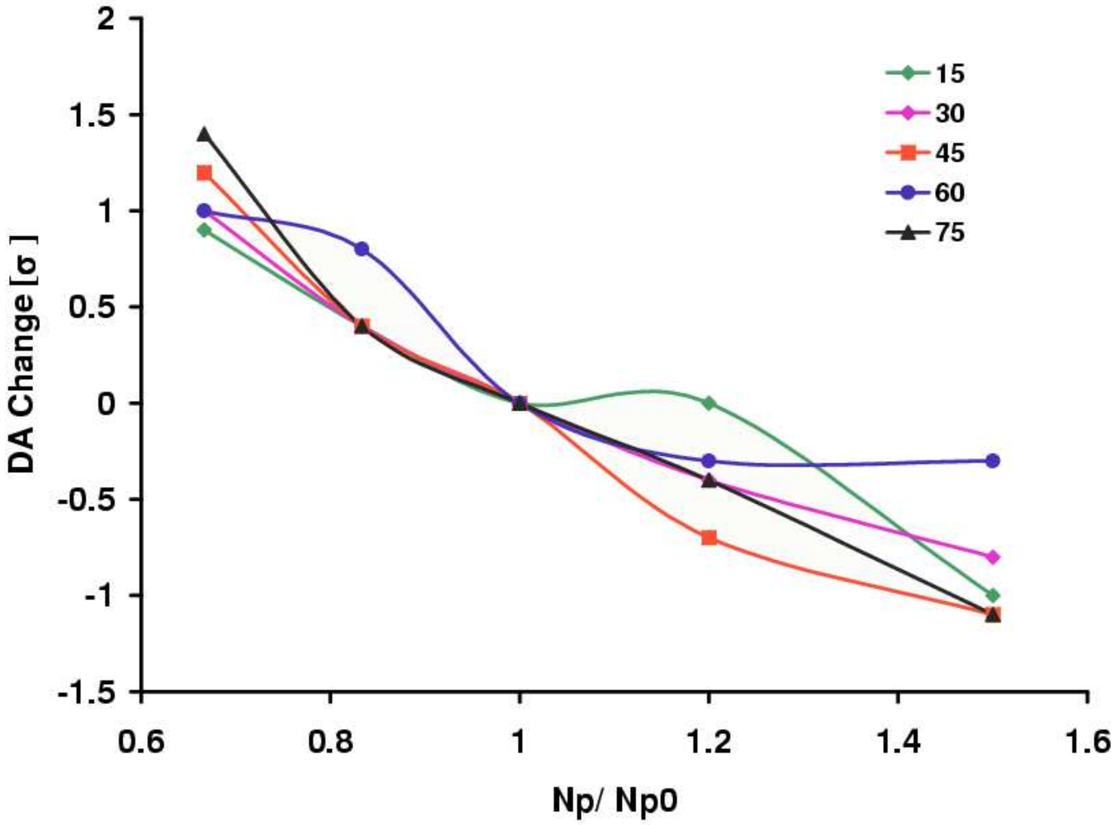

Figure 6: *Minimum dynamic apertures versus the ratios of tested particle numbers per bunch compared to the nominal one. The tracking is performed for 10^5 turns and for the five phase space angles.*

7 Conclusion

Tracking studies have been done for the LHC lattice version V6.2 at collision. As expected, the beam–beam interactions lead to a large reduction of the dynamic aperture. It has been found that very small nonlinearities are sufficient to lead to particle losses when the beam–beam force is present. As an effect, the benefits of the triplet correction system are much reduced, in particular when longer term tracking is performed. The detection of chaotic spikes has shown to be a useful estimate for the long–term dynamic aperture. However, long–term tracking studies over at least 10^7 turns are needed to confirm a dynamic aperture of just 4 σ, for some seeds even below, for the LHC lattice version V6.2. It is also mandatory to test if there is a more favorable tune working point or if one should change the phase advance between IPs. Lastly, it has been shown that a variation between 2/3 and 3/2 of the nominal bunch particle number varies the dynamic aperture by some ± 1 σ or about $\pm 15\%$.

References

[1] Y. Luo and F. Schmidt, "Weak–Strong Beam–Beam Tracking for LHC V6.0 ", LHC Project Report 502.

[2] F. Schmidt, "Run Environment for SixTrack", Beam Physics Note 53,

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[5] F. Schmidt, F. Willeke and F. Zimmermann, "Comparison of methods to determine long–term stability in proton storage rings", CERN SL/91–14 (AP), DESY HERA 91–07, Part. Accel. **35**, pp. 249–256 (1991), http://wwwslap.cern.ch/frs/report/lyasl.ps.gz.

8 Appendix

Case	BB	Triplet Corr.	Part. # [10^{11}]	Turns [10^5]	Tracking Results									
					15		30		45		60		75	
					Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.
1	NO	NO	1.05	1.0	10.2	14.7	10.3	14.6	10.1	13.8	8.8	12.9	8.9	13.2
3		full			14.0	17.3	14.5	17.2	12.9	16.9	13.5	16.8	13.8	17.2
5	YES	NO			6.6	8.4	6.1	8.4	7.0	8.7	7.5	8.6	7.9	9.2
6				10.0	5.2	6.9	5.8	6.8	6.1	7.0	6.6	7.3	7.3	7.8
7		full		1.0	7.7	8.6	7.7	8.6	8.3	9.1	7.7	8.8	8.6	9.5
8				10.0	6.8	7.5	6.4	7.3	6.6	7.2	7.0	7.5	7.4	8.0
9		only b6		1.0	7.1	8.5	6.7	8.5	7.3	8.8	8.2	8.8	8.7	9.4
10				10.0	5.6	7.4	5.7	7.0	6.0	7.1	6.7	7.4	7.3	8.0
11		full	0.7	1.0	8.6	10.3	8.7	10.0	9.5	10.4	8.7	9.9	10.0	10.7
12			0.875		8.1	9.3	8.1	9.1	8.7	9.7	8.5	9.2	9.0	9.9
13			1.26		7.7	8.2	7.3	8.3	7.6	8.5	7.4	8.4	8.2	8.8
14			1.575		6.7	7.7	6.9	7.8	7.2	7.9	7.4	8.0	7.5	8.2

Table 3: *The minimum and average dynamic aperture for different cases .*