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Results of 6D Tracking For LHC Lattice v.5.0 with Insertion Region Triplet Errors

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Abstract

This report summarizes 6D tracking results obtained for LHC lattice version 5.0 at collision energy. The focus is on the evaluation of dynamic aperture reduction by magnetic errors in quadrupoles of inner triplets of low-β insertion regions.

1 Introduction

This work is in the course of US-LHC collaboration and its purpose is to evaluate the effect of magnetic field errors in inner triplet quadrupoles (MQX) on a proton beam dynamics at collision energy ($E = 7$ Tev). These quadrupoles will be produced by LHC collaborators from Fermi National Accelerator Laboratory (USA) and KEK Laboratory (Japan), and will be installed near LHC interaction points to create designed beam focusing at the IPs. Among four LHC interaction ponts two points, IP1 and IP5, are designed to have beta function as low as 0.5 meters. This leads to large beta function values ($\simeq$ 4700m) at the MQX locations. Consequently the errors in these quadrupoles have strongly enhanced effect on beam dynamics. It is expected that at collision energy dynamic aperture would be determined mainly by the MQX.

Let's note that at these studies only magnetic errors in MQX have been taken into account. All the other magnets in LHC rings were assumed to have a designed field and to be perfectly aligned.

The object of interest is long-term dynamic aperture. The required dynamic aperture was defined to be at least 6σ[1]. Time scale for LHC storage is several hours, and, of course, the tracking for this time is far beyond the power of modern computers. So, what is called long-time tracking in this report is the tracking for 50000 turns or just few seconds. A border in betatron amplitude space, beyond which there are particle losses during these 50k turns, determines a survival aperture for this time period. Estimations on the basis of theoretical and experimental works were done to find out what a value would be for required survival aperture obtained from the tracking[2]. Finally, according to discussion with CERN SL/AP in March 1998, the target survival aperture from 50k turns tracking with magnetic errors only is twice as large as the required dynamic aperture, i.e. 12σ.

The collision optics of LHC includes beam-beam collision with a total crossing angle up to 300μrad at all four interaction points. To see clearly the effect of crossing angle on dynamic aperture the tracking studies were carried out in two stages. Firstly, the detailed tracking studies were performed for the lattice without crossing angles. After that, optics modifications corresponding to the crossing angles in horizontal plane were added to the LHC lattice and the tracking cycle using the same seeds of magnetic errors was done. Below the results will be presented both for the lattices with and without crossing angles.

2 Tracking Setup and Machine Model

Tracking was performed with FORTRAN version of TEAPOT code[3]. To take into account synchrotron oscillations RF cavities have been used with the total voltage 16 MV and harmonic number 35640. The correctness of the model and the 6D TEAPOT tracking was verified by extracting from tracking the values of synchrotron tune ($\simeq 0.0021$) and bucket half height ($\simeq 0.35 \cdot 10^{-3}$) that are in good agreement with theoretically calculated values.

Initial coordinates for particles were choosen at 0.5σ step in five directions in transverse X-Y plane with $p_x = p_y = 0$. The initial relative energy deviation for all particles was $0.222 \cdot 10^{-3}$ that corresponds to 2σ of beam energy deviation.

The tracking proceeded in two steps. On first step short-term tracking for 1000 turns was performed in a wide range (typically from 3 to 18 σ) of initial amplitudes. After that, on the second step the long-term tracking for 50000 turns was performed for $3-4\sigma$ (in rare cases even more) just below found short-term survival aperture. The results from short-term tracking were used sometimes also to compare relative effect coming from various kind of magnetic errors.

The magnetic errors were taken from an error table v.1.0 for expected harmonics for High Gradient Quadrupoles obtained from G.Sabbi (FNAL) [4]. These errors are listed in Table 1. European convention is used in this Table with b1, a1 harmonics corresponding to dipole field. Let's note that these errors were applied to all MQX including those which must be made by KEK. 10 different seeds of magnetic errors generated on the basis of Table 1 were used at tracking studies.

Order, n	Normal			Skew		
BODY [unit]	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
3	0.0	0.2	0.5	0.0	0.2	0.5
4	0.0	0.09	0.3	0.0	0.09	0.3
5	0.0	0.04	0.07	0.0	0.04	0.07
6	0.0	0.02	0.03	0.0	0.02	0.03
7	0.0	0.01	0.008	0.0	0.01	0.008
8	0.0	0.004	0.003	0.0	0.004	0.003
9	0.0	0.002	0.0016	0.0	0.002	0.0016
10	0.0003	0.0009	0.0005	0.0	0.0009	0.0005
LEAD END [unit-m]	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
2	0.0	—	—	16.	—	—
6	0.27	—	—	0.0083	—	—
10	-0.0013	—	—	-0.00046	—	—
RETURN END [unit-m]	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
6	0.046	—	—	0.0	—	—
10	-0.0013	—	—	0.0	—	—

Table 1: HGQ magnetic errors in units of 10^{-4} of the main quadrupole field at 1 cm reference radius.

For tracking with the crossing angle the variant of LHC lattice was prepared with the help from J.Miles (CERN). The lattice utilizes dipole correctors that create beam orbit passing off-center in the inner triplet quadrupoles and provide $\pm 150\mu$rad angle in horizontal plane at all interaction points (and, hence, the total crossing andgle is 300μrad in this case).

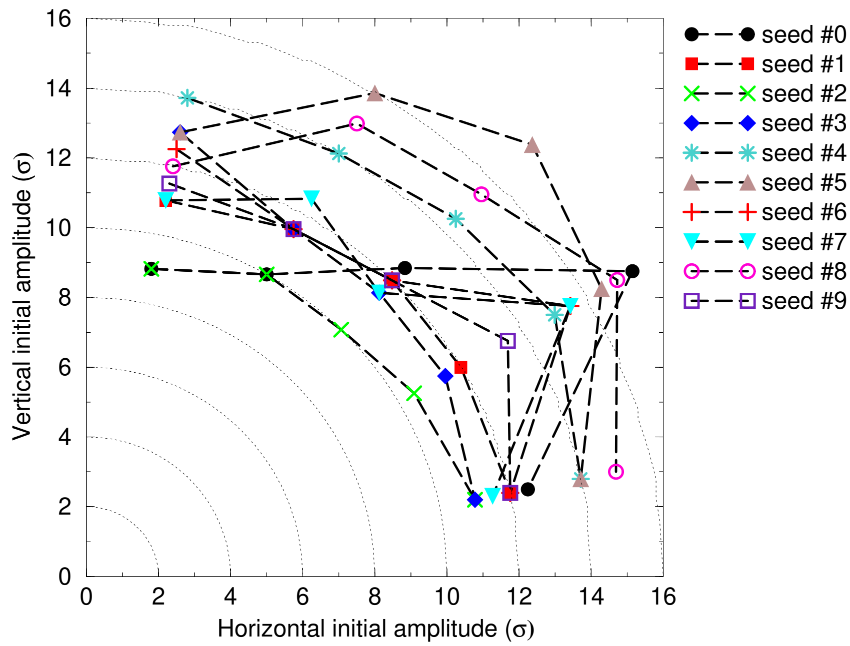

Figure 1: The 50k turn survival aperture for 10 seeds of magnetic errors in MQX

3 Results for the Lattice without Crossing Angle

Figures 1 and 2 provide the summary of results for 50k turns survival aperture at head-on collision. On the Figure 1 the results for all 10 seeds of magnetic errors are shown. The errors include both random and systematic errors in quadrupole bodies and ends. The worst survival aperture was found in the seed #2 and is 8.5σ in nearly vertical direction.

The Figure 2 shows the average over 10 seeds as well as reveals a contribution from systematic error. The quantity ϵ_x/ϵ_T characterizes a direction in $x-y$ plane. Actually this is $\cos^2\phi$ where ϕ is a polar angle in transverse plane encountered from horizontal axis. The survival aperture averaged over all five directions in $x-y$ plane is: $12.7 \pm 1.8\sigma$ and is above the target survival aperture of 12σ. In general survival aperture in vertical direction is about 1σ lower than in horizontal.

The survival aperture at the presence only systematic errors in inner triplet quads was found to be about 14.3 in average with quadrupole end errors and about 15.8 in average without end errors.

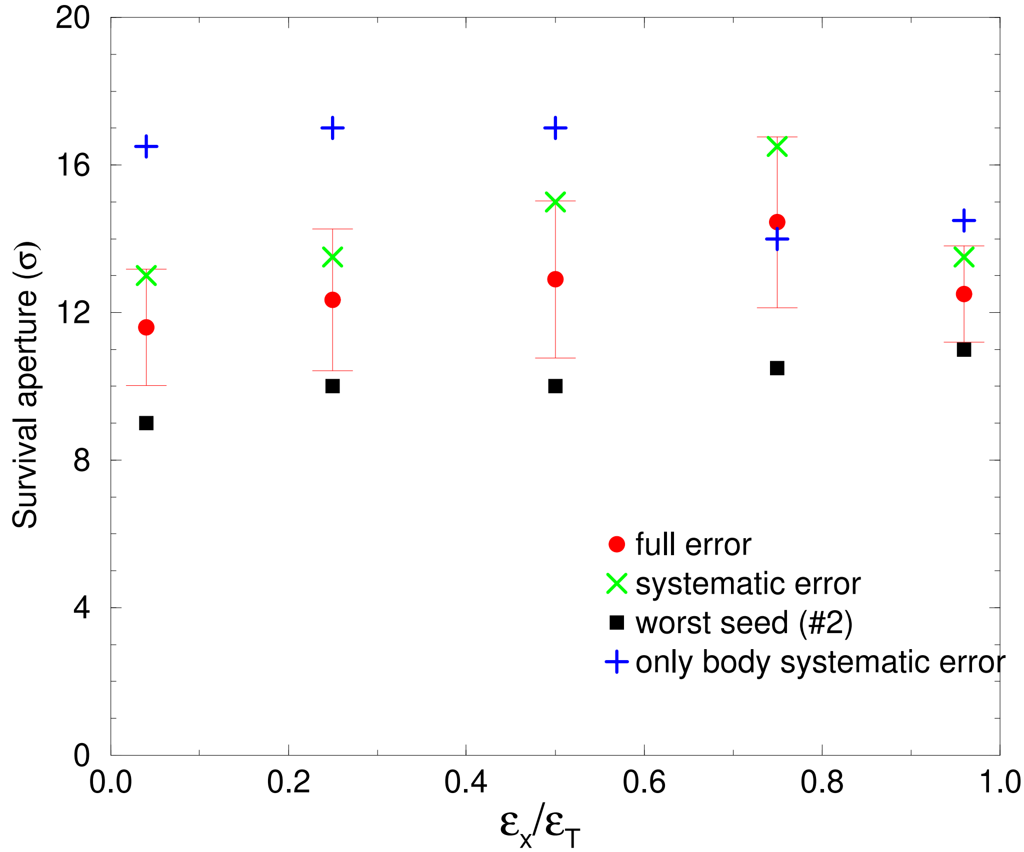

Figure 2: The survival aperture versus a direction in transverse plane. The data averaged over 10 seeds of all magnetic errors in MQX are shown (circles), as well as worst results (squares) and the data with the systematic errors only (crosses)

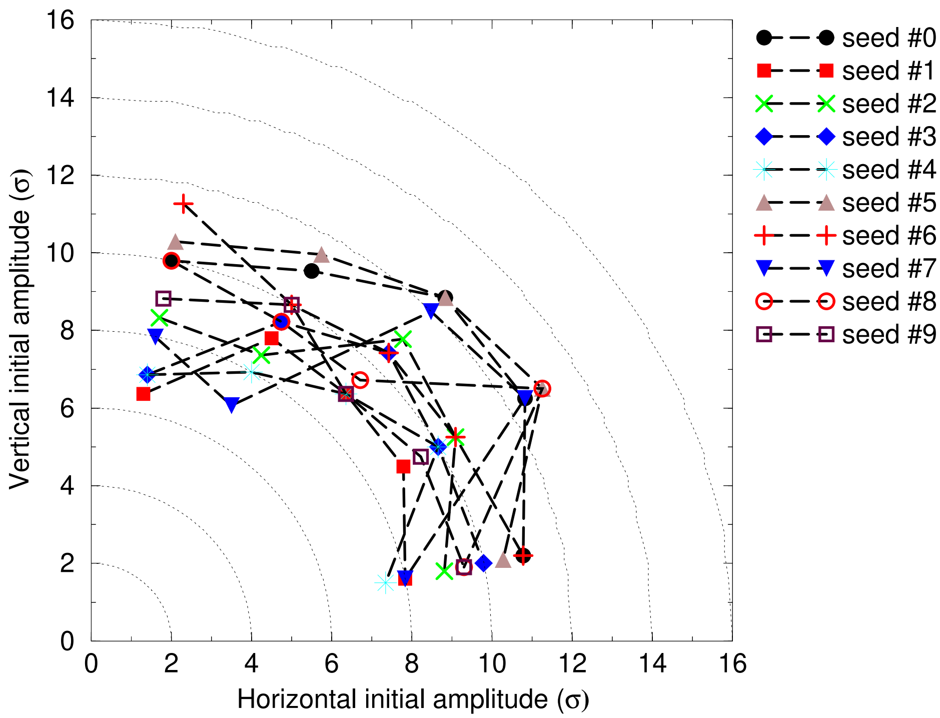

Figure 3: The 50k turn survival aperture for 10 seeds of magnetic errors in MQX for the lattice with crossing angle $300 \mu rad$.

4 Results for the Lattice with Crossing Angle

4.1 Survival aperture

In Figure 3 the results from the tracking with orbit angle equal to 150μrad at interaction points are presented for all 10 seeds of magnetic errors. From this figure the minimal aperture is seen to be 6.5σ for the seed #1.

The average results for full error (random + systematic) are shown in Figure 4 as well as the results obtained with the systematic errors only. The survival aperture averaged over all five directions is $9.8 \pm 1.6\sigma$.

Comparing the data with previous tracking data obtained for the lattice without crossing angle one can conclude that the survival aperture goes down by about 3σ. Also the influence of systematic errors is slightly increased. Tracking with only systematic errors provides 11σ average survival aperture.

The 1000 turns tracking has been used to compare the contribution from different

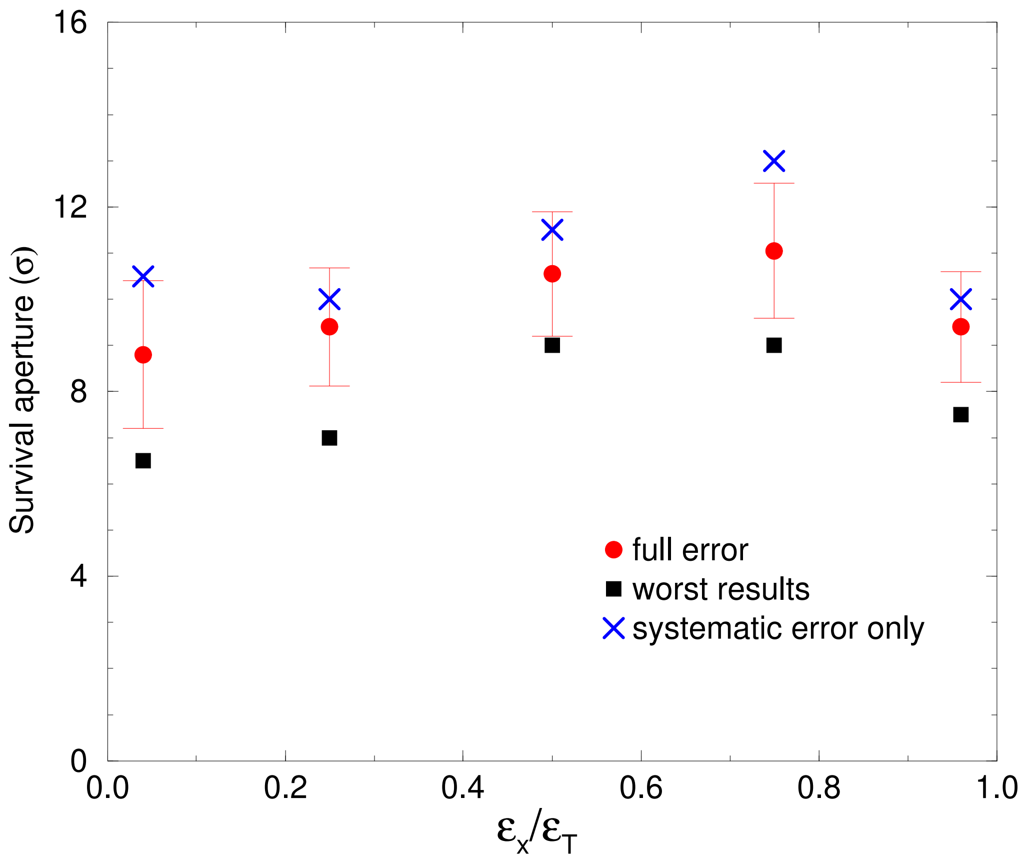

Figure 4: The survival aperture versus a direction in transverse plane for the lattice with crossing angle $300\mu rad$. The data averaged over 10 seeds of all magnetic errors in MQX are shown (circles), as well as worst results (squares) and the data with the systematic errors only (crosses)

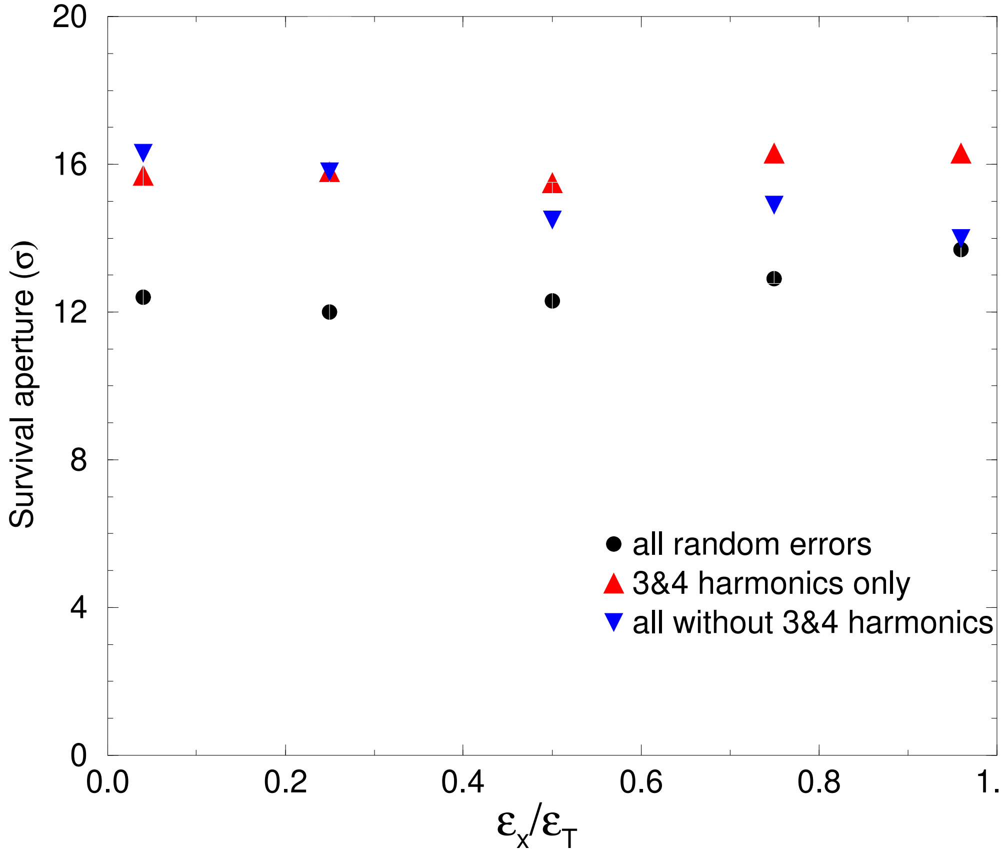

Figure 5: The 1000 turn survival aperture at different sets of magnetic errors harmonics in MQX for the lattice with crossing angle $300 \mu rad$.

error multipoles. The Figure 5 shows the results from this short-term tracking that comes from different set of multipole harmonics. The contribution from random harmonics higher than 4th has been found to be considerable. Increased effects coming from both systematic and higher order random errors can be related with beam trajectories going off center of the quadrupoles at crossing angle optics.

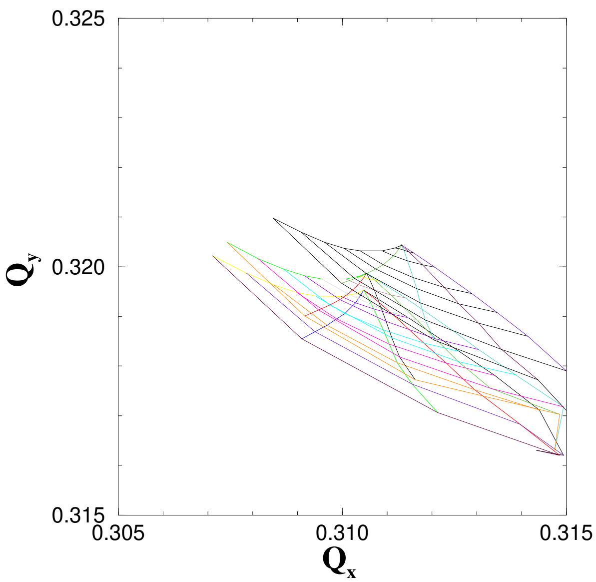

Figure 6: The tune footprints for b6 in lead and return ends only.

4.2 Body-end compensation

For the lattice with crossing angle the validity of methods for compensation of systematic end component b6 [5] has been checked. This includes actually two methods: compensation by optimizing the orientation of lead ends for each MQX quadrupole and body-end compensation using calculated b6 harmonics in quadrupole bodies. The Figures 6, 7 and 8 confirm the large effectiveness of the compensation methods. The tune footprints shown in these Figures corresponds to 13σ in betatron amplitudes. By applying body-end compensation the tune footprint decreases by one order of magnitude.

All results for the survival aperture shown in previous sections were obtained assuming the optimized orientation of lead ends in MQX.

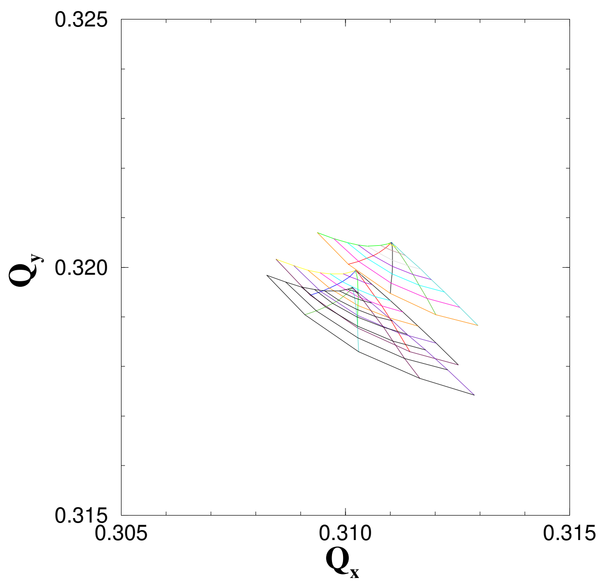

Figure 7: The tune footprints with optimized lead end orientation for b6.

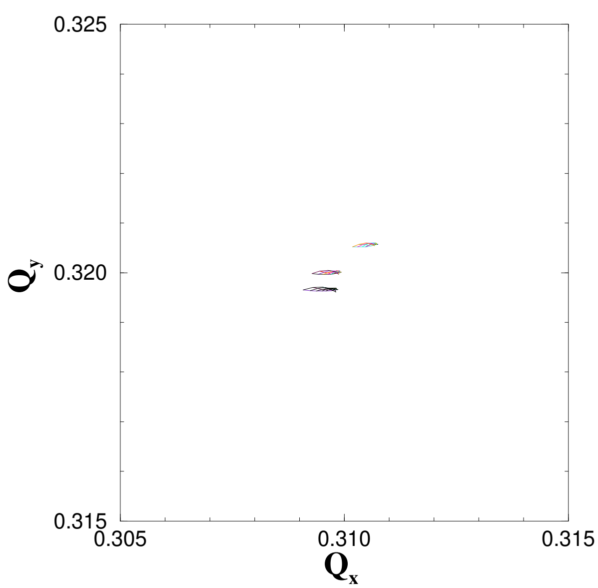

Figure 8: The tune footprints with body-end compensation for b6.

5 Conclusion

Main results obtained from 6D tracking with magnetic errors in inner triplet quadrupoles at collision energy are following:

1. Without crossing angle the average 50k turns survival aperture is 12.7σ.
2. With crossing angle the average 50k turns survival aperture is 9.8σ. This is below the target survival aperture of 12σ. Hence, applying additional correction and compensation methods is neccesary to achieve the target survival aperture.
3. With crossing angle the contribution of systematic and high-order random MQX errors in the dynamic aperture reduction is almost as important as the the contribution from sextupole and octupole error harmonics.
4. With crossing angle the body-end and optimized end orientation compensation methods for b6 end harmonic remain very effective.

Acknowledgments

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