Compensation of Linear Lattice Imperfections in the Large Hadron Collider

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Abstract Closed-orbit and linear coupling corrections have been studied for the LHC lattice, using different samples of the random error imperfections. Distortions in the closed-orbit are mainly due to alignment and field errors of the main magnets. The main source of the linear coupling is found to be the skew quadrupole component of the dipoles, with its random and systematic part. The linear imperfections expected in the LHC are large enough to prevent the confinement of the beam in the vacuum chamber. Beam position monitors and correction dipoles near each lattice quadrupole are able to reduce the r.m.s. closed-orbit distortion to below 1 mm. Skew quadrupoles located in the insertions and powered in four families are sufficient to handle the linear coupling. The dynamic aperture, with the injection optics and realistic corrections of the linear lattice imperfections, has been evaluated by computer tracking simulations.

I. LATTICE MODEL

The layout adopted is that of Ref. [1]. It consists of eight arcs interleaved with eight insertions. Each arc contains 25 regular FODO cells 99 m long, with 90° phase advance. The insertions have a general purpose (GP) design, except those in point Nos. 3 and 7, dedicated to the beam dump and the halo cleaning respectively. The values of the ß-functions at the interaction points (IP) are shown in Table 1. With collision optics, only the insertions Nos. 1, 2, and 5 are tuned to low-ß.

Table 1
Values of ß* [m] at the interaction points

	GP No. 1, 2, 5	GP No. 4, 6, 8	Cleaning No. 7	Dump No. 3
Injection	8.0	8.0	15	220
Collision	0.5	8.0	15	220

A thin-lens version of the lattice has been used for computer tracking simulations. An aperture limitation of 25 mm, as large as the dipole inner coil radius, has been assumed. To introduce synchrotron oscillations an RF cavity has been added. The beams are separated vertically by $\pm 3\sigma$ in all the IPs, and cross horizontally at an angle of ± 100 µrad in all the GP insertions.

The choice of the nominal working point $Q_H = 70.28$, $Q_V = 70.31$, has been based on the optimization of the medium-term (~ 10^5 turns) dynamic aperture, using the computational tools of Ref. [2]. An increase by one unit of Q_H has been considered in order to reduce the linear coupling resonances. Larger horizontal-vertical tune separations have not been retained since they imply either an unacceptable mismatch of the optical functions in the insertions, or a heavy modification of the lattice layout.

II. IMPERFECTIONS

Positioning errors with random Gaussian distributions, truncated at 3σ, and with an r.m.s. value of 0.14 mm for the misalignment and of 0.24 mrad for the tilt are envisaged in the LHC, but in order to take into account alignment difficulties related to the twin aperture design of the main magnets, up to four times larger r.m.s. values have been considered in our simulations. Beam position monitor reading errors of 0.6 mm and the field-shape imperfections in Table 2 are also relevant to the linear lattice behavior of the LHC, and have been included in our simulations together with the higher-order multipole components of the field-shape imperfections quoted in Ref. [2].

Table 2
Field errors in units of 10^{-4} at $R_r = 1$ cm

Errors	Relative field error	a_2 systematic	a_2 random r.m.s.
Dipole	5	0.8	1.7
Quadrupole	5	-	-

III. CORRECTORS

The two LHC rings are treated individually as far as corrections are concerned. Orbit correctors and monitors are located next to each twin lattice quadrupole. Directional monitors are installed near the inner triplets of the GP insertions, where the counter-rotating beams are almost collinear. Correctors are excluded there to avoid coupled orbit distortions in the two LHC rings. Additional correctors and monitors are added in the insertions to take care of the vertical separation and of the crossing angle at the IPs, as well as of the possible orbit mismatch at the outer ends of the dispersion suppressors. The integrated strength of the correcting dipoles is 1.5 T·m in the arcs, and 2.2 T·m in the insertions, where the orbit functions are more irregular and a better correction is required. To decouple the horizontal and vertical motions a global correction is implemented: 92 skew quadrupoles, powered in four families, are installed in the insertions, twelve in each GP insertion, and ten in each machine insertion. Two of the families are almost orthogonal in phase for the main diagonal Q_H-Q_V. The correcting magnets are 0.72 m long, with a gradient of 120 T/m, and are of the same design as the arc tuning quadrupoles.

Sextupole, octupole and decapole correctors à la Neuffer are used in the regular cells [2].

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IV. ORBIT CORRECTION

The correction of the orbit is very efficiently performed with the MICADO algorithm [3], using the full set of correctors. Satisfactory results have also been obtained with a reduced number of correctors in the arcs. Sophisticated powering schemes have thus been considered to reduce in costs. The most promising of them is the one in which the correctors of two consecutive regular cells are connected in series with those of the next two consecutive cells. In a smoothly aligned machine the results of Fig. 1 can be easily reached, and local large misalignments can still be handled.

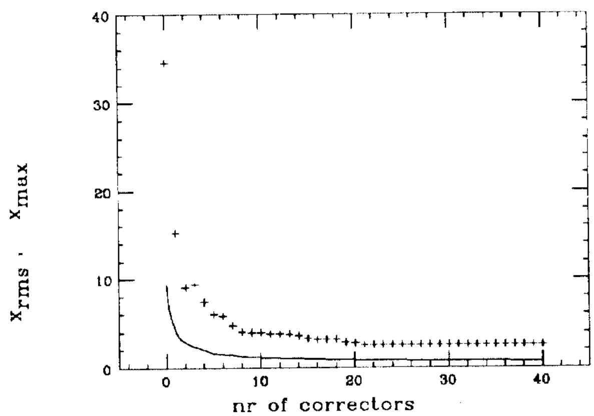

Fig. 1. R.m.s. (continuous line) and maxima (dotted line) of the closed-orbit deviations, as functions of the number of correctors used around the ring

V. LINEAR COUPLING CORRECTION

At injection, the linear coupling of the LHC is mainly due to the systematic and random skew quadrupole component a_2 in the field of the main dipoles. The other sources of coupling, i.e. the tilt of the main quadrupoles, and the vertical orbit in the chromaticity sextupoles, are more than an order of magnitude weaker. This is also true for the collision optics, although in this case the tilt of the inner triplet of the experimental insertions is no longer negligible, and possible axial fields in the experimental devices will need to be locally corrected.

With realistic errors, and the nominal setting of the main quadrupoles gradients, the strength of the main diagonal resonance is as large as almost half a unit in tune, which will make it impossible to operate an uncorrected machine. With one unit separation of the horizontal and vertical tunes, this strength is reduced to 0.02; it can be further diminished with two families of skew quadrupoles orthogonal in phase, by minimizing the value of the closest tune approach with numerical methods. In the example of Fig. 2, where the case of a realistic distribution of a_2 is considered before and after the coupling compensation, tune separations of 0.001 units are reached after a few iterations.

There are two other approaches to globally decouple the machine with the four families of skew quadrupoles, assuming a perfect knowledge of the magnetic imperfections a_2 in all the dipoles. In the first approach, the strength of the correctors is adjusted to cancel the off-diagonal coupling terms of the one-turn transfer matrix computed from IP1. Of course, the results will depend on the choice of the starting point of the computation, but we found this dependence to be almost negligible in practice. In the second approach, the first-order skew resonances $Q_H \pm Q_V = p$ are compensated. At the nominal working points, 70.28/70.31 and 71.28/70.31, with both systematic and random a_2, the two methods lead to a decoupled machine with almost equal compensating strengths.

The proposed decoupling strategies are inadequate to cancel the vertical dispersion around the accelerator: they leave residues of about 0.6 m in the arcs and less than 4 cm at the IPs for the two considered optics. Other correction schemes which could compensate this effect are under investigation.

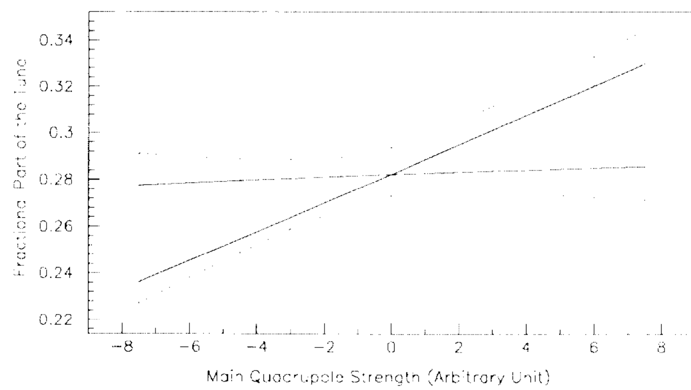

Fig. 2. Fractional part of the tunes as a function of the strength of a tuning quadrupole, before (dotted line) and after (continuous line) the linear decoupling

VI. OPTIMIZATION OF THE WORKING POINT

The choice of the nominal working point of the LHC has been discussed in Ref. [2]. Here we would like to motivate the difference of 0.03 units between the horizontal and the vertical tunes, which has been found to be the best compromise between the necessity for the working point to be far enough from the main diagonal to avoid linear and non-linear coupling resonances, and close enough to keep away from higher-order resonances. Figures 3 and 4 show the medium-term dynamic aperture, i.e. over $2{\cdot}10^4$ turns, as a function of the working point, in the injection configuration, without and with the random and systematic a_2, respectively. Different distances from the diagonal are considered and, in both cases, we see that the maximum beam stability is achieved for Q_H-$Q_V = 0.03$. Furthermore we observe that the results with and without a_2 are practically the same, from which we conclude that the global decoupling, made in this case with the matrix formalism, is very effective, and that the beam stability is essentially determined by the higher order resonances. Nevertheless it has to be pointed out that in a realistic machine the third order skew resonance $3Q_V = 211$ is larger than when a_2 is neglected. This is likely to be due to the local residual coupling in the chromaticity sextupoles, and in the locations of the sextupolar field imperfections. Results in agreement with the previous ones have also been obtained from the detection of chaos by means of the Lyapunov exponent method.

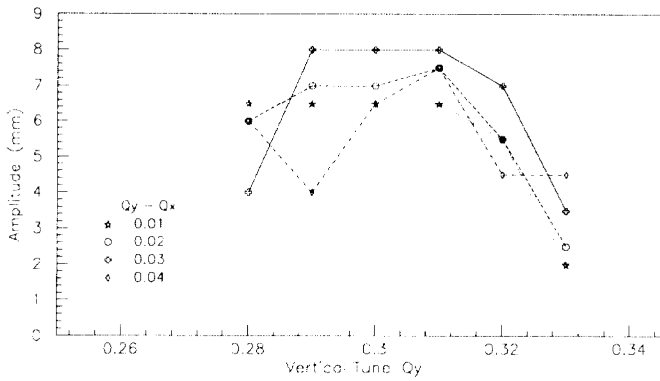

Fig. 3 Medium-term dynamic aperture as a function of the working point, without skew quadrupolar terms

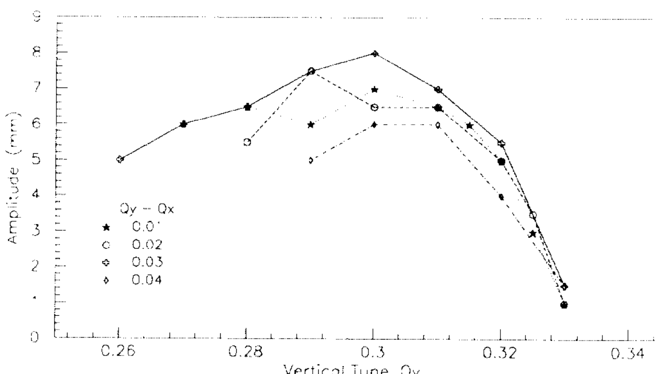

Fig. 4 Medium-term dynamic aperture as a function of the working point, with skew quadrupolar terms

VII. Effects on the Dynamic Aperture

The effect on the short-term dynamic aperture of the a_2 components in the dipoles has been studied with injection optics, and eight samples of the random imperfections in the dipoles. The results are summarized in Fig. 5. The stability region is drastically reduced when uncompensated skew quadrupole errors are added. Most of the reduction is recovered when the global decoupling is applied. For one case, in which the quadrupole field-shape imperfections have also been included, the comparison has been carried out for about 10^6 turns, as shown in Fig. 6. The reduction of the dynamic aperture, with globally compensated a_2 imperfections is of about 1 mm, a result also confirmed by the analysis of the Lyapunov exponent.

The effect of a finite closed-orbit on the dynamic aperture is smaller but still non-negligible. With r.m.s. orbit deviations of 1 mm, a reduction of 0.3 to 0.5 mm has been computed.

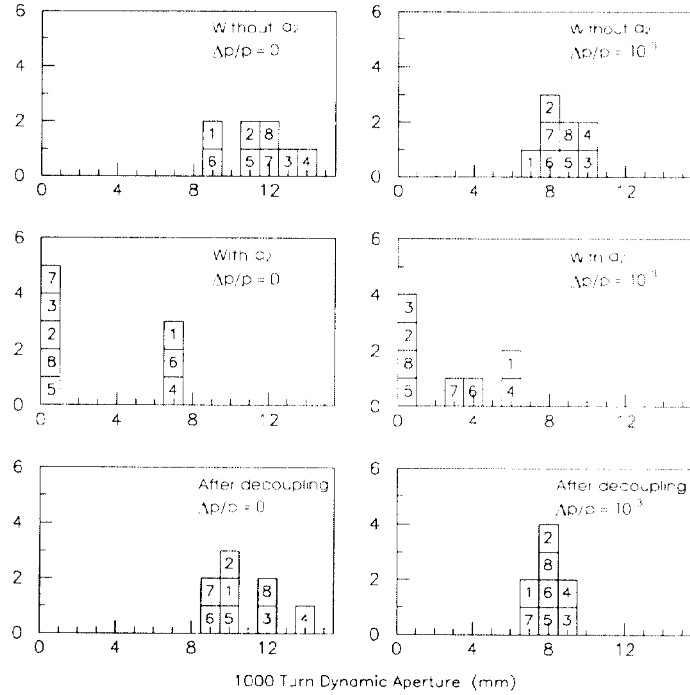

Fig. 5 Short-term dynamic aperture with field-shape imperfections in the dipoles

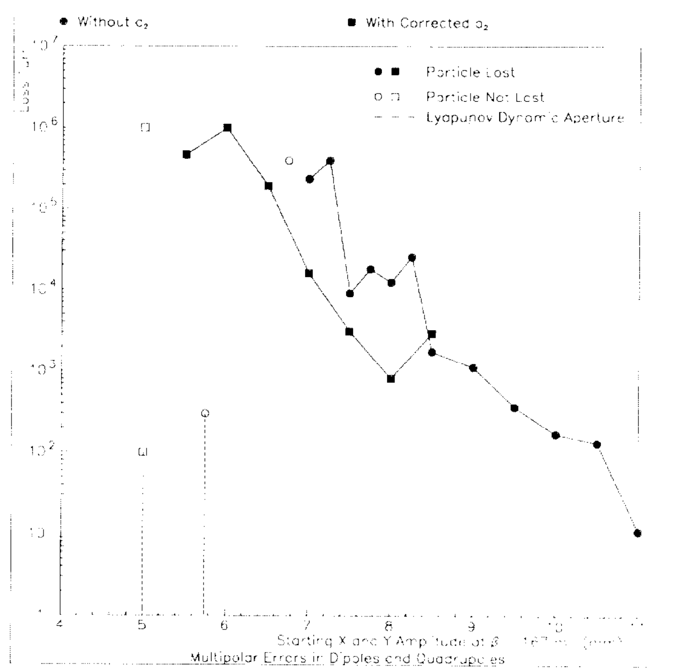

Fig. 6 Survival plot for the LHC with multipole errors in dipoles and quadrupoles, without and with a_2

VIII. Acknowledgements

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IX. References

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