Dynamic Behaviour of the CERN Large Hadron Collider (LHC)

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Abstract

In superconducting hadron colliders the stability of particle motion depends strongly on the field imperfections in the magnets, particularly at injection energy where the effect of persistent currents is maximum and the transverse beam size is large. Several precautions may make the motion of the particles less sensitive to the non-linear components of the magnetic fields. Correction multipoles have to be foreseen in the regular cells, to reduce the non-linear tune shift caused by the *systematic* components of the field errors. The main dipoles may be installed in an ordered sequence to provide an approximate compensation of *random* field components. The closed orbit and the linear coupling have to be corrected with care. Finally, the ripple of the power converters has to be reduced as much as possible. Most of these concepts have been considered in the design of the proposed CERN LHC [1], and extensive computer simulations have been carried out with the injection optics to check their beneficial effect. The results are presented in this report.

1 LATTICE

The lattice is described in reference [2]. Eight arcs are interleaved with eight intersections, six of which have a general purpose (GP) design, and two are to be used for halo cleaning and beam dumping. The length and the phase advance of the arc cells result from a compromise to obtain a large focusing strength, a dense packing of the dipoles and a sufficiently high dispersion to keep the strength of the chromaticity sextupoles low. With bending fields of 10 T and quadrupole gradients of 250 T/m a beam energy of 7.7 TeV can be achieved with peak values $\beta^{max} = 165\ m$ and $D_x^{max} = 1.9\ m$ in the arcs.

At injection energy the beams are vertically separated by $\pm 3\ \sigma$ at all interaction points and cross at a horizontal angle of $\pm 100\ \mu rad$ in the GP insertions. In tracking runs with the MAD program [3, 4] a thin lens lattice was used. Dedicated tracking runs were carried out to observe the reduction of the dynamic aperture when the protection collimators were moved close to the beam (figure 4). The optimum collimator positions (the largest transverse position at which they still completely protect the superconducting magnets from particle losses) with 50 and 56 mm inner dipole coil diameter are assumed to be 6 and 8 mm (converted to β^{max} in the arcs) respectively [5].

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2 IMPERFECTIONS

Recent estimates of the field shape imperfections, based on the measurements of HERA magnets, have been scaled for use with the LHC magnets [6]. The dipole and quadrupole field error coefficients used at injection energy are listed in reference [7]. This allows a comparison of the performances with inner *dipole* coil diameters of 50 and 56 mm.

Quadrupoles with an inner coil diameter of 56 mm are used everywhere except in a limited number of machine insertion quadrupoles, where the beam size is much larger than in the arcs. It has been assumed that the field errors in these specially designed quadrupoles can be kept so small that they have little effect on the dynamic aperture [7].

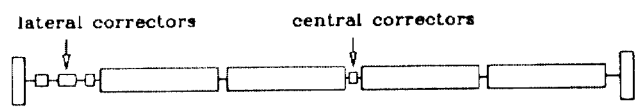

Figure 1: LHC arc half-cell with multipole correctors

3 ORBIT AND LINEAR COUPLING CORRECTION

Orbit correctors and monitors are installed next to the quadrupoles of the arcs and the insertions. The residual closed orbit after correction is assumed to have peak values of 4.5 mm in the arcs.

To decouple the horizontal and vertical motions a global coupling correction is implemented: 92 skew quadrupoles, powered in 4 families, are installed in the insertions. Two of the families are almost orthogonal in phase for the main diagonal $Q_x = Q_y$.

At injection the linear coupling of the LHC is mainly due to the systematic and random skew component a_2 in the main dipoles. Other sources, like main quadrupole tilt and vertical orbit distortion in the chromaticity sextupoles are much weaker. This is also true for collision optics, although in this case the tilt of the inner experimental insertion triplet is no longer negligible. Equally any axial fields in the experimental detectors will need to be locally compensated.

With realistic errors and the nominal setting of the main quadrupoles the width of the main diagonal resonance is almost as large as 0.5, which will make it impossible to operate an uncorrected machine. Separating Q_x and Q_y by one unit reduces this width to 0.02. It may be reduced by another factor 2 with two skew quadrupole families.

Two approaches may be used to globally decouple the machine with 4 skew quadrupole families, assuming the a_2 component of each bending magnet unit is known. The first method cancels the off-diagonal coupling elements in the one-turn transfer matrix. The second method compensates the first order resonances $Q_x \pm Q_y = p$. At the proposed working points 70.28/70.31 and 71.28/70.31 the two methods require almost identical skew corrector strengths, yielding a decoupled machine for which the closest tune approach produces a tune difference $\delta Q \approx 10^{-3}$.

On the other hand, the two proposed decoupling strategies leave an uncompensated vertical dispersion of 0.6 m (maximum) in the arcs and 0.04 m at the IPs. Therefore other schemes are still under investigation.

4 SETTING OF THE NON-LINEAR CORRECTORS AND OF THE WORKING POINT

The systematic multipolar imperfections of the LHC magnets produce a large amplitude and momentum dependent tune shift, resulting in a sizeable reduction of the dynamic aperture. These tune shifts are compensated by an arrangement *à la Neuffer* [8] of sextupole, octupole and decapole correctors located close to the F and D arc quadrupoles and at the center of the arc half-cells (figure 1). Three different strategies [9] have been examined to optimize the strengths of the multipole correctors: two minimize the amplitude-dependent tune shift using respectively *tracking* and *normal forms* evaluations up to eleventh order, while the third minimizes the *momentum dependent tune shift* over the full momentum range of the bucket. These three approaches yield similar performances, which are not significantly reduced if the mid-half-cell octupole corrector is suppressed (table 1).

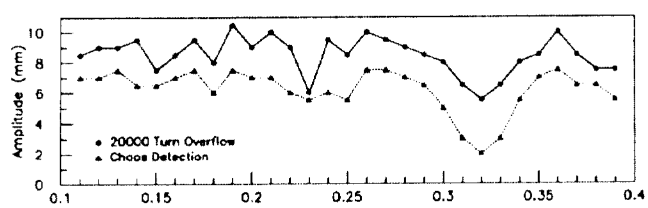

Figure 2: *Medium term dynamic aperture* and *chaotic boundary* vs. the working point (case of 50 mm dipoles)

The performance of the proposed working point [9] 70.28/70.31 was confirmed by tracking over 2.10^4 turns with systematic and random errors corresponding to a 50 mm inner dipole coil diameter. The medium term dynamic aperture and the chaotic boundary are shown in figure 2 for different tune values with $Q_y = Q_x + 0.03$. The selected tune is located in a safe area between the third and the fourth order resonances. The residual effect of the a_2 components after corrections by skew quadrupole corrections is shown in figure 3.

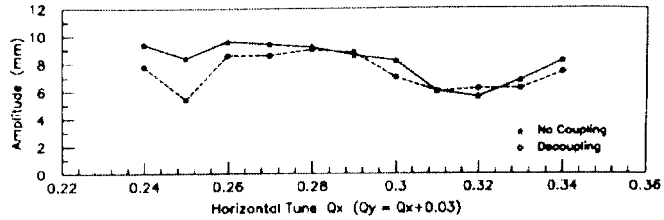

Figure 3: *Medium term dynamic aperture* vs. the working point with and without linear coupling. Solid line: $a_2 = 0$, dashed line: $a_2 \neq 0$ with skew quadrupole correction

5 DYNAMIC APERTURE

Among the large number of parameters which determine the dynamic aperture of the LHC the most important ones had to be identified in order keep the amount of computing time spent on tracking at a reasonable value. In tracking runs the initial betatron emittances of each particle were assumed to be equal in both transverse planes. Synchrotron motion with a relative momentum amplitude $\delta = \pm 10^{-3}$ was included in all long term tracking runs.

Using short term tracking four random error seed combinations (dipole - quadrupole - closed orbit) were selected among a large number: the ones yielding the smallest and the largest short term dynamic aperture, and two intermediate cases. In this way the performances of dipoles with inner coil diameters of 50 and 56 mm were systematically compared by means of long term (5.10^5 turns) tracking. Additional tracking runs were made to assess the sensitivity of the particle motion stability to linear coupling (correction with either 2 or 4 skew quadrupole families), to a small residual chromaticity value, and to the presence of the 14- and 18-pole components (b_7, b_9) in the main dipoles. Lastly, particles were tracked in the presence of a small ripple on the main quadrupole power supply current, containing two frequencies: 50 Hz ($\Delta Q = \pm 5.10^{-4}$) and 200 Hz ($\Delta Q = \pm 10^{-4}$).

The results are presented in table 1. The dynamic aperture of the *reference machine* (first two lines), which is corrected with 4 skew quadrupole families and has $|Q'| < 0.1$ in the momentum range of the r.f. bucket, has been averaged over 4 seeds. The results of the other cases have been computed for a single medium performance seed.

The dynamic aperture was further evaluated in the presence of a primary collimator positioned close to the beam. These runs were made without closed orbit distortion and with a medium field error seed. Figure 4 shows the 10^5 turn *dynamic aperture* as a function of the position of the primary collimator jaws with respect to the beam center. The recommended collimator positions with the 50 and 56 mm dipole inner coil diameter are indicated by arrows. For comparison the *Lyapunov chaotic boundaries* are indicated for the reference machine.

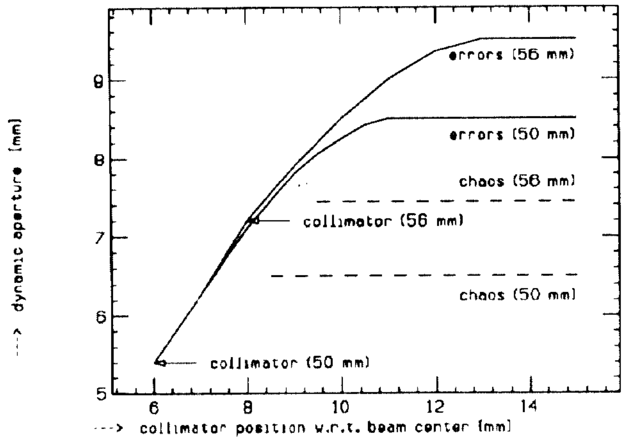

Figure 4: *LHC dynamic aperture* (10^5 turns) in mm at β^{max} of the arcs at injection energy, vs. *primary collimator position*. The horizontal dashed lines show the *Lyapunov chaotic boundaries* (average of 4 seeds) in the presence of orbit distortion and field errors corresponding to the two dipole coil dimensions. The arrows indicate the *optimum collimator positions* and the resulting *dynamic aperture* for these cases

6 CONCLUSIONS

With field errors scaled from the HERA magnets the dynamic aperture of the LHC at injection energy is found to be just sufficient, even with the 50 mm inner dipole coil diameter of the initial design (chaotic boundary at 5.5 σ). This conclusion remains valid in the presence of realistic orbit distortions, a small ripple on the power converters, or imperfect coupling and chromaticity corrections.

However, in the presence of both a realistic *closed orbit distortion* and the proposed *synchrotron radiation shield* [1] the requirement that the collimators protect the magnets against particle losses reduces the mechanical aperture of the primary collimators to values below the chaotic boundary, and thus the dynamic aperture depends more on the collimator position than on the field quality. With a 50 mm inner dipole coil diameter and the primary collimators at the recommended position the resulting dynamic aperture is not larger than 4.5 σ (5.4 mm at β^{max} in the arcs).

Our recommendation is therefore to choose a dipole with a 56 mm inner coil diameter, which is compatible with an 8 mm mechanical half-aperture of the primary collimators, yielding a 6 σ dynamic aperture in the routine operation of the LHC, just inside the chaotic boundary.

7 ACKNOWLEDGEMENTS

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Table 1: *Dynamic Aperture* and *Lyapunov chaotic boundary* in mm at β^{max} of the arcs, calculated from 5.10^5 turn tracking at injection energy without collimation, for different cases with dipole inner coil dimensions 50 and 56 mm

bore	case	D.A.	chaos
50	4 skews, Q'=0	7.75	6.50
56	4 skews, Q'=0	9.06	7.44
50	no central octupole corrector	7.75	6.50
56	no central octupole corrector	8.75	7.75
50	2 skews, Q'=0	8.00	5.25
56	2 skews, Q'=0	9.25	7.50
50	2 skews, Q'=3	6.25	5.75
56	2 skews, Q'=3	7.75	5.25
50	4 skews, Q'=3	8.00	6.25
56	no b_7, b_9 in dipole	9.00	7.75
50	ripple	7.00	6.00

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