EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS-2010-049

DYNAMIC APERTURE STUDIES AND FIELD QUALITY CONSIDERATIONS FOR THE LHC UPGRADE OPTICS

B.J. Holzer, S. Fartoukh, F. Schmidt

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The layout of the interaction region for the LHC upgrade project is based on a number of new magnets that will provide the required strengths to focus the colliding beams as well as to separate them after collision. Due to the smaller beta function at the IP however, the requirements for the free aperture of these magnets are more demanding and the effect of the higher order multipoles is more severe than under nominal LHC conditions. Using tracking simulations to study these effects, target values for the multipole coefficients of the new magnets have been defined as well as a multipole correction scheme that will be used to compensate those field errors which cannot be avoided.

Presented at :
1 rst International Particle Accelerator Conference (IPAC 2010)
May 23-28, 2010, Kyoto, Japan

Geneva, Switzerland
May 2010

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The layout of the interaction region for the LHC upgrade project is based on a number of new magnets that will provide the required strengths to focus the colliding beams as well as to separate them after collision. Due to the smaller beta function at the IP however, the requirements for the free aperture of these magnets are more demanding and the effect of the higher order multipoles is more severe than under nominal LHC conditions. Using tracking simulations to study these effects, target values for the multipole coefficients of the new magnets have been defined as well as a multipole correction scheme that will be used to compensate those field errors which cannot be avoided.

INTRODUCTION

The interaction region for the LHC upgrade project [1] is based on a number of new magnets that will provide the required strengths to focus the colliding beams as well as to separate them after collision. As in the nominal LHC, a triplet of quadrupole magnets “IT” is foreseen for the upgrade optics and as close as possible to this a dipole magnet “D1” to provide an early separation of the beams and limit the number of parasitic bunch crossings. In figure 1 the layout of the new interaction region is shown schematically [1].

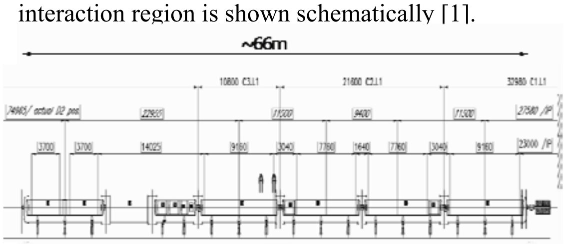

Figure 1: The new LHC interaction region

The corresponding beam optics [2] is shown in fig 2. Maximum values of the amplitude function of β_{max} = 11km are obtained within the IT and D1 magnets. Two direct implications have to be considered in this context: The need for large apertures in the new magnets and the improved field quality that has to be required: Due to the high beta values the sensitivity of the beam with respect to external filed errors is increased. To obtain a sufficient dynamic aperture for the particle beam under these conditions, the influence of the higher order multipoles of the new magnets had to be studied in detail.

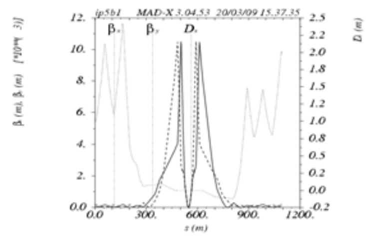

Figure 2: Beam optics in IR 1 for the upgrade LHC

A qualitative but instructive view can already be obtained from the amplitude dependent tune of the beam. In fig 3 the so-called detuning under the influence of the higher order multipoles is presented for the new optics. The particles at large amplitudes are strongly influenced in their dynamics from the nonlinear fields and their working points cover a range of +0.003 ... -0.004.

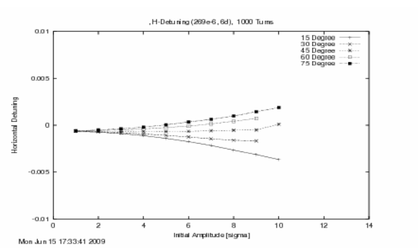

Figure 3: Detuning in the horizontal plane under the influence of strong nonlinear multipole fields of the new low-β quadrupole MQXC.

For comparison and to motivate the calculations presented in this paper we present already here the result of an improved situation: Multipole corrector coils have been introduced and the values of the nonlinear fields have been limited to guarantee a high dynamic aperture: For the same beam optics and beam parameters we get a much better situation (fig 4). A detailed analysis of the range of stable particle movement and the identification of the most severe nonlinear fields has been performed in long term tracking studies using the sixtrack code [3]. The criteria chosen for the simulations are: 30 particle pairs per aperture step,10^5 turns, 60 seeds for the magnet field errors, amplitude values between 6 and 22 sigma of the beam size and 17 angles to sample the physical aperture in the x-y plane. The goal of the study was to identify problematic multipole coefficients that limit the dynamic aperture, establish tolerances for the magnet field distortions and

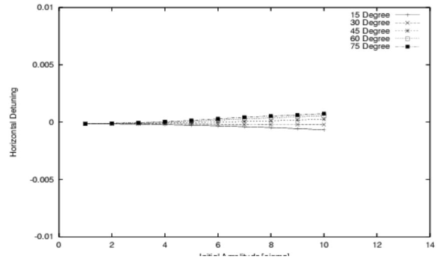

Figure 4: Reduced detuning effect due to improved multipole coefficients

deliver multipole error tables for the different magnets.

DYNAMIC APERTURE

As a first step the predicted multipole errors of the D1 and IT magnets [4, 5] have been studied in a common simulation. In fig 5 the dynamic aperture resulting from the IT errors is compared with the situation where in addition the D1 tolerances have been taken into account. It is evident that the field quality of the separation dipole had to be considered as a problem of its own and treated in an independent study [6].

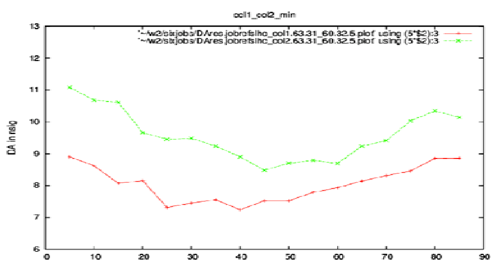

Figure 5: Influence of the D1 multipole fields on the dynamic aperture

Concerning the field quality of the IT quadrupoles, a first improvement has been achieved by installing dedicated multipole correctors. The most important field coefficients a3, b3, a4, b4, b6 were compensated in several steps by introducing specific multipole corrector coils. Fig 6 demonstrates the results: Installing a field compensation for the b3 and b6 multipoles (green data points), a minimum value for the dynamic aperture of about 8 sigma can be achieved. However a considerably better situation is obtained if a more extensive compensation scheme (a3, b3, a4, b4, b6 correctors) is applied (red points). In a next step single multipole errors were scanned and tolerance limits for each multipole coefficient were determined. An illustrative example is shown in fig. 7 where the effect of a single multipole (a5r) on the dynamic aperture is demonstrated:

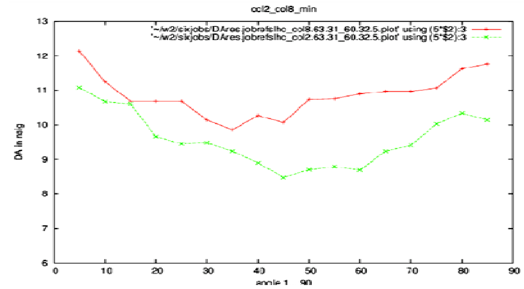

Figure 6: Dynamic aperture limited by the IT multipole errors: green: compensation of b3 and b6 coefficients, red: correction of a3, b3, a4, b4, b6

In the example, the coefficient a5r has been reduced in steps from the original value of $0.46*10^{-4}$ to $0.19*10^{-4}$ to find the tolerance limit.

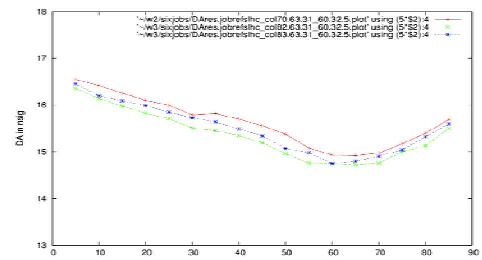

Figure 7: Probing the effect of single multipole fields.

Operational Aspects: Feed Down Effects

Beyond the pure dynamic aperture as a measure of the global well being of the beam, the influence of the multipole errors on the operational aspects is of equal importance. Mainly the strong lower order multipoles n = 2, 3 of the magnets can have an influence on the beam operation and lead to coupling, tune shifts and distortions of the amplitude functions. In the case of the D1 magnet these effects have been studied in detail [6]. As an example we consider the influence of the n=3 multipole. For the upgrade LHC a full crossing angle of Φ = 410 μrad will be applied to reduce the parasitic bunch encounters. Therefore the beams will pass through the IR magnets with an offset of up to Δx ≈ 15 mm and in the presence of a sextupole field b3, a quadrupole error is created:

$$k_1 L = \frac{2B_0 b_3 \Delta x L}{r_0^2} \frac{1}{B\rho}$$

For a value of $b3=3*10^{-4}$, as deduced from dynamic aperture calculations, we obtain a tune shift $\Delta Q=5.9*10^{-3}$ and a β-beat of $\Delta\beta/\beta\approx 3.9\%$ per D1 magnet. In the case of the MQXC magnets the influence of the n=3 multipole error is considered as the most important effect and has been studied using the MAD-X program. On the average of the

60 seeds, a maximum value for the coupling of $\kappa = 0.88*10^{-3}$ has been found. The influence on the beta function amounts to $\Delta\beta/\beta \leq 1.4$ % in both transverse planes. Fig 8 shows an example of such a simulation.

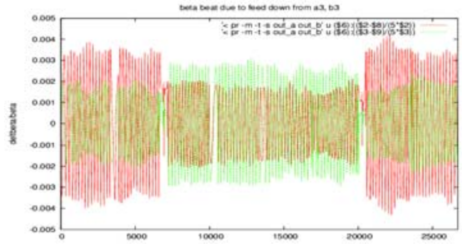

Figure 8: Beta beat due to feed down effects from the a3, b3 multipoles in the IT quadrupole magnets

Considering an overall budget for the beta beat of LHC of $\Delta\beta/\beta$ = 20% and a comparing the coupling obtained via the feed down effects with typical values resulting from other machine imperfections, the influence of the operational aspects due to the n = 2, 3 feed down had to be included in the magnet quality specification [6] and [7].

RESUME

The optics for the phase 1 upgrade of the LHC requires high field quality for the low-β quadrupoles as well as for the separation dipole. Tracking calculations have been performed to establish limits for the higher order multipoles that guarantee sufficient dynamic aperture during the complete energy range of LHC.

Table 1: target values for the MQXC multipole coefficients

n	uncer-tainty	rms	n	uncer-tainty	rms
a1	0.000	0.000	b1	0.000	0.000
a2	0.000	0.000	b2	0.000	0.000
a3	0.890	0.890	b3	0.460	0.890
a4	0.640	0.640	b4	0.640	0.640
a5	0.460	0.198	b5	0.230	0.303
a6	0.870	0.330	b6	1.300	0.960
a7	0.145	0.200	b7	0.120	0.200
a8	0.114	0.160	b8	0.100	0.160
a9	0.080	0.080	b9	0.080	0.080
a10	0.140	0.060	b10	0.200	0.060
a11	0.030	0.030	b11	0.030	0.030
a12	0.020	0.020	b12	0.020	0.020
a13	0.010	0.010	b13	0.020	0.010
a14	0.030	0.010	b14	0.040	0.010
a15	0.000	0.000	b15	0.000	0.000

For both magnet types, a series of multipoles has been identified where compared to the first expectations an improvement is mandatory. Mainly the normal and skew components of the order n=5,6,7,8 will have to be optimised. In addition a multipole corrector package is proposed to compensate the lower order coefficients and to guarantee sufficient dynamic aperture. Table 1 shows the obtained target values for the multipole coefficients of the IT quadrupole and figure 9 summarises the final result: The major steps that have been chosen in our approach are presented in one plot. Combining the effect of the new triplet quadrupoles and the D1 dipole, the minimum dynamic aperture is plotted for the cases of the original error table (no multipole correctors), applying a multipole corrector package for the coefficients a3, b3, a4, b4 and b6, and in addition improving the field quality of the IT and D1 magnets according to the final target values.

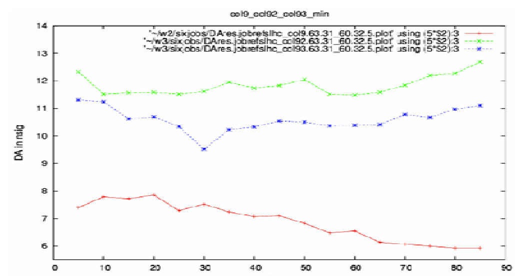

Figure 14: Resume: Dynamic aperture obtained for the original error table with and without corrector scheme (green and red curve), and the result of improved multipole coefficients (blue).

REFERENCES

[1] R. Ostojic, “Overview of IR upgrade scope and challenges”, LHC performance workshop, Chamonix, 2010

[2] S. Fartoukh, “Layout and Optics Solutions for the LHC Insertion Upgrade Phase 1”, these proceedings

[3] F. Schmidt, “Sixtrack”, CERN/SL/91-52(AP)

[4] M.Anerella et al., “Accelerator Project for Upgrade of LHC (APUL)-Conceptual Design Report”, APUL-PUB-004, 2009.

[5] F. Borgnolutti, P. Fessia, E.Todesco, “Electromagnetic design of the 120 mm aperture Quadrupole for the LHC Phase-1 Upgrade”, SLHC project report 0001, 2009

[6] B.J. Holzer, S. Fartoukh, “Linear imperfections and operational aspects induced by the D1 multipole errors for the LHC upgrade phase-1”, SLHC project report 0031, 2010.

[7] B.J. Holzer, “Dynamic Aperture Studies and Field Quality Specifications for the Triplet Quadrupoles of the LHC Phase-1 Upgrade”, SLHC report, to be published.