LHC INTERACTION REGION CORRECTION SCHEME STUDIES*

W. Fischer, V. Ptitsin and J. Wei, BNL, USA; R. Ostojic, CERN, Switzerland; J. Strait, FNAL, USA

Abstract

In a companion paper we showed that the performance of the Large Hadron Collider (LHC) at collision energy is limited by the field quality of the interaction region quadrupoles and dipoles. In this situation, the dynamic aperture can be increased through local multipole correctors. Since the betatron phase advance is well defined for magnets that are located in regions of large beta functions, local corrections can be very effective and robust. We compare possible compensation schemes and propose a corrector layout to meet the required dynamic aperture performance.

1 INTRODUCTION

In the LHC the field errors of the FNAL and KEK triplet quadrupoles are a leading source of the dynamic aperture reduction at collision [1]. Local interaction region correctors are thus proposed to reach the LHC target dynamic aperture of 12 times the transverse rms beam size ($12\sigma_{xy}$).

During the past two years of magnet proto-type manufacturing, testing, and field quality analysis of the US-LHC magnets, there has been several iterations of the magnet design that leads to improvement of the field quality. Accordingly, there has been several iterations of the proposed compensation schemes for the IR region [2, 3]. First, body-end compensation of the systematic b_6 is not planned due to the reduced b_6 in the lead end and the uncertainty in b_6 measurement. Then, magnetic tuning shims are no longer planned due to the reduction of the random b_3 and b_4 errors and mechanical complications associated with shimming. Finally, the corrector layout and strength requirements are modified after CERN's decision have the Q1 and Q3 quadrupoles built by KEK, and to have the Q2A and Q2B quadrupoles built by FNAL.

Fig. 1 shows the tentative location of the proposed correctors assumed for this study. We choose the corrector strenght such that the action angle kick accross the interaction region is minimized [4]. For this, two correctors per order and interaction region are needed. An accurate measurement of the multipole errors in the quadrupoles is necessary. A local correction scheme like this does not prevent the implementation of global correction schemes proposed in references [5, 6] in the future. During the workshop, it became clear that as the systematic b_{10} in the body of KEK-built quadrupoles is further reduced, it is neither necessary nor desirable to plan for any b_{10} correctors. On the other hand, due to strength requirements for the b_6 correction, fewer layers of correction elements should be designed in the corrector package that contains the b_6 element. Fig. 2 shows the final proposed layout from the workshop [7].

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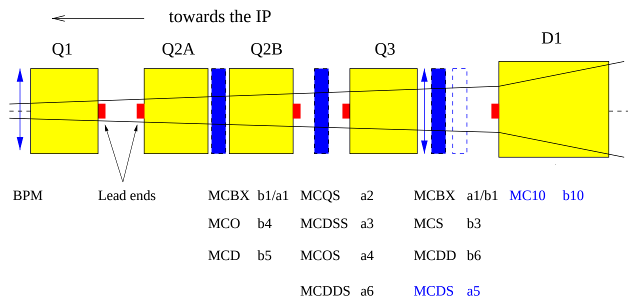

Figure 1: Tentative layout of the LHC inner triplet region assumed for the study of this paper.

In Sec. 2 the correction algorithm is presented in short. In the following section the effectiveness of four correcion schemes is evaluated with element-by-element particle tracking over 1,000 turns. Only IP1 and IP5 are corrected in these studies.

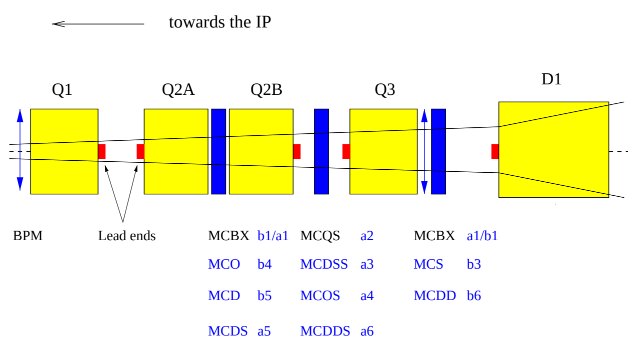

Figure 2: Final proposed layout of the LHC inner triplet region from this Workshop.

2 IR COMPENSATION SCHEMES

The error compensation is based on the minimization of action-angle kicks [4] produced by each multipole error b_n (or a_n) over a pair of inner triplets. Using two correction elements of each multipole order c_n (either a_n or b_n), we minimize the sum

$$\int_L dlC_z B_0 c_n + (-)^n \int_R dlC_z B_0 c_n, \quad z = x, y \qquad (1)$$

taking advantage of the negligible betatron phase advance within each triplet and D1, and approximate the phase advance between the triplets by 180°. The integral is over the entire left-hand-side (L) or right-hand-side (R) MQX triplet and D1. In dipoles B_0 is simply the main field, in quadrupoles it is the field at the reference radius R_{ref}. In general, the weights C_z in Eq. 1 are chosen according to the multipoles as:

	even b_n	odd b_n	even a_n	odd a_n
C_x	$\beta_x^{n/2}$	$\beta_x^{n/2}$	$\beta_x^{(n-1)/2}\beta_y^{1/2}$	$\beta_x^{(n-1)/2}\beta_y^{1/2}$
C_y	$\beta_y^{n/2}$	$\beta_x^{1/2}\beta_y^{(n-1)/2}$	$\beta_x^{1/2}\beta_y^{(n-1)/2}$	$\beta_y^{n/2}$

The compensation is equally effective for both intersecting beams, since the optics of the interaction region is anti-symmetric. However, it does not take into account the closed-orbit deviation due to the crossing angle, and the fact that the crossing planes are respectively vertical and horizontal in the two high luminosity interaction points. On the other hand, the effect of this closed orbit feeddown is partially compensated by the feeddown from the correctors.

3 CORRECTION SCHEME COMPARISON

There are three corrector packages (MCX1, MCX2, MCX3) in each triplet (see Fig. 1 and Fig. 2). Each MCX1 and MCX3 contains two dipole layers, and each MCX2 contains a skew quadrupole layer. A straightforward approach (scheme 1, see Tab. 1) is to have 3 additional layers of nonlinear skew multipoles (a_3, a_4, a_6) for MCX2, and two additional layers of nonlinear multipoles for MCX1 and MCX3. These layers could be a combination of any of b_3, b_4, b_5 and b_6 layers. For each multipole, two correction elements, located symmetrically at both sides of the IP, can be activated to minimize the kick in both the x and y directions (compare Eq. 1). Due to the lattice symmetry both beams are corrected.

Scheme 1 increases the dynamic aperture by 38% in the unmixed and 28% in the mixed case. With an additional a_5 corrector (scheme 2) the improvement is 42% and 32% respectively. A further improvement can be achieved using a b_{10} corrector, as shown in Tab. 2. However, a b_{10} corrector is difficult to built is not needed with the KEK multipole error table version 3.0 [1].

Fig. 3 depicts the effect of correction scheme 4 on the tune space. The tune spread of particles with transverse amplitudes up to 6 times the rms beam size is reduced from more than 4×10^{-3} to about 7×10^{-4}.

We also investigated the effect of misalignment of the corrector layers. With an rms misalignment of 0.5mm in the horizontal and vertical planes we find no degradation of the dynamic aperture(see Tab. 3).

Table 1: Interaction region correction schemes. Only the non-linear correctors are shown.

	MCX1	MCX2	MCX3	remark
scheme 1	2 layers	3 layers	2 layers	
	b_4, b_5	a_3, a_4, a_6	b_3, b_6	
scheme 2	3 layers	3 layers	2 layers	
	b_3, b_5, b_6	a_3, a_4, a_6	b_4, a_5	
scheme 3	2 layers	3 layers	2 layers	scheme 1
	b_4, b_5	a_3, a_4, a_6	b_3, b_6	+ b_{10}
scheme 4	3 layers	3 layers	2 layers	scheme 2
	b_3, b_5, b_6	a_3, a_4, a_6	b_4, a_5	+ b_{10}

Table 2: Comparison of local IR corrector effectiveness assuming that the interaction region quadrupole errors are measured to a 5% rms accuracy. The dynamic aperture (DA) is given in units of σ_{xy}. The physical aperture of 60 mm corresponds to about $14\sigma_{xy}$.

Case	DA mean	DA rms	DA min
UNMIXED:			
no correction	8.5	1.4	7
scheme 1	11.8	2.4	8
scheme 2	12.1	2.2	9
scheme 3	15.4	1.8	12
scheme 4	15.9	1.7	13
MIXED:			
no correction	10.0	1.5	8
scheme 1	12.8	1.1	10
scheme 2	13.2	1.3	11
scheme 3	16.1	1.8	13
scheme 4	17.6	1.6	14

Table 3: Effect of corrector displacement. The dynamic aperture (DA) is given in units of σ_{xy}.

Case	DA mean	DA rms	DA min
MIXED scheme 4	17.6	1.6	14
MCX1-3 displaced with 0.5 mm rms	17.8	1.3	15

The required strength of the multipole correctors can be provided by 50cm long spool pieces wound using the LHC sextupole corrector wire and operating at less than 50% margin at 600A [8]. At IP2, the IR correctors are also designed to reduce the effect of the D1 errors during low-β heavy ion operations [9]. We computed the maximum corrector strength order by order out of a distribution of 80 values (systematic multipole error with positive and negative sign $\times$ 10 random error seeds $\times$ 2 interaction regions $\times$ 2

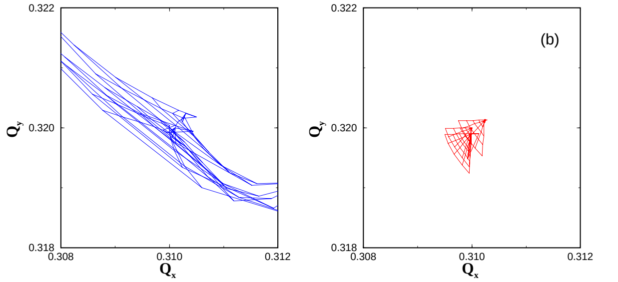

Figure 3: Effect of IR multipole correction on the covered tune space. (a) shows the uncorrected machine and (b) the corrected machine with scheme 4.

correctors per interaction region). The result for correction scheme 2 is shown in Fig. 4 for the KEK multipole error tables version 2.0 and 3.0 (both together with the FNAL multipole error table version 2.0). The available correction strength is sufficient for all orders of multipole errors.

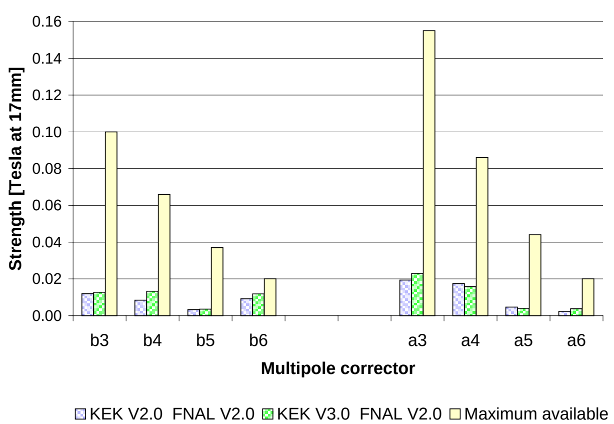

Figure 4: Available and needed corrector strength for scheme 2. The needed corrector strength shows the maximum out of a distribution of 20 machines with two correctors each at IP1 and IP5.

4 SUMMARY

Local nonlinear interaction region correctors, up to multipole order 6, are proposed for compensating the interaction quadrupole errors. These correctors can improve the dynamic aperture by 2-3σ_{xy}. The required correction strength is well within the available strength.

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