EFFECT OF FIELD ERRORS IN MUON COLLIDER IR MAGNETS ON BEAM DYNAMICS*

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Abstract

In order to achieve peak luminosity of a Muon Collider (MC) in the 10^{35}cm^{-2}s^{-1} range very small values of beta-function at the interaction point (IP) are necessary ($\beta^* \leq 1$ cm) while the distance from IP to the first quadrupole can not be made shorter than ~6 m as dictated by the necessity of detector protection from backgrounds. In the result the beta-function at the final focus quadrupoles can reach 100 km making beam dynamics very sensitive to all kind of errors. In the present report we consider the effects on momentum acceptance and dynamic aperture of multipole field errors in the body of IR dipoles as well as of fringe-fields in both dipoles and quadrupoles in the case of 1.5 TeV (c.o.m.) MC. Analysis shows these effects to be strong but correctable with dedicated multipole correctors.

INTRODUCTION

Muon Collider (MC) is presently considered as a possible option for the high energy frontier machine which can be built at FNAL [1]. To satisfy a number of challenging requirements on the MC lattice, a new approach to the interaction region (IR) chromaticity correction was developed and applied in the design of 1.5 TeV (c.o.m.) MC ring [2]. The IR layout and optics functions for $\beta^* = 1$ cm are shown in Fig. 1.

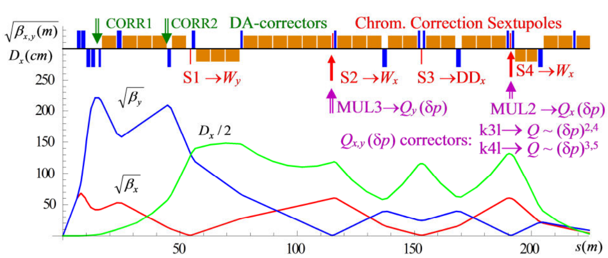

Figure 1 (color): IR optic functions and layout with correctors: chromaticity correction sextupoles S1-S4 and multipoles MUL1-MUL3, spherical aberration correctors CORR1 and CORR2.

In order to generate dispersion at the S1 location the first dipole (orange rectangle at the top of Fig. 1) is placed immediately after the final focus doublet which is cut in short pieces to place tungsten masks between them. Due to large β-functions (maximum values 53 km and 4.4 km) the aperture of IR magnets has to be also large (up to 16 cm), making the fringe-fields potentially detrimental.

Also, it is desirable that the IR dipoles have an open mid-plane (OMP) to avoid showering of muon decay electrons in a vicinity of the superconducting coils as well as to reduce background fluxes in the detector central tracker. Preliminary analysis of such dipoles [3] showed that in order to obtain on average good field quality in the region occupied by the beam the relatively large values of higher order geometrical harmonics are necessary.

Here we analyse the effect of fringe fields and multipole errors in IR magnets on beam dynamics.

FRINGE FIELDS

Extensive discussion of the fringe field (FF) effects in accelerator magnets [4] with a comprehensive list of reference suggested that these effects can be important in some special rings, e.g. in small rings with large beam emittances and short magnets.

They can be important for the MC ring as well due to already mentioned very large β-function values, large magnet aperture and short length of quadrupole pieces (< 2 m). The aperture radii R_{ap} of the closest to IP quadrupoles are equal to 40 mm, 55 mm, and 80 mm [2,3]. The fringe fields extend over length l_{FF}~$2R_{ap}$ which is still smaller than the length of the magnet interconnect region (30-40cm) so that there is no cancellation of FF from one magnet exit and another magnet entrance.

Fringe Field Simulations with MADX

MAD-X [5] PTC module [6] allows treatment of the FF effects in quadrupoles using the so-called "hard-edge" approximation [7]. According to [4] the FF region can be considered as short if $|\beta'_{x,y}| l_{FF} << \beta_{x,y}$ with $\beta'_{x,y}$ being derivatives of $\beta_{x,y}$-functions. Though this condition is fulfilled for IR quadrupoles it is important to understand how big is the contribution from higher order terms.

To extend the MAD-X capabilities beyond the hard-edge approximation its PTC tracking module has been modified to accept magnet maps generated for realistic FF falloffs by an external code.

Exporting Magnet Maps from COSY

The effect of realistic FF profile can be simulated with code COSY INFINITY [8]. Simulations [9] have demonstrated strong FF influence on both linear and non-linear particle motion. The conclusion was that the hard-edge approximation is insufficient and realistic FF falloffs described via the Enge functions should be taken into account.

The exported from COSY maps contain linear part which strongly perturb linear optics. In order to preserve it, the PTC and COSY maps have been combined as $M^{[1]}_{\text{FR-1}} \circ M^{\text{PTC}}_{\text{FF=OFF}} \circ M^{[1]}_{\text{FR-2}}$, where $M^{\text{PTC}}_{\text{FF=OFF}}$ is PTC map for the magnet body, $M^{[1]}_{\text{FR-1}}$ and $M^{[1]}_{\text{FR-2}}$ are the COSY

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maps of FF at magnet entrance and exit with the linear part replaced by unit matrices.

Dynamic Aperture with Fringe Fields

The 1000-turn dynamic aperture (DA) was calculated for four FF options: 1) no FF; 2) PTC FF in quadrupoles; 3) COSY FF maps in quadrupoles; 4) COSY FF maps in both quadrupoles and IR dipoles. Figure 2 shows boundaries of stable motion in the plane of initial coordinates at IP. Figure 3 shows the stable area S_{xy} vs particle relative momentum deviation δ_p.

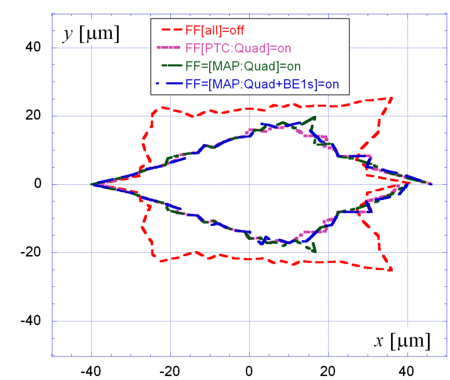

Figure 2: DA in the (x-y) plane at IP for δ_p=0.

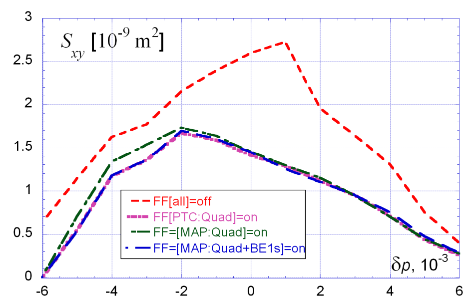

Figure 3: DA area as function of δ_p.

Thus, inclusion of FF in our lattice results in a significant reduction of the stable area (~45%). However, the difference between the results obtained with PTC hard-edge approximation and COSY maps is quite small and can be explained by tacit inclusion of dipole FF in PTC, not announced in the documentation.

MULRIPOLE ERRORS IN DIPOLES

The OMP design which can be used for the IR superconducting dipoles instead of the traditional $\cos\Theta$-design can potentially mitigate problems with heat deposition in the cold mass and with detector backgrounds. However, the OMP dipoles have increased high-order multipole errors (ME) [3]. According to the published data [3], a 6 m-long OMP dipole provides nonlinear kicks with strengths k2l=-1.41·10^{-2}, k4l=-3.30·10^{+2}, k6l=-5.77·10^{+6}, and k8l=-5.44·10^{+10} in MADX notation.

Chromaticity Correction with Multipole Errors

The IR linear chromaticity is corrected with sextupoles S1-S4 (Fig. 1): S1 located at the first minimum of β_x serves for minimization of the vertical chromatic function W_y [2] while S2 and S4 at locations of small β_y minimize W_x. The sextupole S3 installed at the center of the chromaticity correction section (CCS) helps to control the second order dispersion.

For horizontal and vertical high-order chromaticity correction respectively, multipole correctors MUL2 and MUL3 with octupole and decapole coils were added at two locations in CCS (Fig. 1).

Multipole errors in IR dipoles produce strong effect on chromaticity increasing the Q_y-spread within the range $\delta_p = \pm 0.3\%$ from 0÷0.04 up to ±0.15. Using the described above correctors it was possible to restore correction of Montague chromatic functions $W_{x,y}$ and $Q_{x,y}(\delta_p)$-curves. Figure 4 shows the resulting tune dependence on δ_p.

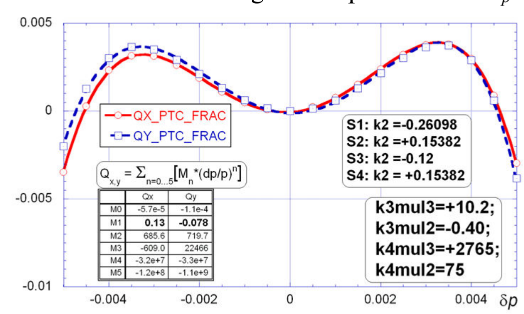

Figure 4: The corrected $Q_{x,y}(\delta_p)$ dependence with all multipole errors included.

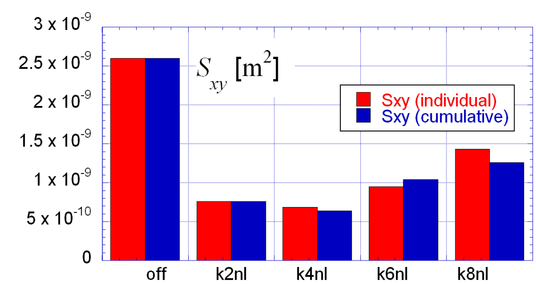

Figure 5: The DA area at different multipole errors.

Dynamic Aperture with Multipole Errors

DA has been simulated using 1000-turns particle tracking with MADX PTC_TRACK module for different contents of ME kicks. Fig. 5 shows both individual (red) and cumulative (blue) effects of ME kicks on the value of the stable area S_{xy}. By the cumulative effect of e.g. decapole error (k4l) we understand the joint effect of the sextupole and decapole errors with the higher multipoles excluded.

The DA is most seriously affected by sextupole and decapole errors. The higher multipoles partially compensate their effect but not enough to restore the DA at its original value. Therefore additional correctors are necessary for spherical aberration correction.

Two such correctors - CORR1 and CORR2 shown in Fig. 1 – were added to provide sextupole, octupole, and decapole kicks referred to in the following by the MADX coefficient name (k2l, k3l, or k4l respectively) with the suffices "%corr1" or "%corr2".

Correction of the effect of sextupole and decapole errors on DA was studied separately. Optimal values of sextupole strengths k2l%corr1 and k2l%corr2 were found by scanning.

Figure 6 shows DA boundaries for three cases: 1) no multipole errors (red); 2) with sextupole errors in IR dipoles (magenta); 3) with sextupole errors corrected by sextupole coil in CORR1.

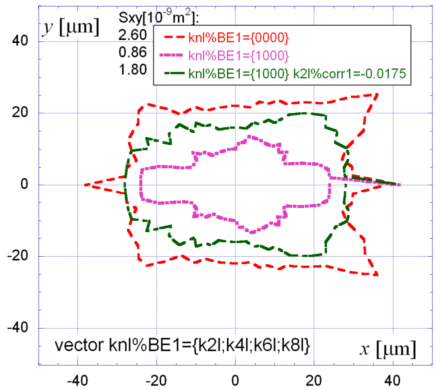

Figure 6: Effect of CORR1 on DA in the (*x*-*y*) plane.

Figure 7 shows DA boundaries for three cases: 1) no multipole errors (red); 2) with sextupole errors corrected by the CORR2 sextupole (green); 3) with uncorrected decapole errors added (blue).

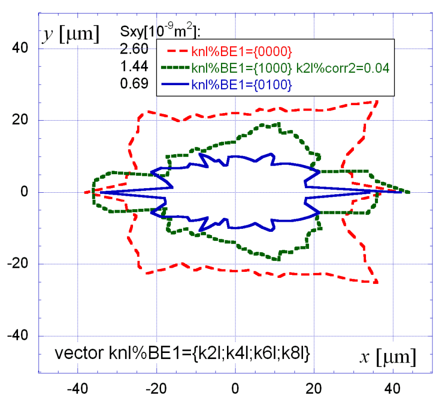

Figure 7: Effect of CORR2 and k4l-error on DA.

The sextupole errors reduce the stable area S_{xy} by a factor of 3 (from $2.60\times10^{-9}\text{m}^2$ down to $0.86\times10^{-9}\text{m}^2$). Both CORR1 and CORR2 are quite effective against sextupole errors but still do not restore the DA completely.

Decapole Errors

As can be seen in Figs. 5 and 7 the decapole errors produce the most detrimental effect on DA which neither CORR1 nor CORR2 could correct. Even stronger effect these errors produce on the off-momentum particles.

Figure 8 shows $S_{xy}(\delta_p)$-curves without multipole errors (red) and with decapole errors (blue). The drastic reduction in S_{xy} with δ_p as small as 0.1% is not a result of chromatic tune shifts which are shown in the same plot with magenta and green curves and are quite small.

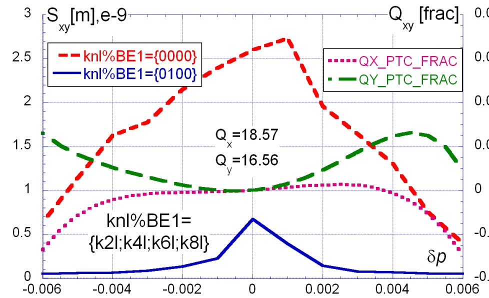

Figure 8: Effect of the decapole errors on DA and tunes for the off-momentum particles.

SUMMARY

To study the effect of fringe fields and multipole errors in IR magnets on beam dynamics in the MC lattice we made some extensions and modifications to the MADX code in more detail described in [10].

The effect of fringe-fields in IR quadrupoles on dynamic aperture was found to be significant and require correction which we have not attempted yet.

The effect of sextupole errors in IR dipoles is quite strong but can be effectively compensated with correctors already included in the design.

The decapole errors in IR dipoles are found to produce the most detrimental effect on dynamic aperture especially for off-momentum particles. We have not looked yet if higher order multipole errors can mitigate the decapole effect at $\delta_p \neq 0$. If the open-midplane design will be chosen for IR dipoles, it will be necessary to put additional correctors between them for local correction of decapole errors.

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