Study of the Alignment Tolerance and corrector strength in the Fermilab Main Injector Lattice

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I. INTRODUCTION

The multipurpose opertation of the Fermilab Main Injector(FMI) requires that orbit of the trajecting particle be as smooth as possible. In this paper we discuss the study of alignment tolerance required for the Fermilab Main Injector. Both the systematic and random misalignments of the magnetic elements have been studied. We have also studied alignment tolerance of the Beam Position Monitor (BPM). A random misalignment sigma of 0.25 mm for quadrupole and sextupole in the transverse planes (x,y), a dipole roll sigma of 0.5 mrad, systematic misalignment of ± 2 mm with long periods and BPM alignment sigma of less than 1 mm should be achieved. If we can achieve this level of alignment tolerance, we will be operating the FMI correctors at half their full strength at high energies ($>$ 100 GeV/c), giving us enough strength to correct for any unforeseen problem. In these calculations we have not studied the tolerance on the longitudinal placement of the magnetic elements.

II. TRACKING CONDITIONS

The tracking condition used in this study is described in detail in the MI Note 0088[1]. The misalignment of all the magnetic elements and beam position monitors are included in these calculation. In the Main Injector lattice there are 208 quadrupoles, 128 are recycled Main Ring quadrupoles, while the rest are newly fabricated. Located inside these quadrupoles are the beam position monitors. The vertical and horizontal beam position are measured at the focusing and defocusing quadrupoles respectively. The vertical and horizontal displacement of the particles are corrected by applying corresponding kicks just after these position monitors.

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The closed orbit error in the horizontal plane is due to 1) random quadrupole misalignments in horizontal plane and 2) random errors in the dipole field. Whereas the deviations in the vertical plane are mainly caused by 1) random quadrupole misalignment in the vertical plane and 2) the dipole roll. Table 1 summarizes the contribution of different errors to the closed orbit error.

Beside misalignments, the closed orbit error also depends on the dipole magnetic errors, both systematic and random. The Main Injector lattice has two different sizes dipole magnets, their magnetic lengths are 6.096 and 4.096 meters at 120 GeV. The magnetic length of these dipoles varies with energy due to the saturation of the ends. This change in length introduces a systematic change in dipole strength, which also contributes to the horizontal closed orbit error. The Closed orbit error due to change in length is non zero at all energies except 120 GeV. The random error of the body multipoles of the dipoles are calculated by using the measurements of the similar, Main Ring B2 dipoles. We calculate $\sigma(\Delta B/B)$ of the dipole to be 10.0e-4. Since these calculations we have build and measured 10 R&D dipoles for the FMI. These measurements confirm our initial calculations of dipole magnetic multipoles and their random errors based on two prototype Main Injector dipoles and Main Ring B2 dipoles[2].

III. Calculations

All of the calculations discussed in this paper is done using FMI lattice MI18. The current version of the lattice MI19 is essentially the same with detailed descriptions. The thin element tracking program TEAPOT[3] has been used in these simulations.

A. Random misalignment error

To study the effects of the random misalignments of the magnetic elements we have kept all the other parameters (magnetic errors) effecting the closed orbit errors fixed and varied only the sigma of the required alignment precision. From the Main Ring and Tevatron experiences [4] we believe that a misalignment sigma of 0.25 mm can be achieved in the x and y directions for the Main Injector. In our calculations we have random misalignments for dipoles, quadrupoles, sextupoles and BPM in both horizontal and vertical planes. We have also considered roll (or angular misalignments) of these magnetic elements. Table 2 summarizes the results of these calculations, where we have varied the sigma of the alignment tolerance. We also present the maximum corrector strength required to correct the closed orbit error in each case. In determining the maximum corrector strength we have consider the envelop of maximum corrector strength ignoring a few who lies outside this envelop. Corrector strength required to correct the closed orbit errors around the Main Injector Ring are shown in Fig. 1-6. In the worst case considered, where the sigma of the magnet misalignment is 0.5 mm and magnets have a roll with sigma of 0.5 mradian, the envelope of the maximum corrector strength required at 120 GeV is about 75 μradian. There are a few places in the lattice where required corrector strength are larger. We will make an attempt to fix the misalignment at these places to reduce the orbit distortion at that location, hence reducing the required corrector strength. The FMI correctors have 180 μradians of corrector strength at 120 GeV. It should be noted that dipole alignment is not very critical considering the rather flat magnetic field.

A. Systematic misalignment error

The survey marker inside the FMI tunnel will be transferred from outside the tunnel at six locations around the ring. It is expected that during this transfer there will be an error made in the horizontal and vertical location of the marker. The horizontal error will be considerably larger than the vertical. To study the effect of this error we have modeled the FMI lattice with a systematic misplacement of the magnetic elements in the horizontal direction as shown in Fig. 7. In this simulation the FMI was divided into six sectors. All the dipoles and quadrupoles were displaced from their original location to follow the systematically displaced orbit as shown in Fig. 7. Fig. 8-11 shows the displacement of quadrupoles and dipoles with respect to closed orbit. Plotted on the X axis are the magnet number starting from MI60 going in the anti-proton direction.

This systematic displacement of the lattice was superimposed on the randomly misaligned lattice with 0.25 mm sigma described earlier. The closed orbit error in the horizontal and vertical planes were 5.93 mm and 4.4 mm respectively before the addition of the systematic displacement, with systematic displacement it increased to 6.42 mm and 4.7 mm.

We have studied the effect of this systematic misalignment on the dynamical aperture of the FMI at 8.9 GeV. In our simulations we correct the lattice for closed orbit errors due to random misalignment after that we add the systematic misalignment to the lattice. we do not correct the closed orbit error introduced due to this systematic misalignment throughout the ring. The dynamical aperture doesnot change. Fig. 12 shows the survival plot of before and after the addition of systematic misalignments for one seed.

A. BPM misalignment error

We have studied the effect of the BPM misalignment on the closed orbit error and the dynamical aperture of the FMI. The nominal BPM misalignment we use in the tracking calculations have a sigma of 0.25 mm in both horizontal and vertical planes. In Table 3 we present the results of the closed orbit errors as a function of BPM misalignment error. In these calculations all the other magnetic and misalignment errors are also present to give the magnitude of change in closed orbit error due to additional BPM misalignment. It is clear from the table that there is no significant difference between sigma of 0.25 mm and 1.0 mm. From Table 1 it seems that closed orbit error due to each error adds in quadrature. The closed orbit error due to additional BPM misalignment also adds in quadrature. The additional closed orbit error due to larger BPM misalignments can be accounted for if we add the additional BPM misalignment to the previous closed orbit error in quadrature. Corrector strength required to correct this additional closed orbit error is linear with additional error. With a BPM misalignment sigma of 1 mm there is nosizable increase in the corrector strength.

We have studied the effect of BPM misalignment sigma of 1 mm on dynamical aperture of the FMI at 8.9 and 120 GeV. Fig 13 and 14 shows the survival plots of the particles with

BMP misalignment sigma of 0.25 mm and 1.0 mm. Since the dynamical aperture is defined by the largest amplitude particle which didnot survive, we see a loss in aperture by 3 mm and 4 mm for 8.9 and 120 GeV respectively.

IV. CONCLUSION

These calculations shows that we should try to achieve a random misalignment sigma of 0.25 mm for quadrupoles and sextupoles in the transverse directions. A systematic misalignment caused due to transfer of survey marks should be kept to ± 2 mm with long periods. We know that transfer of survey marker will be made at six locations around the ring, every effort should be made to minimize that this error does not have smaller wave length. BPM placement error has direct effect on the dynamical aperture of the FMI. Every effort should be made to keep the BPM misalignment sigma smaller than 1 mm.

V. REFERENCES

[1] C. S. Mishra, F. A. Harfoush, "Study of the Fermilab Main Injector Lattice". MI notes # 0088.

[2] F. A. Harfoush and C. S. Mishra, "Systematic and Random Errors for Main Injector Tracking," Fermi Internal Notes, *MI-0066*,in PAC93 proceedings.

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Table 1

The Contribution of different errors to the Closed orbit error at 8.9 GeV/c.

	ERROR	Closed orbit error H (mm)	Closed orbit error V (mm)
1)	Dipole systematic errors including change in effective length	1.05	0.0
2)	Dipole Random error	5.04	0.0
3)	Quadrupole systematic and random error	0.0	0.0
4)	Dipole, Quadrupole, Sextupole and BPM misalignments sigma = 0.25mm	2.62	4.09
5)	All errors and misalignments	5.93	4.37

Table 2

Close orbit errors as a function of misalignments

	Misalignment Discription	Energy GeV/c	Closed orbit error H (mm)	Closed orbit error V (mm)	Corrector Strength (micro radian)
1)	Dipole, Quadrupole, Sextupole and BPM misalignment sigma = 0.25 mm	8.9	6.83	4.27	50
	Dipole Roll = 0.5 mrad	120	5.83	3.49	50
1)	Dipole, Quadrupole, Sextupole and BPM misalignment sigma = 0.50 mm	8.9	9.83	7.64	75
	Dipole Roll = 0.5 mrad	120	7.60	6.50	75
1)	Dipole, Quadrupole, Sextupole and BPM misalignment sigma = 0.50 mm	8.9	9.85	7.64	75
	Dipole,Quadrupole, Sextupole and BPM Roll = 0.5 mrad	120	7.61	7.64	75

Table 3

Effect of BPM misalignment on closed orbit errors

	BPM misalignment sigma	Closed orbit error	
	sigma x= sigma y (mm)	H (mm)	V (mm)
8.9 GeV			
	0.25	6.82	4.27
	1.0	6.83	4.31
	2.5	7.07	4.70
	5.0	8.04	6.01
120 GeV			
	0.25	5.83	3.52
	1.0	5.89	3.67