Defining the Systematic and Random Multipole Errors For Main Injector Tracking

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Abstract

At the Fermilab Magnet Test Facility (MTF) measurements of magnet field shape and strength have been performed. The tracking of the Fermi Main Injector (FMI) lattice requires a detailed knowledge of the magnetic field quality and its variation from magnet to magnet. As of this date only two prototype dipole magnets have been built, not enough to do a statistical analysis. For this purpose we have used old Main Ring dipole measurements. Measurements on a subset of Main Ring (MR) quadrupoles are also available. From the different sets of measurements available to us we have separated in our simulation the end multipoles from the body multipoles. Such a dissection of the magnet enables us to study more closely the effects of the end multipoles on the performance of the Main Injector. In particular we have studied the closed orbit errors due to variations in effective length of the long and short type dipoles. Tables of multipole errors are presented at both injection (8.9 GeV/c) and slow extraction (120 GeV/c) energies.

I. Introduction

Data from the Main Ring B2 dipole measurements are carefully selected to derive statistical information that can be applied to the MI dipoles. The data were obtained with a rotating coil and measured at 97A, 210A, and 1700A. The B2 dipole strength was obtained from a stretched wire probe 1" wide. The new MI prototype dipoles have been measured by a Hall probe, NMR probe, rotating coil, and flat coil probe. The Hall and NMR probe measures field at any (x, y, z) location in the magnet. The rotating coil is a cylindrical probe of radius 0.86" with wire windings on the surface and measures the integrated (over the length of the probe) multipoles of the magnet. These measurements are analyzed with a 1" reference radius. The flat coil is a probe with several coil windings around a rectangular frame. The probe measures the integrated relative flux as a function of position by translation of the probe. It can also measure the integrated relative flux as a function of magnet current.

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II. Systematic and Random Errors

A. Case of Dipoles

The Main Injector lattice has both a long and a short type dipole magnets. Their magnetic lengths at 120 GeV/c have a ratio equal to $\frac{2}{3}$, and their respective lengths are 6.096 and 4.064 meters. The magnetic length of these dipoles varies with energy due to saturation of ends. Because the end pack design is the same for both types of magnets the absolute change in effective length for each magnet will be the same. However the relative change in each case will be different. To study what effect this might have on the closed orbit of FMI the field errors due to the end dipole are separated from the body field errors. Multipoles due to dipole end are defined in TEAPOT in a separate element called MULTIPOLE. Because a dipole component in MULTIPOLE has the undesired effect of changing the reference orbit of the machine it is represented by a horizontal kick HKICK equal to

$$H_{kick} = \frac{\Delta L}{2L_{ref}} \times (\frac{2\pi}{904/3}) \qquad (1)$$

where ΔL is the absolute change in effective length and L_{ref} is the reference length at 120 GeV/c. An increase or decrease in bending angle of the particles is corrected by changing the dipole field strength. In TEAPOT this is taken into account by adding a systematic field error to the dipoles. The multipoles at each end, both normal and skew, are calculated from the following equation:

$$\int B_n dl = \int_{-\infty}^{\infty} B_n dl - \int_{L_o} B_n dl \qquad (2)$$

where L_o is the physical length of the magnet, and B_n is the n-th field multipole. In our case $L_o = 240''$. Details of the calculations are given in [1,2]. The integrated end multipoles quoted in Tables 1,2 are in units of 10^{-4} at a 1" radius, and normalized to the integrated body dipole. They represent the latest end pack design. Body multipoles and end multipoles can be directly added to obtain the total integrated multipole. The random errors of the body multipoles are calculated, as mentionned earlier, from the B2 dipole measurements. A conservative estimate of dipole strength variation has been used since measurements on the available sample have been limited by measurement errors. A small sample measured over a short period of time shows a variation of 2.5 units. No random errors are added to the end dipole.

B. Case of Quadrupoles

The values of the systematic and random errors of the quadrupoles are calculated using the Main Ring quadrupole measurements. The available measurement system provides limited information on quadrupole strength. A conservative assumption is made. It is observed that the variation of the octupole strength with current is very small suggesting a geometric effect. All skew quadrupole field errors are turned off for the convenience of the simulation. Using a coupling compensation scheme any linear coupling effects due to the presence of skew quadrupole can be corrected for.

Results are again summarized in Tables 1,2 at both injection and slow extraction energies.

II. RESULTS

A. Closed Orbit Errors

In the Main Injector lattice there are 208 quadrupoles. Located inside these quadrupoles are the beam position monitors. The vertical and horizontal beam positions are measured at the focussing and defocussing quadrupoles respectively. The vertical and horizontal displacement of the particles are corrected by applying corresponding kicks just after these position monitors. A typical uncorrected closed orbit for a given seed in both the horizontal and vertical plane at 8.9 GeV/c is shown in Fig. 2. The maximum corrector strength necessary to correct the orbit deviations in both planes is within the range of available corrector bend strength.

B. Betatron Function Errors

Fig. 1 is a sample plot of the horizontal and vertical beta function with all errors included and for a given seed. Variation in beta function from seed to seed is quite noticeable. The rms of these variations is in good agreement with what analytical formula predicts due simply to random quadrupole errors. This implies, and not surprisingly, that the major source of error contributing to the beta variations is the quad random error. More results on the closed orbit errors and betatron errors are presented in [3].

IV. CONCLUSION

The separation of the end dipole field errors from the body field errors made it possible to analyze how important the variations in effective length of the long and short dipoles in the FMI are. Effects on closed orbit and beta function variations were found to be negligible. Studies have also shown that the two source of field errors dominating the performance of the FMI are the assumed

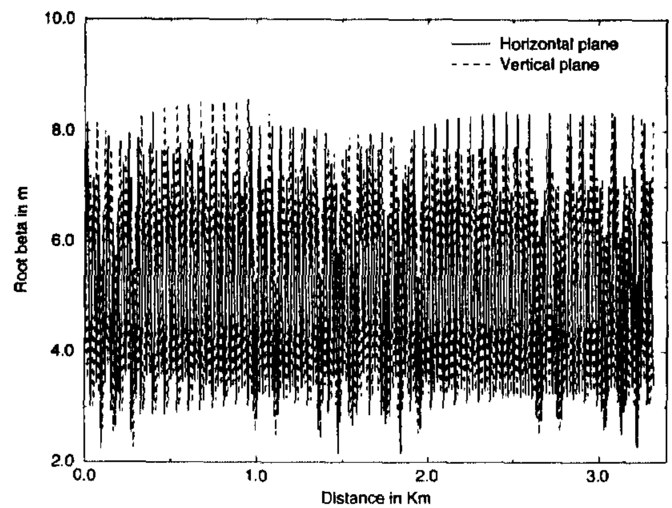

Figure 1: Sample beta function with all errors included

quadrupole random errors and the octupole error in the recycled Main Ring quadrupoles. A shuffling scheme of the quadrupoles supplemented by an octupole correction scheme greatly improves the characteristics of the machine. This is explained in more details in [4].

V. REFERENCES

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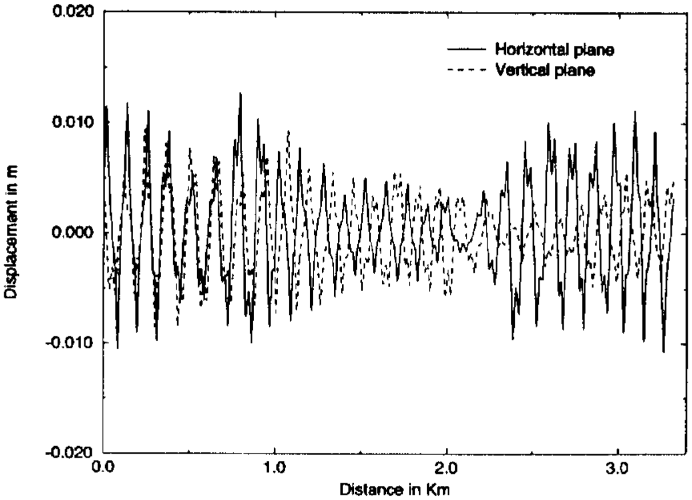

Figure 2: Uncorrected closed orbit at 8.9 GeV/c

Magnet Type	Multipole Order	Normal Errors		Skew Errors	
		$< b_n >$	σb_n	$< a_n >$	σa_n
Dipole Body	dipole	-4.68	10.0	–	–
	quad	-0.13	0.45	–	–
	sext	0.43	0.61	-0.04	0.22
	8	0.09	0.13	0.00	0.41
	10	0.18	0.32	0.03	0.15
	12	-0.03	0.10	0.00	0.19
	14	-0.01	0.23	-0.05	0.08
Dipole End	dipole	2.02	–	0.00	–
	quad	0.03	–	–	–
	sext	0.256	–	0.03	–
	8	-0.021	–	0.02	–
	10	-0.095	–	0.00	–
	12	0.009	–	-0.03	–
	14	0.002	–	0.00	–
MR Quads (Recycled)	quad	–	24.0	–	–
	sext	0.50	2.73	0.12	1.85
	oct	5.85	1.02	-1.16	2.38
	10	-0.10	1.12	0.42	0.47
	12	-1.82	0.63	0.40	0.70
	14	0.21	0.64	-0.55	0.44
	16	1.41	0.64	–	–
	18	-0.03	0.12	0.14	0.16
	20	-0.80	0.06	0.02	0.07
MI Quads (Newly built)	quad	–	24.0	–	–
	sext	–	2.73	–	–
	oct	-0.39	1.02	–	–
	10	–	1.12	–	–
	12	-1.39	0.63	–	–
	14	–	0.64	–	–
	16	1.29	0.64	–	–
	18	–	0.12	–	–
	20	-0.73	0.06	–	–

Table 1: Magnetic errors used in the 8.9 GeV simulation (see text for details & units)

Magnet Type	Multipole Order	Normal Errors		Skew Errors	
		$< b_n >$	σb_n	$< a_n >$	σa_n
Dipole Body	dipole	0.00	10.0	–	–
	quad	-0.30	0.21	–	–
	sext	-1.16	0.49	-0.03	0.17
	8	0.02	0.06	-0.02	0.29
	10	-0.09	0.25	-0.04	0.07
	12	-0.04	0.06	-0.01	0.21
	14	-0.08	0.25	-0.05	0.08
Dipole End	dipole	0.00	–	0.00	–
	quad	0.08	–	–	–
	sext	-0.52	–	0.05	–
	8	-0.012	–	0.02	–
	10	0.084	–	0.05	–
	12	0.008	–	-0.03	–
	14	-0.021	–	0.01	–
MR Quads (Recycled)	quad	–	24.0	–	–
	sext	1.69	2.29	-0.47	3.14
	oct	5.29	1.29	0.68	0.43
	10	-0.72	0.90	0.41	0.34
	12	-1.71	0.16	-0.31	0.14
	14	-0.25	0.92	-0.02	1.11
	16	1.37	0.92	–	–
	18	-0.22	0.92	0.06	0.25
	20	-0.82	0.33	-0.05	0.08
MI Quads (Newly built)	quad	–	24.0	–	–
	sext	–	2.29	–	–
	oct	-0.10	1.29	–	–
	10	–	0.90	–	–
	12	-1.41	0.16	–	–
	14	–	0.92	–	–
	16	1.32	0.92	–	–
	18	–	0.92	–	–
	20	-0.74	0.33	–	–

Table 2: Magnetic errors used in the 120 GeV simulation (see text for details & units)