Simulation of the dynamical performance of the Main Injector at 8.9 GeV.

C. S. Mishra, F. A. Harfoush

Introduction

Simulations to study the performance of the Main Injector at the injection energy of 8.9 GeV are described in this paper. We present a detailed study of the Main Injector lattice including the closed orbit errors, betatron function errors, tune versus amplitude, and dynamic aperture. The tracking calculations include the magnetic field errors, both systematic and random, and misalignment errors. In this paper we will briefly describe these errors along with the tracking conditions. A detailed description of these errors and their calculation can be found in MI66[1]. A thin element tracking program TEAPOT[2] has been used for these simulations.

Tracking Conditions and Errors

The Main Injector lattice has two different sizes dipole magnets, there magnetic lengths are 6.096 and 4.064 meters at 120 GeV. The magnetic length of these dipoles decreases with energies due to the saturation of ends, and at 8.9 GeV their length is 2.5 mm larger than the nominal at 120 GeV. This change in length introduces a non zero dipole multipole at each end of the magnet, and is represented in TEAPOT by a horizontal kick given by

$$H_{kick} = (\Delta L/2L_{ref}) * (2\pi/904/3) \qquad \text{radian}$$

Where ΔL is 2.5 mm. This additional bending of the particle, is corrected by decreasing the dipole excitation, calculated by eq-(14) of MI66.

The ends of the magnet have different magnetic multipoles than the body of the magnet. Further the two ends of the dipole are slightly different due the presence or absence of nearby bus work, leading to the labels "BUS END" or "NO BUS END". For the tracking calculation the two ends and the body are treated as a separate magnets . The end multipoles, both normal and skew, are calculated by using the method described in the section 2.2 of MI66. The multipoles used for these calculations were calculated by using the measurements where the 80" rotating coil was placed 50" inside the magnet rather than 30" as described in MI66. This change gives us more consistent results at all the energies. These values are also in better agreement with the fit to the flat coil data between -1" to +1" in x. Multipole error values quoted for the dipole ends in Table 1 are obtained by dividing the integrated multipole moments by eight, (the length of a long dipole magnet 240" divided by 30"), so that their values can be directly compared with the dipole body multipole errors. The random errors of the body multipoles are calculated by using the measurements of the B2 dipoles at 210 Amps.

The values of the systematic and random errors of the quadrupoles are calculated using the Main Ring quadrupole measurements. There are a very limited number of measurements available for MR Quads. Normal multipoles are calculated by using the 195 Amps measurements, whereas the skew multipoles are calculated using the measurements at 1575 Amps. The variation of the octopole strength and random errors with current are small.

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 removed.

Table 1 summarizes all of the multipoles as used in the input file to TEAPOT. Multipole field errors are quoted in units of 10^{-4} at a displacement of one inch.

The misalignment of all the magnetic elements and beam position monitors has been included in this calculation. The sigma of the alignment error with respect to the closed orbit is 0.25 mm in both horizontal and vertical directions. In addition dipole magnets have a roll angle of 0.5 mrad sigma.

Base tune of $(Q_x, Q_y) = (26.425, 25.415)$ were used in all the simulations. This tune is different than (26.407, 25.409) which was used for the Main Injector calculations before. This change in tune was necessary to increase the dynamic aperture, with all magnetic and misalignement errors turned on, the presence of an RF, and with chromaticity adjusted to -5,-5. In the lattice there are 18 RF cavities, each operating at $V_{rf} = 0.0218$ MV. The RF frequency is set to 53 MHz corresponding to a harmonic number of 588.

Closed orbit errors and Corrector strength

In the Main Injector lattice there are 208 quadrupoles. 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.

A typical uncorrected closed orbit in both the horizontal and vertical plane is shown in Fig 1. The average RMS closed orbit deviation before correction is 6.3 mm horizontal and 4.3 mm vertical for the selected seed. After three iterations of the orbit corrections the average RMS closed orbit deviation is reduced to 3.5×10^{-4} mm (H) and 3×10^{-6} mm (V).

We have studied the contribution of each magnetic errors and the displacement error to the average RMS closed orbit deviation for this seed. The total error is not a simple combination of all of these errors. There are some cancellation between errors. The result is summarized in Table - 2. Most of the orbit deviation is due to random errors . Fig 2 shows the distribution of uncorrected horizontal and vertical RMS closed orbit errors for

20 different seeds. The average RMS deviation of each seed is 5.0 mm and 3.9 mm in the horizontal and vertical planes respectively. The maximum corrector strength required to correct these orbit deviations is 150 $\mu radians$ in both planes. In the Main Injector we plan to use recycled Main Ring dipole correctors and also use newly build dipole correctors. At 8.9 GeV the Main Ring dipole correctors can provide 570 μ radian and 350 μ radian of horizontal and vertical corrections respectively. The new correctors will be stronger, which will help correct the orbit at higher energy.

Betatron Function Errors

Fig 3(a) shows a plot of the horizontal and vertical beta function of the Main Injector without any errors. In all of these figures solid line is for β_x and long dashed line is for β_y. The root beta calculated without including any error with TEAPOT is same as calculated previously for MI using MAD. Fig 3(b) is a plot of $\Delta\beta/\beta$ when all the errors are included. Further studies have shown that the asymmetry between the left and right half of the figure is due to random errors. Fig 3(b) to Fig 3(f) are the plots of the $\Delta\beta/\beta$ function with all the errors, for different seeds. The sigma of these deviations is about 10%. Fig 4(a) to Fig 4(f) shows the percentage change in beta function due to dipole systematic errors which includes the effect of change in the effective length of the dipole magnets, only the change in effective length of dipole magnets, dipole random errors, quadrupole systemetic and random errors and the magnet alignement errors recpectively. We have selected the seed which generated the Fig 3(b) for these figures. It is clear from these figures that most of the β function variations are due to dipole and quadrupole random errors and magnet alignement errors. The randomness of these errors leads to asymmetry between the two halves of the MI which is a result of some kind of cancellation between these errors. We are in process of developing a shuffling scheme for the placement of the quadrupoles[3].

Tune versus amplitude and dynamical aperture results

We have studied the survival of particles launched at different amplitudes in the Main Injector at the injection energy. A single particle will go around 35000 turns at the injection energy of 8.9 GeV during any operation that involves filling the ring with six Booster bunches. A particle is launched with a maximum horizontal displacement of equal to "A" at a location where the horizontal beta function is at its maximum of 80 meters. The maximum vertical displacement of the same particle is 0.4A (x/y=2.5) also at beta of 80 meters. Synchroton oscillation were included in the simulation by launching all particles with an amplitude of $\delta_{max} = (\Delta p/p)_{max} = 2.0 \times E - 3$.

Fig. 5 shows the variation of horizontal and vertical tunes as the amplitudes of the motion was increased. The numbers on the tune plot correspond to the initial amplitude "A" of a test particle, in millimeters. Points on the plot lie on a straight line up to an amplitude of about 17 mm, with the spacing between points increasing linearly. Both the horizontal and vertical tunes depend quadratically on amplitude, for moderate amplitudes.

This octupolar detuning is dominated by a combination of the systematic octupole error in the recycled Main Ring quadrupoles, and second order sextupole effects.

Particles were launched from 1 mm to 25 mm amplitude. Particles with an amplitude above 19 mm did not survive for the full 35000 turns of the simulation, for this particular seed. Similar simulations were performed for five different seeds. Fig 6 is a survival plot, displaying how many turns a particle survives the 35k turns in the Main Injector, as a function of initial amplitude. If the dynamical aperture of the machine is defined as the smallest amplitude particle that did not survive for 35000 turns, then the dynamical aperture for the Main Injector at the injection energy is predicted to be 22 $\pm$ 1.4 mm, corresponding to a normalized emittance of $59.2 \pm 10.2\pi$ mm mradians.

To study the discussed detuning effects we have varied the octupole strength of the Main Ring quadrupole and sextupole strength of the Main Injector dipole ends. Reducing the end sextupole to half the nominal value has no significant effect on the quadratic detuning. Also there was no change to the dynamic aperture of the machine. When we set the octupole (b_3) component of the quadrupole to zero, the detuning is very small. Fig. 7 is a tune-tune plot for different initial amplitudes with half nominal sextupole strength of the dipole ends and $b_3 = 0$ for the MR quads. This study was done for only one seed. For this seed with nominal MR quads octupole particles with amplitude larger than 19 mm did not survive. Particles with amplitude larger than 24 mm did not survive when we set the $b_3 = 0$ for the MR quads. We are in process of developing a correction scheme, using the octupole correctors placed in the ring for 120 GeV slow extraction, to cancel or reduce the total octupole of the ring at 8.9 GeV. This will help us improve the dynamic aperture of the MI.

Dipole End Sextupole Strength

We have also studied the strength of the chromaticity corrector sextupole to correct the chromaticity of the machine to -5,-5 at injection. The total integrated sextupole strength (end+body) of the Main Injector dipole is 2 units. Unless the the strength of the dipole end sextupole is reduced, it will require bipolar sextupole power supplies to adjust the chromaticity to -5,-5. The Main Injector dipole magnet end pack design is still in progress. It is expected that the new end packs design will have less than half the present sextupole strength. All the calculation should use half the nominal sextupole strength for the dipole ends.

References

1. F. A. Harfoush and C. S. Mishra, MI notes 0066

2. L. Schachinger and R. Talman, Particle Accl. 22, 35(1987).

3. S. Peggs, MI notes (number to be assigned), June 1992.

Table 1

Magnetic errors used in the 8.9 GeV simulation

	Multipole order	Normal $< b_n >$	σb_n	Skew $< a_n >$	σa_n
Dipole Body	dipole	-4.68	10.0	-	-
	quadrupole	-0.13	0.45	-	-
	sextupole	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 BUS	Dipole	2.05	-	0.0	-
	quadrupole	0.03	-	-	-
	sextupole	0.92	-	0.03	-
	8	-0.02	-	0.02	-
	10	-0.09	-	0.04	-
	12	0.04	-	-0.03	-
	14	-0.07	-	0.00	-
Dipole end NO BUS	Dipole	2.05	-	0.0	-
	quadrupole	0.03	-	-	-
	sextupole	0.99	-	-0.07	-
	8	-0.08	-	-0.02	-
	10	-0.11	-	-0.05	-
	12	-0.06	-	0.03	-
	14	-0.09	-	0.00	-
Recycled new Main Ring quadrupole	quadrupole	-	24.0	-	-
	sextupole	0.50	2.73	0.12	1.85
	8	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

Newly Built	quadrupole	-	24.0	-	-
Main Injector	sextupole	-	2.73	-	-
quads	8	-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 2

Close Orbit Errors for one seed

Errors	**Plane**	**RMS Diviation** mm
All	H	6.3
	V	4.3
Dipole systematic (including ΔL)	H	1.1
	V	0.0
Dipole Random	H	5.1
	V	0
Quad Systematic	H	0.
	V	0.
Quad Random	H	0.
	V	0.
Displacement and Rotational Error	H	2.6
	V	4.2
Change of effective length	H	1.1
	V	0.

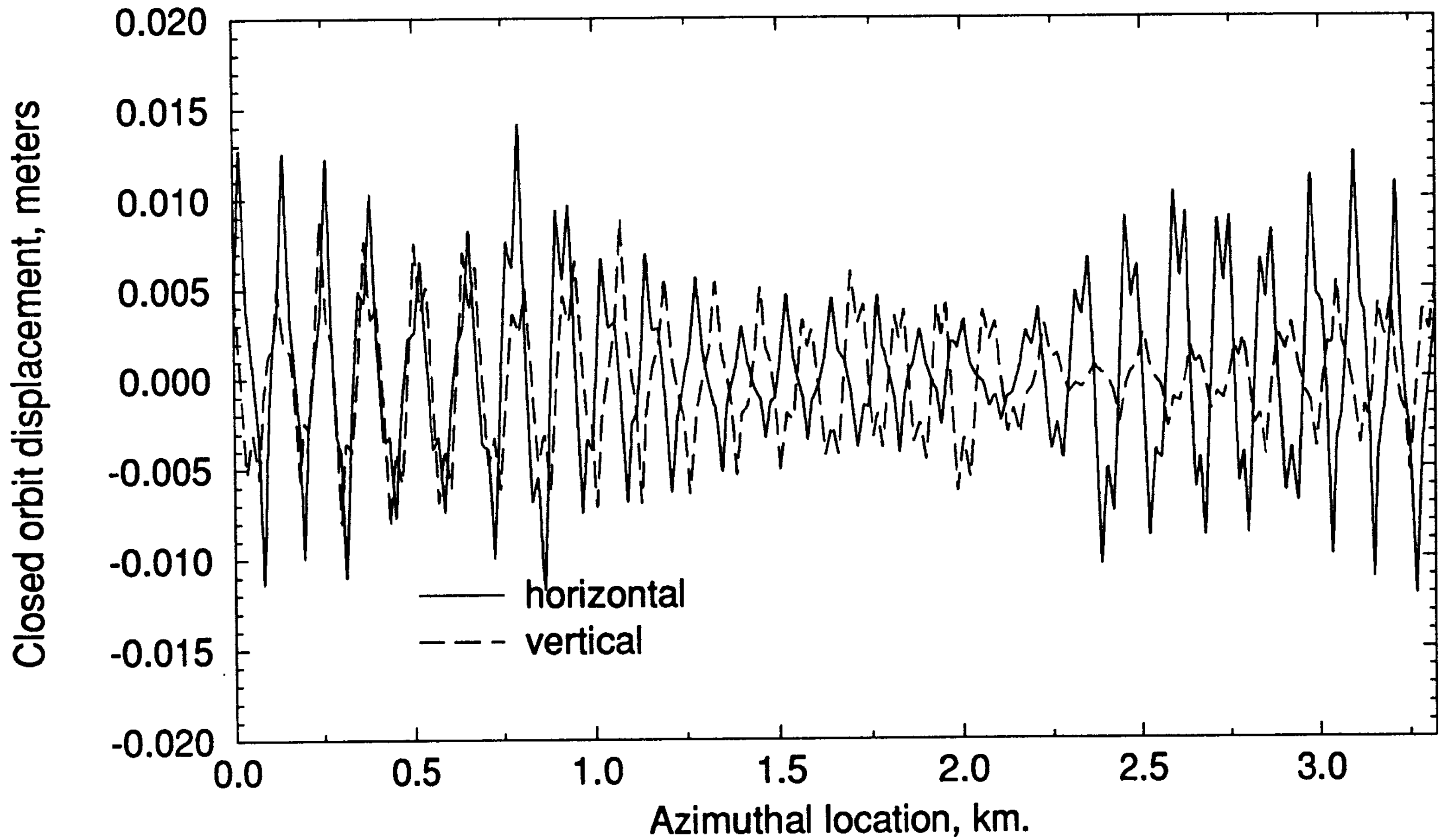

Fig. 1 Closed orbit errors before correction