*Particle Accelerators*, 1996, Vol. 55, pp. [397–406] / 151–160
Reprints available directly from the publisher
Photocopying permitted by license only

# EFFECTS OF MAGNETIC MULTIPOLES ON MAIN INJECTOR LATTICE

C.S. MISHRA

*Fermilab*, Batavia, IL 60510, USA*

*(Received 5 February 1996; in final form 5 February 1996)*

In this paper we discus the effects of higher order multipoles and magnetic element misalignments on the Main Injector lattice parameters. These higher order multipoles limits the dynamical aperture of the machine. We also discuss how the correctors in the lattice can be properly used to reduce the effect of unwanted multipoles on the aperture of the Main Injector.

*Keywords:* Magnetic multipoles.

## 1 INTRODUCTION

The Fermilab Main Injector (FMI) is a new 150 GeV proton synchrotron, designed to remove the limitations of the Main Ring in the delivery of high intensity proton and antiproton beams to the Tevatron. Studies has been made to understand the performance of the Main Injector. These calculations show that the Main Injector's dynamical aperture is larger than its design value of $40\pi$ mm mradian at injection.

Tracking simulations have revealed that the dominant factor limiting the dynamical aperture of the Main Injector are the large octupole component and the random errors in quadrupole strength of the recycled Main Ring quadrupoles. This paper describes a correction scheme which reduces the effect of these on the performance of the FMI, specially for the slow extraction operation.

The FMI will be constructed using a newly designed conventional dipole magnets and mostly recycled quadrupoles from the Main Ring. The FMI lattice has two different types of cells, the normal FODO cells in the arcs and

---

*Operated by University Research Association under contract with the Department of Energy.

straight sections and the dispersion-suppressor FODO cells adjacent to the straight sections to reduce the dispersion to zero in the straight sections.

Simulations results of the FMI at its two most critical times, injection and slow extraction are presented in this paper. The FMI lattice includes the magnetic field errors, both systematic and random, and misalignment errors. Studies of closed orbit errors, betatron function errors, tune versus amplitude and dynamical aperture are presented in this paper. A thin element tracking program TEAPOT[1] has been used for these simulations.

## 2 TRACKING CONDITIONS

All simulations were performed with the alignment errors and the magnetic field errors. Although a complete explanation of all the errors listed in Table I is too lengthy to be included here, some comments are in order. A more detailed description of these parameters is published elsewhere.[2] Multipole field errors for magnets are quoted in units of $10^{-4}$ at a displacement of one inch. These systematic and random errors for dipoles are calculated using the Main Injector production dipoles measurements. Figure 1 show the field profile of the Main Injector dipole field at various energies. The values of the systematic and random errors of the quadrupoles are calculated using the Main Ring quadrupole measurements. The Main Ring quadrupoles have a large octupole component and random error. The variation of the octupole 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. The values of the systematic and random errors of the other quadrupoles are calculated using the measurement of new quadrupole magnets.

The misalignment of all the magnetic elements and beam position monitors has been included in these calculations. The RMS 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 an RMS roll angle of 0.5 mrad.

Base tune of $(Q_x, Q_y) = (26.425, 25.415)$ were used in all the simulations, with unoptimized fractional tunes that were derived as follows. Slow extraction requires that the horizontal tune be moved onto a half integer without crossing a major resonance. It is conventional practice to operate near tune diagonal, but with tune spread by, say, 0.01, with the horizontal

TABLE I Magnetic errors used in the 8.9 GeV simulation

| *Magnet Type* | *Multipole Order* | *Normal Errors* | | *Skew Errors* | |
|---|---|---|---|---|---|
| | | $<b_n>$ | $\sigma b_n$ | $<a_n>$ | $\sigma a_n$ |
| Dipole | dipole | -1.1 | 5.0 | – | – |
| | quad | -0.75 | 0.23 | – | – |
| | sext | -0.51 | 0.09 | -0.16 | 0.62 |
| | 8 | 0.03 | 0.08 | -0.30 | 0.11 |
| | 10 | 0.16 | 0.08 | 0.05 | 0.26 |
| | 12 | 0.02 | 0.08 | -0.53 | 0.14 |
| | 14 | 0.16 | 0.15 | -0.01 | 0.23 |
| 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 | – | 8.0 | – | – |
| | sext | – | 1.26 | 0.48 | 1.44 |
| | oct | 6.20 | 1.02 | -1.95 | 1.36 |
| | 10 | 0.05 | 0.5 | -0.42 | 0.27 |
| | 12 | -1.66 | 0.25 | 0.495 | 0.42 |
| | 14 | 0.21 | 0.64 | -0.55 | 0.44 |
| | 16 | 1.41 | 0.64 | – | – |
| | 18 | -0.06 | 0.05 | -0.04 | 0.07 |
| | 20 | -0.8 | 0.07 | -0.06 | 0.08 |

tune larger to avoid crossing the coupling resonance during slow extraction. Finally, all test particles had a tune modulation amplitude in both plane of 0.01, due to non-zero net chromaticity and finite amplitude synchrotron oscillation. It is necessary to be at least this far from major resonances. Assuming that the 2/5 resonance is the resonance closest to the half integer that must be avoided, all of the above conditions are satisfied if $Q_y > 25.41$, $Q_x = Q_y + 1 + 0.01$. The base tunes were moved an extra 0.005 away from the 2/5 resonance, without getting unduly close to the half integer.

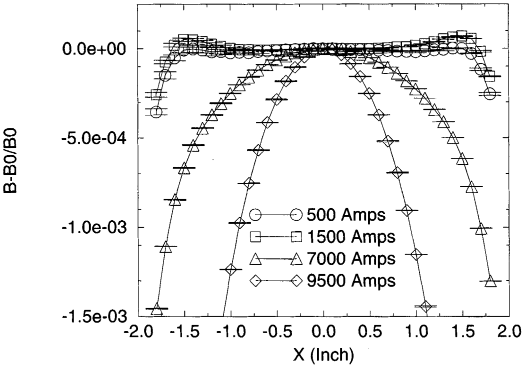

FIGURE 1 Field uniformity, $\Delta B/B$, measure in the Main Injector dipole. The four curves correspond to 8.9, 27, 120 and 150 GeV/c excitations.

In the lattice there are 18 RF cavities, each operating at $V_{rf} = 0.0218$ MV and 0.0555 MV at 8.9 and 120 GeV respectively. The RF frequency is set to 53 MHz corresponding to a harmonic number of 588. Synchrotron oscillation were included in the simulation by launching all particles with an amplitude of $\delta_{\text{max}} = (\Delta p/p)_{\text{max}} = 2.0 \times 10^{-3}$.

## 3 TRACKING RESULTS

### 3.1 Closed Orbit and Betatron Function Errors

Figure 2 shows two superimposed histograms, representing the distribution of uncorrected horizontal and vertical closed orbit errors that are found when 19 different seeds are used to construct independent sets of random errors. The average values over all the seeds of the root mean square orbit deviation for each particular seed is 5.0 mm in the horizontal, and 3.9 mm in the vertical.

In order to correct these orbits for a typical seed, the maximum required corrector strength is less than 100 mm in both the horizontal and vertical planes. A typical uncorrected closed orbit is shown in Figure 3, where the two traces represent horizontal and vertical displacements. After three iterations of the orbit correction scheme, the average root mean square closed orbit deviation is reduced to $4.8 \times 10^{-4}$ mm in the horizontal, and $1.0 \times 10^{-8}$ mm in the vertical.

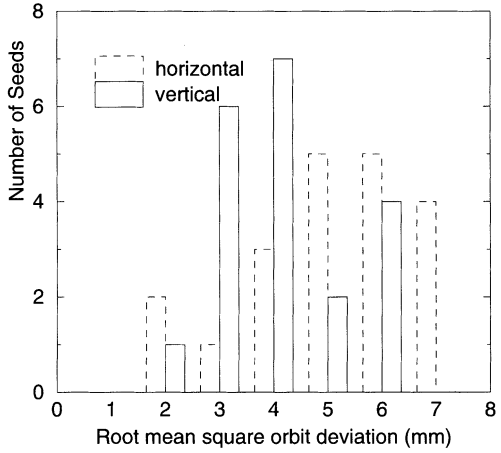

FIGURE 2 Distribution of uncorrected horizontal and vertical closed orbit errors for 19 different seeds.

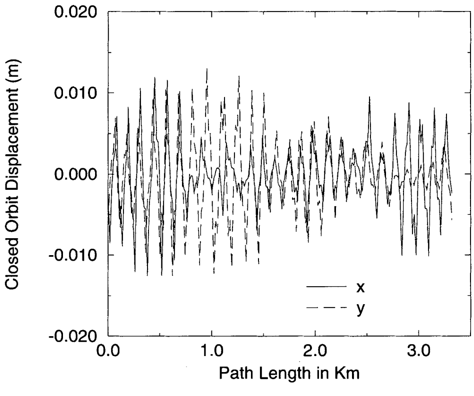

FIGURE 3 Typical uncorrected closed orbit resulting from misalignment and strength variations.

Figure 4 shows a plot of the typical variation of the horizontal and vertical beta functions in the Main Injector due to all sources of errors. These include dipole and quadrupole strength and misalignment errors. The main source of betatron function errors is the random quadrupole error of $2.4 \times 10^{-3}$ measured in the Main Ring quadrupoles that are to be recycled. Due to limited

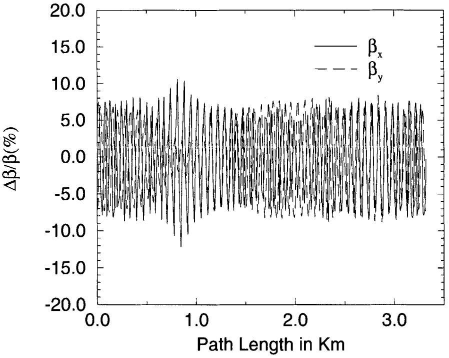

FIGURE 4 Typical beta function variation resulting from magnetic multipole errors.

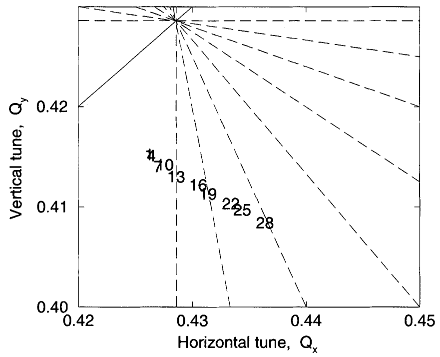

FIGURE 5 Tune vs amplitude in the Main Injector at 8.9 GeV/c, based on tracking for a typical seed. Numbers on the plot refer to the launch amplitude of a test particle in millimeters.

measurement and understanding of the measurement data, it is conservatively higher limit for the random quadrupole error in Main Ring quadrupoles. Newly built Main Injector quadrupoles have random quadrupole errors of $8.0 \times 10^{-4}$.

Figure 5 shows the variation of horizontal and vertical tunes in the Main Injector as the amplitude of motion was increased, for a typical seed. The numbers on the tune plane plot correspond to the amplitude of a test particle, in millimeters. This detuning is dominated by a combination of the systematic octupole error in the recycled Main Ring quadrupoles, and second order sextupolar effects. Point with an amplitude above 28 mm did not survive for the full 35,000 turns of the simulation, for this particular seed.

*3.1.1 Dynamical aperture* The long time behavior of the Main Injector at injection was tested by launching an array of particles at different amplitudes. In what follows, a test particle is labeled with an amplitude of A millimeters when, in the absence of nonlinear phase space distortions, it achieves a maximum horizontal displacement of A at a location where the horizontal beta function is 70 m. The maximum vertical displacement of the same particle is 0.4A ($x/y = 2.5$) also at a beta of 75 m. 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. At 120 GeV where slow extraction of the proton beam is planned the beam will stay in the ring for a maximum of 1.0 sec (flattop). At 120 GeV we have simulated this by 100 k turns.

Figure 6 is a survival plot, displaying how many turns a particle survives in the Main Injector, as a function of its initial amplitude. Different symbols in the plot correspond to the 5 different seeds that were used. Particles that survived to the end of the simulation are plotted on a plateau at the 35,000 turn limit. If the dynamic aperture for a particular seed is defined as the amplitude of the smallest amplitude particle that does not survive for 35,000 turns, then the dynamic aperture for the Main Injector at the injection energy is predicted to be $30.6 \pm 0.5$ mm, corresponding to a normalized emittance of $127 \pm 4\pi$ mm-mr.

The Main Injector, as discussed above, has a dynamic aperture at injection of over $120\pi$ mm-mr, corresponding to $\pm 30.6$ mm amplitude in the horizontal plane. The injection and extraction regions, unfortunately, require physical restrictions near the center of the aperture. While these devices limit the available physical aperture, it is still substantially greater than $40\pi$ mm-mr. To preserve the large physical aperture, good closed orbit control is required, especially at injection. To ease demands on the dipole correction elements, it is intended to induce closed orbit distortions at the extraction-device locations by intentionally misaligning quadrupoles in a controlled manner.

In the vertical plane, the dipole beam tube has an inner dimension of $\pm 24$ mm, corresponding to an admittance of over $80\pi$ mm-mr at injection and at a $\beta$ of 60 m. The injection devices will likely limit the emittance of the injected beam (but not the circulating beam) to somewhat less than this, but still provide an aperture much larger than what is desired.

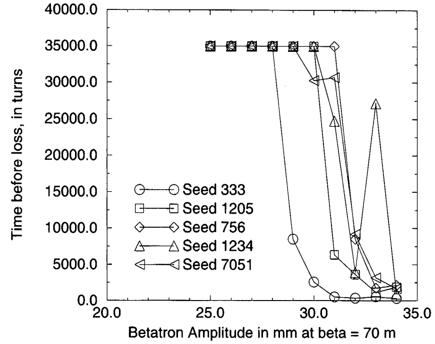

FIGURE 6 Survival plot for the Main Injector at 8.9 GeV/c.

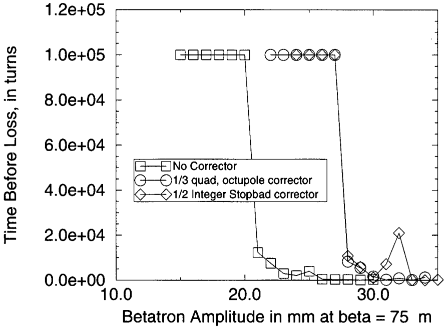

FIGURE 7 Survival plot for the Main Injector at 120 GeV slow extraction, with and without corrections.

## 4 CORRECTION SCHEME

At 120 GeV, close to the half integer resonance extraction, the horizontal tune is changed from $Q_x$ = 26.425 to 26.485. This is achieved by ramping the main quadrupoles in 0.1 sec. The detuning of the particle will remain the same at this setting and will result in loss of large amplitude particle. The slow extraction septum is placed at 16 mm. We have studied the dynamical aperture of the FMI for slow extraction. In this regime particles remain in the FMI for 1.0 sec equivalent to about 100 k turns. A survival plot is shown in Figure 7. The dynamical aperture at 120 GeV is reduced from 34.6 ± 0.5 to 20.67 ± 1.25 mm. These calculations have not taken into account other effects like power supply ripples and space charge. If included we expect a further reduction in the dynamical aperture. Because the beam behavior is more unstable at slow extraction a bigger dynamical aperture is desirable.

The focusing and defocusing quadrupoles are powered by two separate buses, and the current in each bus can be different. All the recycled MR quadrupoles will be measured for field quality before they are placed in the FMI. A smart shuffling scheme can be worked out that reduces the rms error in quadrupole field strength around the ring. A simple scheme is to divide the quadrupoles into two groups. One group will contain the quadrupoles with a strength higher than the total mean value and another group will contain the lower strength. This separation into two groups will reduce the rms error of quadrupoles by creating two non gaussian distributions. We have studied the effect of this quadrupole selection procedure by generating Monte-Carlo distributions of the quadrupole strength.

The variation in $\Delta\beta/\beta$ can be further reduced by canceling the natural half-integer stopband of the FMI. This is achieved by using the trim quadrupoles placed in the ring for slow extraction. These trim quadrupoles can be used as extraction element for slow extraction, and as correctors at all other energies. The FMI lattice has 54 octupoles and 16 trim quadrupoles placed around the ring for extraction. There are additional 8 corrector octupoles in the ring. We are evaluating the possibilities of adding 8 more similar octupoles. The MR quadrupoles have a positive octupole component almost invariant with energy. The extraction and corrector octupoles will be used to zero the total octupole component in the ring. Just like trim quadrupoles these octupoles will be used as extraction element for slow extraction and as correctors at all other energies. The bipolar power supply on these magnets will enable us to use them for slow extraction, and as correctors at all other energies.

The detuning of the particles at 120 GeV is considerably reduced by the smaller quadrupole random error and the octupole correction elements. Detuning of particles with large amplitude is reduced by about 30%. Figure 7, is the survival plot before and after correction for one seed at the slow extraction tune of $(Q_x, Q_y) = (26.485, 25.425)$. The dynamical aperture increases by about 7 mm. This is due mainly to the reduced $\Delta\beta/\beta$, and to the smaller total octupole in the FMI.

## 5 CONCLUSION

These calculations show that the Main Injector design exceeds the design specification of $40\pi$ mm mradians normalized emittance at injection. The larger octupole and the random variation of the quadrupole strengths are the limiting factor for this dynamical aperture. A correction scheme using the magnetic elements placed in the FMI and quadrupole shuffling makes it possible to reduce the effect of the large quadrupole random error and octupole multipole. This correction scheme will provide us with additional aperture at all energies, specially for the 120 GeV slow extraction.

### *Acknowledgements*

We thank R. Talman for providing the tracking code TEAPOT and answering questions relating these calculations.

### *References*

[1] L. Schachinger and R. Talman, Particle Accl. 22, 35(1987).
[2] F.A. Harfoush and C.S. Mishra, "Systematic and Random Errors for Main Injector Tracking," Fermi Internal Notes, *MI-0066*,in PAC93 proceedings.