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Stability of Beam in the Fermilab Main Injector

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Abstract

The Fermilab Main Injector is a new 150 GeV protron synchrotron, designed to remove the limitaions of the Main Ring in the delivery of high intensity proton and antiproton beams to the Tevatron. Extensive studies has been made to understand the performance of the Main Injector. In this paper, we present a study of the Main Injector lattice, which includes magnetic and misalignment errors. These calculations shows the Main Injector's dynamical aperture is larger than its design value of 40π mm mradian at injection.

I. INTRODUCTION

The Fermilab Main Injector (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 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. Results shows that the dynamical aperture meet the design specifications. A thin element tracking program TEAPOT[1] has been used for these simulations.

II. TRACKING CONDITIONS

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 changes with energies due to the saturation of ends, and at 8.9 GeV their length is 2.46 mm larger than the nominal at 120 GeV[2]. This change in length introduces a non zero dipole multipole at each end of the magnet. This additional bending of the particle, is corrected by decreasing the dipole excitation.

The ends of the magnet have different magnetic multipoles than the body of the magnet. For the tracking calculation the two ends and the body are treated as separate magnets . The dipole body and end multipoles, both normal and skew, are calculated by using the method described in[3]. At present we have only two prototype Main Injector dipoles, so the random errors of the body multipoles are calculated by using the measurements of the B2 dipoles at 210 Amps for 8.9 GeV.

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. 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. Table 1 and 2 of ref [3] 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 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. This tune is different than (26.407, 25.409) which was used in earlier calculations. This change in tune was necessary to increase the dynamic aperture, with all magnetic and misalignement errors turned on, the presence of RF, and with chromaticity set to desired value. 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.

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III. TRACKING RESULTS

A. Closed orbit and Betratron Function Errors

In the Main Injector lattice there are 208 quadrupoles, 128 are recycled Main Ring quadrupoles, rest are newly designed. 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.

The average RMS closed orbit deviation before correction is 5.9 mm horizontal and 4.4 mm vertical for the selected seed. After three iterations of the orbit corrections the average RMS closed orbit deviation is reduced to 2.3×10^{-4} mm (H) and 7.2×10^{-7} mm (V). Most of the close orbit deviation is due to dipole random and misalignment errors . Figs 1a and 1b show the distribution of uncorrected horizontal and vertical RMS closed orbit errors for 20 different seeds at 8.9 and 120 GeV. 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 100 *μradians* in both planes at these energies. In the Main Injector we plan to recycle Main Ring dipole correctors and also use newly build dipole correctors. At 8.9 GeV the Main Injector dipole correctors can provide 2000 μ radian and 1300 μ radian of horizontal and vertical corrections respectively.

Due to the presence of the dipole and quadrupole random errors and magnet alignment errors there is a variation of the β function around the FMI from an ideal lattice. Figs 2a and 2b show the distribution of the horizontal and vertical $\Delta\beta/\beta$ when all the errors are included. The sigma of these deviations is about 5%. The variation in β can be further reduced by using correction scheme utilizing extraction quadrupoles in the lattice. Since all the Main Ring quadrupoles will be measured before their placement in the FMI we can develop a shuffling scheme of quadrupoles for their placement in FMI.

B. Dynamical Aperture

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. 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 but 100k turns. A particle is launched with a maximum horizontal displacement "A" defined at a location where the horizontal beta function is at its maximum of 75 meters. The maximum vertical displacement of the same particle is 0.4A (x/y=2.5) also at a beta of 75 meters. Synchroton oscillation were included in the simulation by launching all particles with an amplitude of $\delta_{max} = (\Delta p/p)_{max} = 2.0 \times E-3$. Particles were launched from 15 mm to 35 mm amplitude. Simulations were performed for five different seeds. Figs 3a and 3b are survival plots, displaying how many turns a particle survives in the Main Injector at 8.9 and 120 GeV, as a function of initial amplitude. If the dynamical aperture of the machine is defined as the smallest amplitude particle that did not survive, then the dynamical aperture for the Main Injector at the injection energy is predicted to be 34.4 ± 0.8 mm, corresponding to a normalized emittance of $96.8 \pm 4.5\pi$ mm-mradians.

C. Other Studies

We have studied the effect of power supply ripples on the FMI performance. It is expected that the FMI power supply will achive similar regulation as Main Ring power supply, i.e. $\pm$ 300 ppm and $\pm$ 60 ppm at injection and extractions respectively. This ripple causes a shift in tune-tune plane of about $\pm$ 0.017(h) and $\pm$ 0.019(v) at injection and $\pm$ 0.008(h) and $\pm$ 0.005(v) at 120 GeV. This does not seem to be a serious problem.

We have also studied the alignment tolerance of the magnetic element and have concluded that it is important and feasible to achieve the alignement tolerance described in this paper.

IV. CONCLUSION

These calculations show that the Main Injector design exceeds the design specification of 40π 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 has been developed to increase this dynamical aperture which is not necessary at 8.9 GeV but will be desired for 120 GeV slow extraction.

V. ACKNOWLEDGMENTS

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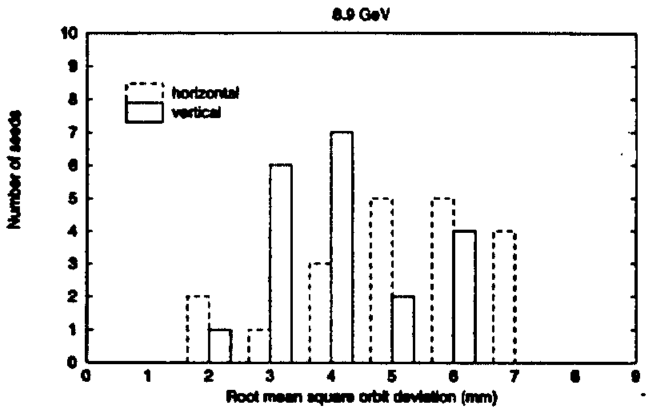

Fig. 1a Histogram of Closed orbit errors before correction

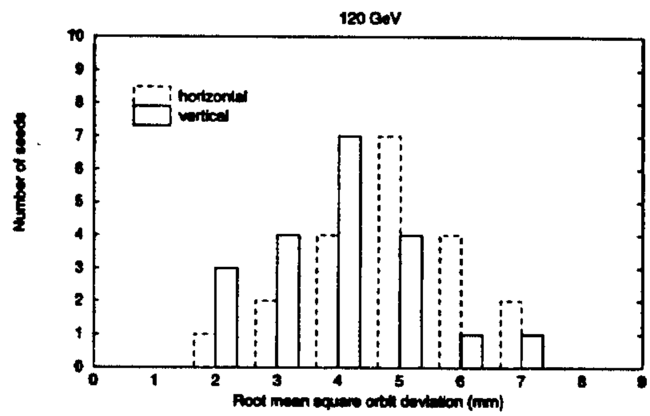

Fig. 1b Histogram of Closed orbit errors before correction

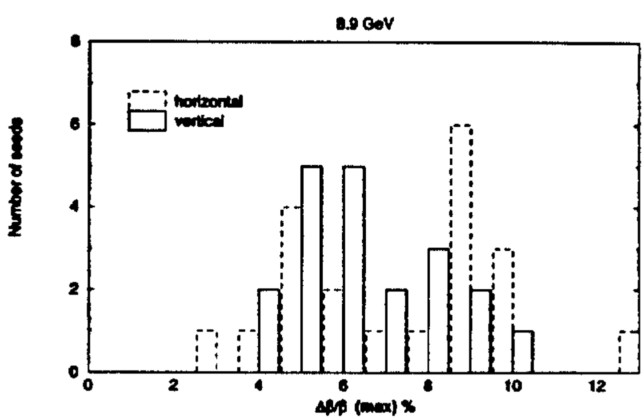

Fig. 2a Histogram of Maximum ($\Delta\beta/\beta$)

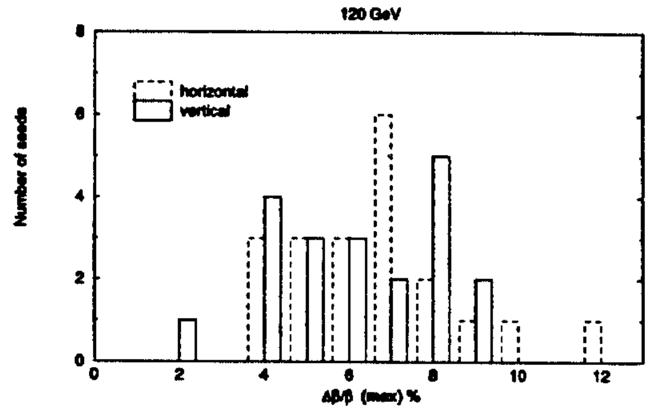

Fig. 2b Histogram of Maximum ($\Delta\beta/\beta$)

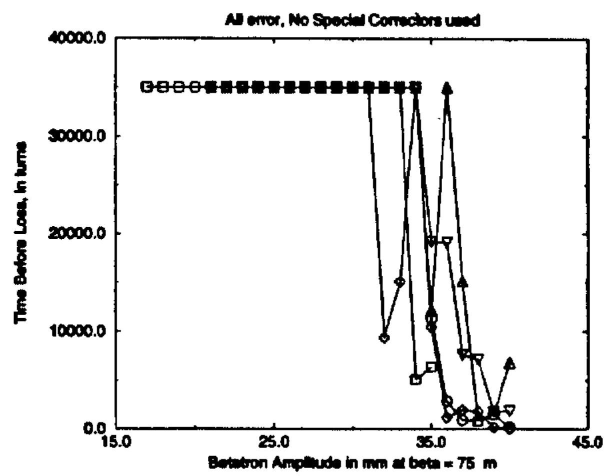

Fig. 3a Survival Plot at 8.9 GeV

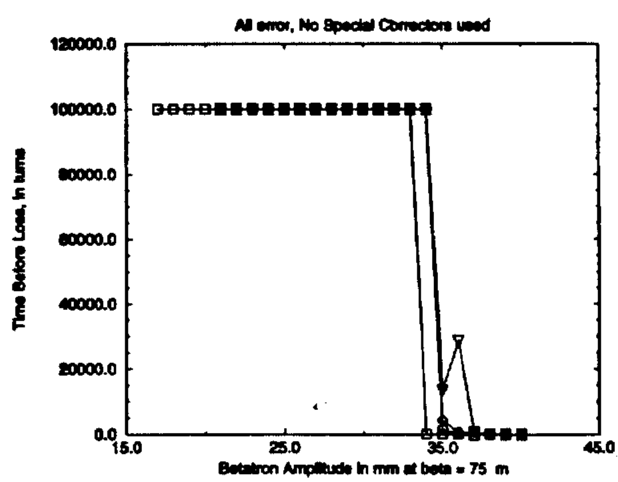

Fig. 3b Survival Plot at 120. GeV