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C.S. Mishra, F.A. Harfoush and J. Johnstone

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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C. S. Mishra, F. A. Harfoush, and J. Johnstone
*Fermi National Accelerator Laboratory**
Batavia, Illinois 60510

Abstract

Recent modifications to the tracking code TEAPOT have allowed us to simulate both ramp and slow extraction in the Fermilab Main Injector at 120 GeV/c . This calculation includes all the magnetic field and alignment errors. Preliminary results from this calculation are presented here and compared with other calculations. Further studies to optimize the strength and ramp of the extraction elements are in progress.

I. INTRODUCTION

The Fermilab Main Injector (FMI) is designed to provide high intensity slow extracted beam, 3×10^{13} protons every 2.9 sec with 33% duty factor. This 120 GeV/c beam will be used for the studies of CP violation and rare Kaon decays and detector R&D. The new FMI will enable a state of the art Kaon experiment, in a similar amount of running time, to improve the upper limits of rare Kaon decays by two orders of magnitude.

The slow extraction in FMI is planned by exciting the half-integer resonance. The half-integer resonance is a linear resonance and can be induced by a quadrupole field. The beam in this case is either entirely stable or entirely unstable. The extraction rate is controlled by using an octupole field, which splits the beam phase space into stable and unstable region. In this paper we describe the simulation of slow extraction in FMI. The FMI lattice we have used contains all errors and appropriate extraction elements. Due to CPU limitations, ramping is done in few hundred turns. In all these calculations a modified version of the thin element tracking code TEAPOT [1], and MAD [2] are used.

II. EXTRACTION CONDITIONS

The FMI lattice used in these calculations has the dipole body and end multipoles, both normal and skew, calculated by using the method described in [3]. The values of the systematic and random errors of the quadrupoles are calculated using the Main Ring quadrupole measurements. All skew quadrupole field errors are turned off, for the convenience of the simulation. Tables 1 and 2 of [3] summarize all of the multipoles. 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 0.25mm in both horizontal and vertical planes. In addition dipole magnets have an rms roll angles of 0.5 mrad. In the lattice there are 18 RF cavities, each operating at $V_{rf} = 0.0555$ MV at 120 GeV. The RF frequency is set to 53 MHz corresponding to a harmonic number of 588. Synchroton oscillation was included in the simulations by launching all particles with an amplitude of $\delta_{max} = (\Delta p/p)_{max} = 0.3E\text{-}3$ at 120.0 GeV.

The base tune of FMI is $(Q_x, Q_y) = (26.425, 25.415)$. Before the extraction process the FMI is corrected by the methods described in [4]. The extraction process begins by changing the main quadrupole power in order to raise the horizontal tune closer to the half integer 26.485. Using the 32, 0th-harmonic octupoles, placed in the ring an amplitude-dependent tune shift and consequently a tune spread in the beam is induced. The existing octupole component of the Main Ring quadrupoles adds up to the 0th-harmonic octupoles and help this process. The 0th-harmonic octupoles are not used as correctors during slow extraction. The 53rd harmonic quadrupoles are turned on to achieve a desired orientation of the phase space. Sixteen of these recycled Main Ring quadrupoles are distributed around the ring, separated into two orthogonal families (cosine and sine). One family alone excites the 53rd harmonics for resonant extraction, while both families are used to cancel the natural half-integer stopband of the machine. The strength of the quadrupoles and octupoles are chosen so that at the end of the initial ramp the stable phase-space area is as large as the emittance of the circulating beam.

The 53rd harmonic quadrupoles are further ramped to increase the width of the half-integer stopband and start moving the stopband through the beam. Small amplitude (smaller tune) particles remain stable, with their phase-space motion on subsequent turns oscillating between the fixed points. Every turn the stable phase-space area shrinks and the large amplitude particles enter the stopband and become unstable. The unstable particles

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streams out along the separatrix until they jump across the wires of electrostatic septum. The particles with horizontal amplitude larger than the horizontal location of the septum are kicked to provide enough separation between the circulating and extracted beams at the lambertson.

III. EXTRACTION SIMULATIONS

The FMI extraction will take place over 1.0 sec or 100k turns for 3×10^{13} protons. A real simulation of this process will require a considerable amount of CPU time. Simulations of the quadrupole and octupole ramp and final extraction process have been done in several hundered turns by using the modified TEAPOT and MAD. The new modified TEAPOT code can do both the tracking calculations and model the extraction. The added feature of this code is that it allows one to ramp the magnetic elements, by adding the addtional strength to a particular magnetic element as error, after a certain number of particle turns. This simulation in reality corresponds to fast resonant extraction, in which the beam is fully extracted within a few milliseconds. The extension of this simulation and extraction process to longer time spans is a straight forward procedure.

Initial particle positions and transverse momenta were generated randomly from uncoupled, gaussian distribution in both planes. 1000 particles were tracked in these simulations. Before launching these particle the FMI lattice is corrected by the method described in [4]. The simulation begins by increasing the horizontal tune of the machine from the nominal value of .425 to .485 using the main quadrupole circuits. During the first hundred turns the desired orientation of the phase-space at the septum is achieved by slowly energizing the appropriate 53rd harmonic quadrupole and 0th harmonic octupole circuits. In the present simulation the strength of these elements is increased every turn of particle tracking. At this stage the stable phase space region is just large enough to enclose the emittance of the beam as shown in 1.

The extraction septum is turned on for subsequent tracking. This provides a horizontal kick to the particle whose amplitude is larger than 16 mm, the location of the septum wire. The 53rd harmonic quadrupoles are slowly ramped over several hundred turns. This makes the particles move along the separatrix with their amplitude growing exponentially every turn until they ultimately jump the electrostatic septum wire. Figs 2,3 show the phase space of these particles after 50 turns at the electrostatic septum and lambertson. One can clearly observe the separation between the circulating and extracted beam is achieved. These calculations are done using the modified version of the TEAPOT code. The location of the septum and lambertson are choosen such that there is about 83 deg of phase advance between them. Figs 4,5 show the same after 150 turns, where most of the particles are already extracted. During this process of ramping and extraction only 2% of the particles were lost. 1% were lost when their amplitude became so large that they hit the aperture of the machine, while the other 1% were lost by particles hitting the septum wire. At present the extraction rate simulated by TEAPOT is not quite uniform. More study is needed to control the rate of extraction, which can be done by changing the rate of the two ramps.

In an independent study tracking with the code MAD was performed. In this simulation similar input and ramp were also used. Figs. 6,7 show the phase space distribution of the particle after 500 turns. In this calculation a local orbit bump provides the angular offset at the septa, and ensures that the extracted beam is consistent with the trajectory and aperture of the 120 GeV/c beamline to switchyard.

IV. CONCLUSION

The simulations described in this paper show that the proposed slow extraction scheme for the FMI will work with high efficiency. Further details of the strength of the extraction elements and speed of ramp for uniform extraction is being worked out. Results obtained with the modified TEAPOT version seem to be in agreement with MAD results.

V. ACKNOWLEDGMENTS

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V. REFERENCES

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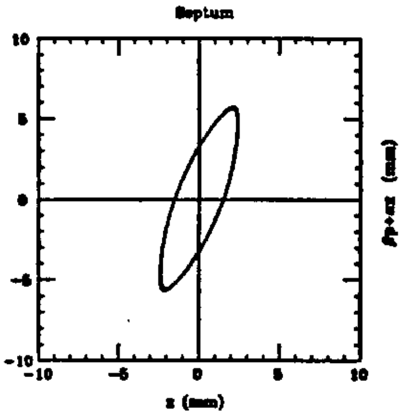

Figure 1: Stable phase space region of the beam

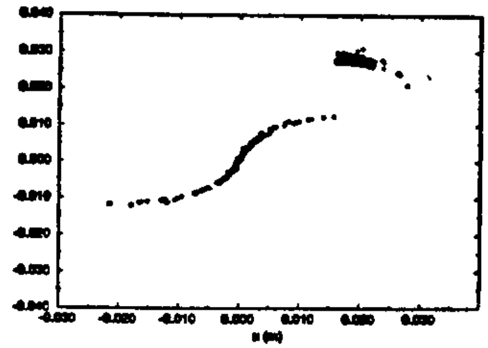

Figure 2: Phase space at electrostatic septum for turn=50

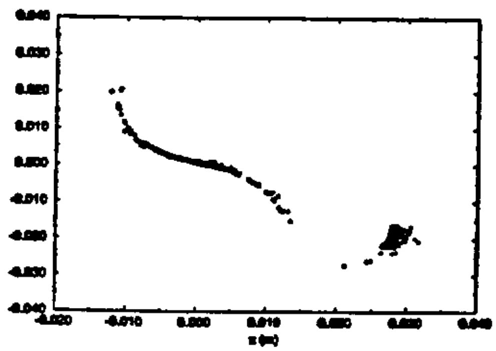

Figure 3: Phase space at lambertson for turn=50

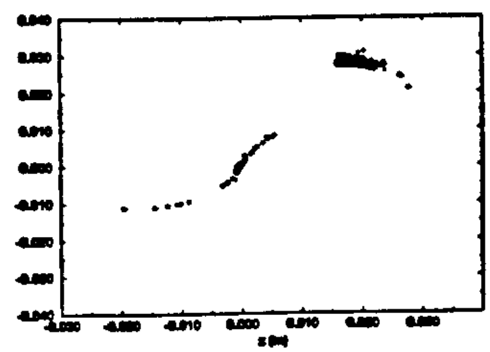

Figure 4: Phase space at electrostatic septum for turn=150

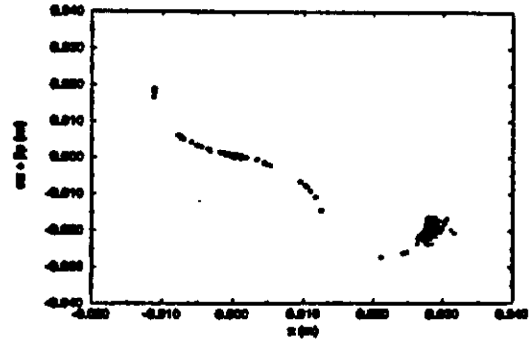

Figure 5: Phase space at lambertson for turn=150

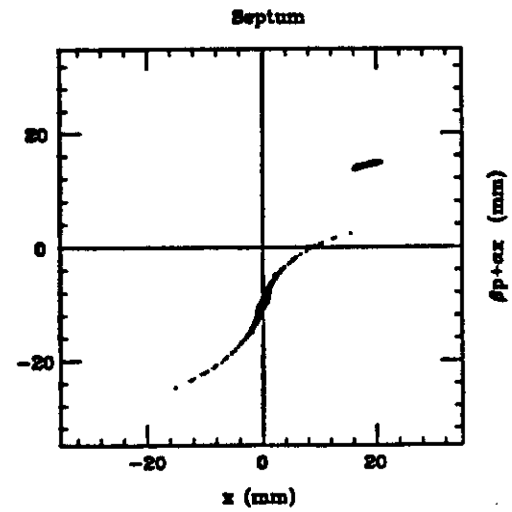

Figure 6: Phase space at electrostatic septum for turn=500 using MAD

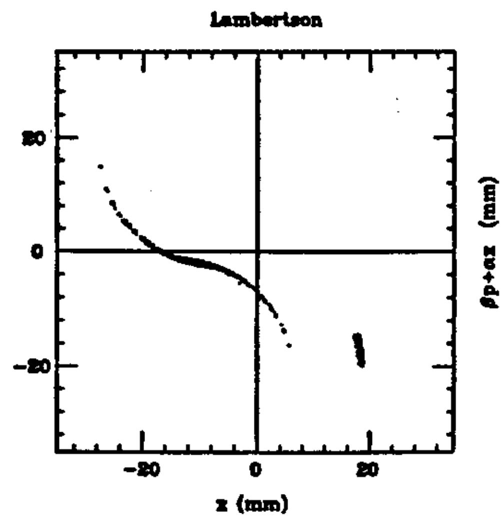

Figure 7: Phase space at lambertson for turn=500 using MAD