Design and Multiparticle Simulation of the Half Integer Slow Extraction System for the Main Injector

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Abstract

One of the roles of the new Main Injector ring, in the second phase of the Fermilab upgrade, is to deliver all year round the slow extracted 120 GeV test beams. The half-integer slow extraction system design and results from a Monte-Carlo simulation of fast spill are presented. The simulation was performed with a computer tracking program based on the TEVLAT program with a large number of particles (up to 1000). Particle tracking included the systematic errors produced by the magnetic multipoles within the dipoles and quadrupoles as well as random multipole errors.

I. Introduction

The Main Injector will replace the existing Main Ring in the Fermilab Accelerator Complex and allow significant enhancements to both the Fermilab collider and fixed target programs. Number of protons delivered to the antiproton production target or total number of protons delivered to the Tevatron will be two-three times higher than the present one. In addition the Main Injector will provide continuous 120 GeV beam to the experimental area during the collider operation, a capability which does not presently exist in the Main Ring [1]. The Main Injector will be built from newly constructed dipole magnets. In this report we present a design system for the half-integer resonant extraction for the Fermilab Main Injector. One of the major intentions of this project is to reconfirm the quality of the magnetic field in the Main Injector dipole and quadrupole magnets at 120 GeV operation. The beam size at 120 GeV is too small (for the normalized emittance of $c = 40 \pi mm mrad$) to cause any concerns about the aperture. The particle trajectories during the slow extraction process deteriorate away from the axis. At high values of the magnetic field slow extraction represents the major aperture probe and sets the limits on the magnetic field quality. In the simulation process different quality of the magnetic field in the dipoles and in the quadrupoles were examined. In the first part of the report a short introduction into the half-integer resonant extraction is presented with the positions and roles of the quadrupole and octupole magnets. A modeling of the half-integer resonant extraction with a computer program based on the TEVLAT [2] is shown in part II. The magnetic field errors in the dipoles and the quadrupoles were included in the simulation and the results of a Monte-Carlo simulation are presented.

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extraction quadrupole, was located at the opposite side of the ring.

The position of the electrostatic septum was selected at the kicker magnets due to unavoidable small beam losses at the wire array of the septum. The beam loss will not induce radioactive damage to the kicker magnet. The length of the electrostatic septum was 3.6 meters. The septum high voltage was 54.4 kV across a 14 mm gap between the electrode and the wire array. This kick was strong enough to establish a 6 mm distance for the extracted beam at the magnetic septum. The magnetic channel - Lambertson magnet has a magnetic field-free region where the beam circulates through the center of the aperture. The beam is bent in the vertical plane within the extraction channel. The smallest separation between the field free region and the extraction channel is 2 mm. The separation wall of the vacuum chamber in the field free region has two sides with an angle of 45° degrees.

### III. Computer Simulation

The slow extraction should provide a smooth constant rate of extracted beam throughout the cycle. Particles in the beam have unavoidable tune spread which arises from the final beam momentum spread: the tune shift due to chromatic effects and space charge tune shift which is intensity dependent. The tune spread also comes from the nonlinear elements: the guide field nonlinearities, sextupoles or other nonlinear elements which induce betatron amplitude tune shift. The spill rate is usually divided into two kinds: a slow spill - where the length of the spill is of the order of more than one second and a fast spill where the length of the spill is of the order of 200 turns (one turn = 10 μsec). The time scale of the fast spill is small enough that a computer simulation of the complete process (with 1000 turns) is possible without any approximation within reasonable computer time. The computing was performed with the workstation SUN SPARK-1. The code in simulation, developed in Fermilab [2], is a kick code where the particle ensemble is propagated from element to element. The multipole field of the dipoles is presented with kicks of thin elements in the middle of the dipole. The simulation of the extraction process was performed only after the length of the ring, the natural chromaticities, the betatron functions, and the tunes obtained by one particle tracking showed complete agreement with results obtained with the SYNCH computer program. The particles' (400-1000 particles) initial positions, slopes of both coordinates, and momentum offsets, were chosen randomly. When the slow extraction process was simulated the gradients of the main quadrupoles in the lattice were first set to produce the horizontal tune of 22.485 with the vertical tune at a previous value of 22.4. The chromaticity sextupoles changed the chromaticity to values ~+3. The slow extraction quadrupoles and zero-harmonic octupoles were tuned to produce a stable phase space where an ensemble of particles oscillates with well defined stable points, as presented in fig. 1. The slow extraction quadrupoles could follow either a half sinusoidal or a linear ramp pulse above a d.c. value. The extraction of particles occurred when the pulsed part of the slow extraction quadrupoles was turned on. The electrostatic wire array was placed at 17 mm away from the center of the horizontal aperture. When a particle reached this distance it would undergo a horizontal kick of 0.12 mrad. If during this motion in a horizontal space a particle hit the wire (effective thickness of 0.1 mm) it was considered lost. This was used as an efficiency measurement and at the same time this was a way to determine if the step size in process was correctly defined. During a design procedure there is always a compromise between the efficiency which can be reached and the shape of the phase space of the extracted particles. The further position of the septum array from the aperture center is the smaller losses are but the worse magnetic field in the dipoles is. The maximum horizontal offset through the dipoles, in the whole Main Injector ring and before particles reached the septum array in the ring, was 44.9 mm. Because the electrostatic septum was placed close to the extraction Lambertson septum the extracted particles travel through a short part of the ring. The maximum horizontal offset in the magnets reached by the extracted particles was 25.4 mm. At the time of the tracking studies the new Main Injector magnet had not been built yet and the magnetic field quality was not known. The magnetic multipole in the dipole field $B(x)$ at offset $x$ are defined as

$$B(x) = Bo[1 + 1/2b_2x^2 + 1/4b_4x^4 + \ldots],$$

and $Bo$ is the vertical field at the center. The Main Injector will replace the present Main Ring in Fermilab. The multipole content of the two kinds of the Main Ring dipoles (B1 and B2 dipoles) is known and has been measured. In the simulations a set of multiples from the B2 Main Ring dipoles, which should resemble the Main Injector dipoles, were used. Because the Main Ring dipoles saturation occurs at higher current values (magnets were designed for the 400 GeV machine) the values of all multiples were doubled. At Fermilab values of the multipole in the magnetic field are defined as the relation ship between the field produced by the multipole and the main dipole field $Bo$ at the distance of one inch multiplied with 104. The average values of the measured (at the current of 1700 A normal multiples in the Main Ring dipoles are presented in Table 1. The multipole expansion was cut at the eleventh pole. The simulation was performed with the twice higher multiples presented in table 1. During the simulation process multiples in the dipole magnetic field were chosen randomly from dipole to dipole. The limits in the values of multipole were set by the standard deviations obtained in magnetic measurements (in the table 1 "sdev").

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Figure 1. The phase space trajectories during the half integer resonant slow extraction.
The distributions of an ensemble of 400 particles in the phase space at the electrostatic and magnetic septum, during the simulation, are presented in figures 2 and 3, respectively.

![Figure 2](image1.png)  
*Figure 2. Slow extraction simulation during the fast spill. The distribution of 400 particles in the phase space at the electrostatic septum (540 turns).*

![Figure 3](image2.png)  
*Figure 3. Slow extraction simulation during the fast spill. The distribution of 400 particles in the phase space at the Lambertson magnet (540 turns).*

Most of the quadrupoles in the Main Injector will be the reused Main Ring quadrupoles (according to the design report [1]). At the high field the octupole harmonic in the Main Ring quadrupoles had been measured to be 6 Fermilab units with respect to the field of the quadrupoles at 1 inch ($B_q/B_0 = 8.0 \times 10^{-4}$). Another set of simulation runs with the measured value of the octupole multipole within the quadrupole magnets was performed. The influence of the octupole harmonic from the quadrupoles on the particle distribution in the phase space showed that the strength of the zero-harmonic octupole needed to be lowered. The error in quadrupole misalign-