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# FERMILAB MAIN INJECTOR COMMISSIONING STATUS

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## Abstract

The Fermilab Main Injector construction project is nearing completion. The commissioning of the Main Injector began in late 1998. The status of the beam studies and fulfillment of the project commissioning milestones is presented.

## 1 INTRODUCTION

The Main Injector accelerator is a 150 GeV proton synchrotron constructed to replace the original Fermilab Main Ring as the injector into the Tevatron and as a high intensity, fast-cycling accelerator for antiproton production and for supporting a fixed target program using 120 GeV protons. The Main Injector project received first funding in FY92, and its final funding in FY98. Completion of the Main Injector ring civil construction occurred in 1997, and fabrication and installation of the technical components for the ring was completed in 1998. The civil construction for the beamline enclosure connecting the Main Injector to the Tevatron and Antiproton Source began in September 1997, at which time removal of the Main Ring components for refurbishing and reuse in the Main Injector began. Installation of the beamline equipment continued into late 1998.

The 750-m beamline enclosure connecting the Booster to the Main Injector was constructed earlier, and components were installed in 1996. This beamline is comprised primarily of permanent magnets as a prototype for fabrication of ring-quality permanent magnets for the Recycler Ring. Commissioning of the MI-8 beamline was begun in February 1997.

## 2 COMMISSIONING SCHEDULE

The commissioning of the Main Injector (MI) ring began in September 1998. At this time, the MI ring installation was complete (except for resonant extraction devices) but installation activities continued both on the Recycler ring and on the MI-Tevatron beamlines. Therefore, MI commissioning activities were carried out on weekends only, with installation activities during the week.

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In addition to weekend running, there have been three extended periods of MI commissioning (i) November 22-29; (ii) December 19-January 13, and (iii) January 24-February 14.

## 3 COMMISSIONING GOALS

There are seven commissioning goals associated with the Main Injector, which are to be fulfilled to satisfy the project milestones with the Department of Energy. These goals relate to the energy and intensity of the beam to be delivered to another machine or user (the Tevatron, the Antiproton Source, or a fixed target beamline) and to the repetition rate at which this beam is accelerated and extracted. Due to the various accelerator improvement projects underway in the Tevatron and the Antiproton Source, beam could not be delivered to either of them during this commissioning period. Similarly, there are as of now no 120 GeV beamlines constructed and ready for beam. Therefore, the definition of the milestones requires only that beam is accelerated in the Main Injector, not delivered to the ultimate intended designation. The milestones are as follows, along with the status.

1. 150 GeV proton energy for injection into the Tevatron. *This milestone was accomplished on November 28.*
2.  $2 \times 10^{13}$  protons injected per Tevatron cycle. *This milestone was accomplished on January 6. (Since the Tevatron is filled via two successive MI cycles, this corresponds to  $1 \times 10^{13}$  protons per MI cycle.)*
3. 75% proton/antiproton transmission efficiency. *This milestone was accomplished (with protons) on November 28.*
4. 120 GeV proton energy for antiproton production and test beam. *This milestone was accomplished on November 27.*
5. 2.5 second cycle time to 120 GeV. *This milestone was accomplished on November 27.*
6.  $2 \times 10^{12}$  protons to antiproton target per cycle. *This milestone was accomplished on December 31. (As noted above, this milestone was satisfied by accelerating beam of the desired intensity in the Main Injector, but delivering the beam to the MI abort.)*
7.  $2 \times 10^{13}$  protons resonantly extracted per cycle. *This milestone is yet to be accomplished.*

The last milestone, which requires both the highest intensity and the commissioning of the equipment for the resonant extraction, is by far the most challenging. Some progress has been made on both of these issues. The resonant extraction equipment (electrostatic septa and

#### 4 COMMISSIONING HIGHLIGHTS

The commissioning was begun in a step-by-step process requiring the approval of the Beams Division Head (and advisory committees) before proceeding to the next step. The first weekend was devoted to Booster extraction set-up, tuning the 750-m long MI-8 beamline and into the MI-10 straight-section, through the injection Lambertson magnet and to the end of the MI-10 straight. The second weekend was spent on one-half turn beam, taking beam from MI-10 around to the beam abort at MI-40. This included timing in and adjusting the level of the injection kickers at MI-10. Finally, on the third weekend, circulating beam was attempted. Happily, circulating beam was accomplished within the first hour of attempting to circulate. Successive weekends were devoted to turning on the rf, adjusting the orbit, tune and chromaticity, power supply studies to improve regulation, and finally, to accelerate beam.

Concurrent with beam commissioning, shifts were devoted to power supply commissioning, beginning at low rms currents and eventually ramping the magnets to the full design peak and rms currents. A DOE milestone related to the full power testing of the dipole circuit was accomplished on December 21.

As the push for higher intensity began, so did vacuum avalanching. As more intense beams were injected, there was a rise in the pressure by one to two orders of magnitude. This pressure rise was related primarily to the bunch intensity, but also depended more weakly on the total intensity in the ring. The rise was sufficient to cause the vacuum valves to close. This situation has since been changed by using the much-higher pressure Pirani gauges for the vacuum sector permits rather than the ion pump pressures. At the slow repetition rate for most of the commissioning (in interest of keeping the residual activation levels in the ring as low as reasonably achievable), typically one beam cycle every 15-30 seconds, the ion pumps were able to recover most of the pressure rise between beam pulses, although the background level did rise slowly. For reference, the typical pressures without beam are in the low  $10^{-8}$  Torr range. The pressure bump was also confirmed to be due to beam intensity and not beam loss. With subsequent running, the pressure rise was observed to decrease, and it is not believed that this will be a long term problem, even at the nominal cycle time as short as every 1.5 seconds. Figure 2 shows a vacuum burst near the end of the running period.

The need for dampers became apparent also as we pushed the intensity up. Longitudinal dampers were commissioned first, and transverse dampers have been installed and are in the process of being commissioned. Without transverse dampers, the MI has been operating with large chromaticities ( $\sim 30$ ) before transition.

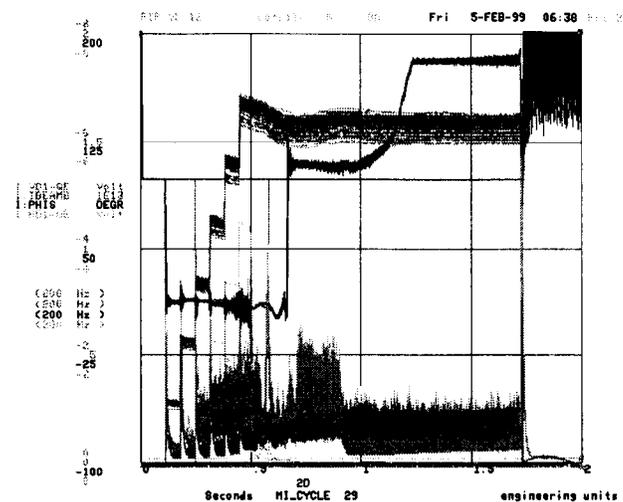


Figure 1. Beam intensity at the best performance of the Main Injector to date. Six Booster cycles are injected and accelerated to 120 GeV.

special quadrupoles for improving the spill quality) were installed in January, and preliminary studies were conducted in February. During this same time period, the intensity was increased to  $1.6 \times 10^{13}$  protons per cycle, as shown in Figure 1. In this figure, the four signals being fast-time plotted are the beam intensity (I:BEAMB), the synchronous phase angle (I:PHIS), and the error signals from the horizontal and vertical narrow band 1-Q dampers. As can be seen in the figure, the overall efficiency in the Main Injector is in the vicinity of 90%. The large step in synchronous phase mark transition, after which there are no losses. The slight rise in the intensity signal after transition is an instrumentation problem, which is not understood.

The commissioning goals, including the last one, are still conservative with respect to the operational goals of the Main Injector. The nominal design goals of the MI include accelerating  $5 \times 10^{12}$  protons per cycle for antiproton production, and  $3 \times 10^{13}$  protons per MI cycle for both Tevatron and MI fixed target programs. To achieve the design goals will require the Fermilab Booster to push its intensity about 25% above its previous record performance. While that goal appears achievable without major upgrades, it will likely require considerable time to fine-tune the Booster. This effort is underway, including realignment activities to optimize the transmission and intensity performance.

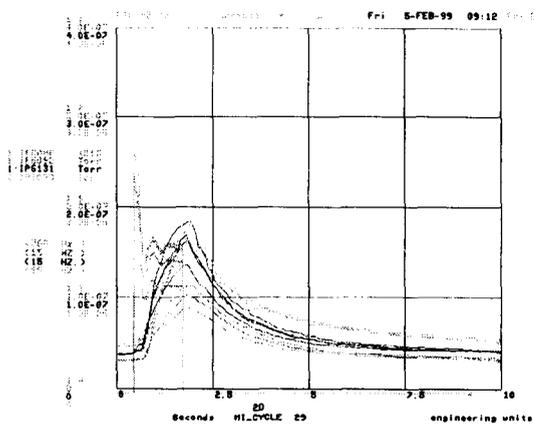


Figure 2. Pressure rise due to high intensity beam.

The optics of the Main Injector ring have been measured and compared with the design lattice. The details of measurement and online-model calculations can be found in Ref 2-3. The measurements are in very good agreement with the design values of the Main Injector lattice functions. Figure 3 shows the measured and calculated dispersion in the Main Injector at 8 GeV. The vertical dispersion is close to zero everywhere, and the horizontal dispersion is near zero in the straight sections.

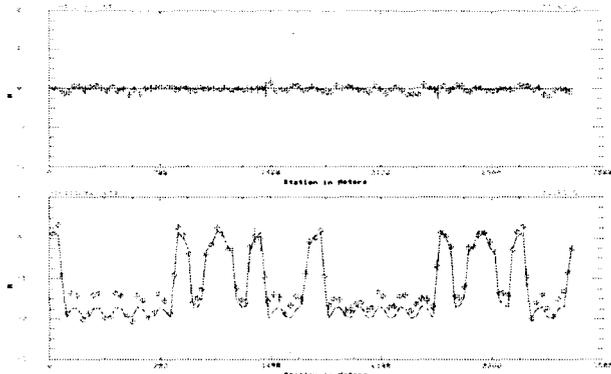


Figure 3. Measured and design values of the Dispersion functions in the Main Injector.

The commissioning of the beamlines between the Main Injector and the Tevatron and Antiproton Source has also begun. The P1 line connects the Main Injector to the F-0 location in the Tevatron. Beam can be injected into the Tevatron by energizing four Lambertson magnets at F-0, or, with the Lambertson magnets turned off, beam continues upwards into the P2 line, which is a modified section of the old Main Ring, connecting to the Antiproton Source line at F-17. The P1 line is designed to handle 1) 8 GeV proton beam from Main Injector to the Antiproton Source for commissioning studies, or antiprotons from the Source to the Main Injector, 2) 120 GeV protons for antiproton production or for the 120 GeV

fixed target program, 3) 150 GeV protons to the Tevatron and 4) 150 GeV antiprotons from the Tevatron, for deceleration in the MI and recooling in the Recycler. Eight GeV protons have been delivered to the Antiprotons Source, but neither the P1 nor P2 lines have been commissioned at higher energies. The optics of both the MI-8 line and the P1 line (at 8 GeV) agree well with the design lattices[2].

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