BEAM BASED MEASUREMENTS OF HYSTERESIS EFFECTS IN FERMILAB MAIN INJECTOR MAGNETS

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Abstract

Operation of the Fermilab Main Injector is sensitive to magnetic field differences due to hysteretic effects. Measurements using the beam are reported with various current ramps. This will provide magnetic field information for accelerator operations with better ramp control than is available from magnet test facility data. This makes possible improved low field reproducibility with mixed 120 GeV and 150 GeV operation of the Main Injector.

OPERATIONAL CONSIDERATIONS

The Fermilab Main Injector is a multipurpose synchrotron designed for injection at 8 GeV and extraction at 8, 120 or 150 GeV. Protons and antiprotons are accelerated to 150 GeV for injection to the Tevatron by accelerating them in opposite directions. Protons are accelerated to 120 GeV and extracted in a single turn for antiproton or neutrino production and resonantly extracted for experiments in the fixed target area. Ramps are initiated by a time line generator capable of synchronizing the Main Injector with the Tevatron and other Fermilab machines. Figure 1 shows a time line with typical ramp profiles for Main Injector dipole current. This figure shows cycles for antiproton production and one cycle for transfer of protons to the Tevatron. The Fermilab physics program requires changes in the mix of these required cycles as often as many times per day. Conditions with no 120 GeV cycles and conditions with no 150 GeV cycles are both experienced.

The acceleration ramps are specified by requesting momentum *vs.* time and using a model of the magnetic field response to specify current *vs.* time[1] based on the measured magnetic fields[2]. The power supply system uses measurements of the current, not the field achieved, for controlling the magnet current ramps. Tune control is achieved in a similar fashion[3]. If the field achieved is sufficiently matched to the specification, the RF feedback will accommodate small momentum errors. If the ramps are sufficiently reproducible, tune changes can be programmed to achieve the desired tune. It was expected that some adjustments of the ramp details would be required to match the current ramps to the required magnet response through use of changes in the hysteresis.

Measurements of the hysteresis properties of the Main Injector magnets were carried out at the Fermilab Magnet Test Facility. However, the power supply system used for these measurements had only unipolar voltage drive so the downramp current changes were limited to those achieved

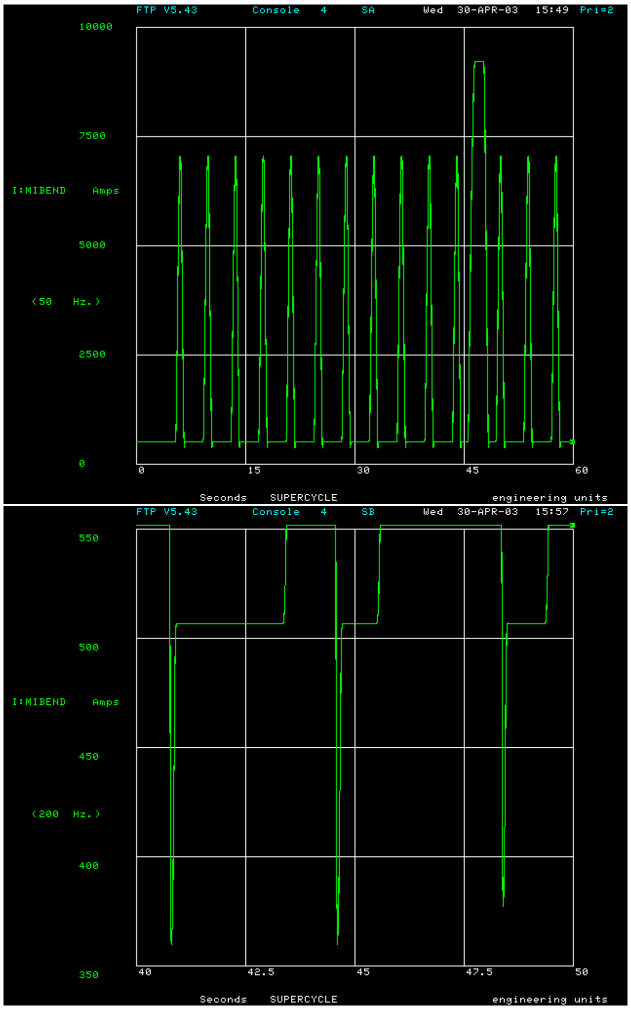

Figure 1: Main Injector Dipole magnet current *vs.* time in seconds in typical operation. Upper figure shows full scale with many 120 GeV ramps and a single 150 GeV ramp. Lower figure expands scale to show reset current following 120 and 150 GeV ramps. The injection porch requires a current just above 500 A.

with the inductive and resistive load attached. Even in laminated magnets, eddy current effects would be expected to modify the fields achieved. Thus, we expected and have found that the hysteresis depends on the downramp ramp rate in addition to the dependence on peak and reset currents. We carried out studies during commissioning to determine suitable ramps to attempt to match the injection fields achieved after 120 and 150 GeV ramps. This study extends those measurements using improved software and a larger variety of ramps.

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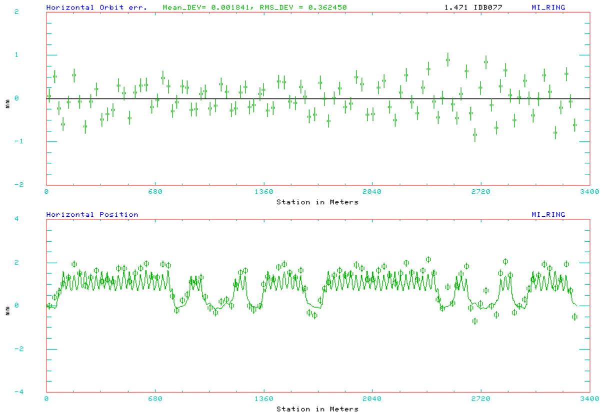

Figure 2: Orbit on standard 120 GeV ramp following a ramp with 130 GeV peak and standard -300 GeV/sec downramp. Reference orbit taken on standard 120 GeV Ramp following another standard 120 GeV ramp. The lower plot shows the measured orbit difference and that calculated for a difference of dp/p = -0.82×10^{-3}. The upper plot shows the difference between measured and calculated orbits.

MEASUREMENTS

Ramp Specification

To specify the ramp properties that we control for hysteresis measurements, we consider the following ramps segments: injection porch, upramp, flattop, downramp, and reset. The reset portion extends the downramp below the injection momentum to allow a portion of the transition from hysteresis curve of downramp type[2]toward the upramp curve. Since the approach to the upramp is exponential, if the reset is sufficiently low, the injection field changes will depend linearly on small reset differences. The desire to ramp quickly limits the reset to values well above zero.

Measurement Technique

Since we currently operate many 120 GeV antiproton production cycles for each 150 GeV cycle, we concentrate on making the 150 GeV cycle reset appropriate to allow the next 120 GeV cycle to experience the same injection field as those on 120 GeV cycles which follow other 120 GeV cycles. Using the I90 Application Program[4], the closed orbit of the injected beam is measured after injection into fixed rf buckets prior to initiation of rf feedback. The beam is injected into fixed frequency rf buckets so the closed orbit is set by the rf frequency and the magnetic field, not by the injected beam momentum. Analysis of the orbit in terms of fractional momentum error is accomplished within the program. To avoid issues of Beams Position Monitor (BPM) offsets, each data set is compared with a reference set obtained on a typical 120 GeV acceleration cycle. Some measurements show orbit differences which are completely dominated by the momentum error term which in turn reflects changes in the mean value of the bend field. Others additionally show some effects of dipole magnet-to-magnet variations and tune differences or other focusing effects. The average BPM error is sensitive to the momentum offset and independent of tune or other errors which are reflected in the RMS BPM error. By adjusting the momentum error input to the program until the average BPM error is zero, one can find the momentum offset which describes a data set.

Data and Analysis

Figure 2 shows results from analysis of a typical orbit difference measurement. The fitted pattern of the beam

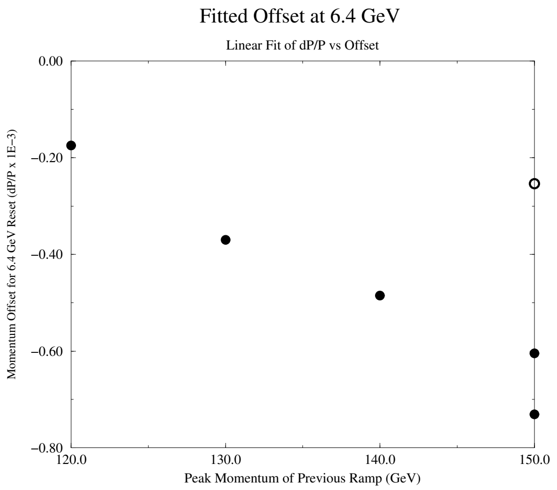

Figure 3: Momentum Offset at 6.4 GeV Reset *vs.* Peak of Previous Ramp for ramps with standard -300 GeV/sec downramp. Open circle for -150 GeV/sec downramp.

Table 1: Fit Momentum Errors for 6.4 GeV Reset from linear fit of offset *vs* reset for sets of ramps with various peak currents. Where downramp rate is not shown it includes segments other than those in the ramps used for standard operation.

Reset	**dp/p**	**downramp rate**
GeV/c	$\times 10^{-3}$	**GeV/c/sec**
150	-0.605	-300 GeV/s
130	-0.142	
100	-0.886	
50	-0.416	
27	-0.057	
150	-0.731	-300 GeV/s
140	-0.485	-300 GeV/s
130	-0.370	-300 GeV/s
120	-0.175	-300 GeV/s
100	-2.927	-300 GeV/s
150	-0.253	-150 GeV/s

position differences is characteristic of the Main Injector lattice with regions of regular cells interspersed with regions designed to provide zero dispersion. We interpret the fractional dp/p error described by the program as due to a hysteretic change in the bend field at the standard injection current.

For a set of peak currents, measurements were taken using a range of reset currents. The fractional momentum error *vs.* requested reset momentum was fit to a straight line and the fit momentum offset for a 6.4 GeV reset (that used prior to the 120 GeV cycle reference orbit) was obtained. In Figure 3 we show these offsets for measurements with peak currents 120 - 150 GeV where the downramp matched the standard operational downramp with -300 GeV/sec maximum slope. Also shown is the fit result for a 150 GeV peak ramp with -150 GeV/sec downramp.

To display the linear dependence of the fractional bend field error (as measured by the orbit dp/p) on reset momentum, we subtract the fitted offset at 6.4 GeV reset from the data set and plot it *vs.* requested reset momentum. We show the full range of our measurements in the lower plot of Figure 4 while the upper plot expands the scale. We see that ramp-to-ramp variations up to $\pm$0.2E-03 are typical. The fitted dp/p at 6.4 GeV for this data are shown in Table 1. Included are several sets of data with different downramps and data with peak current below the 120 GeV comparison ramp.

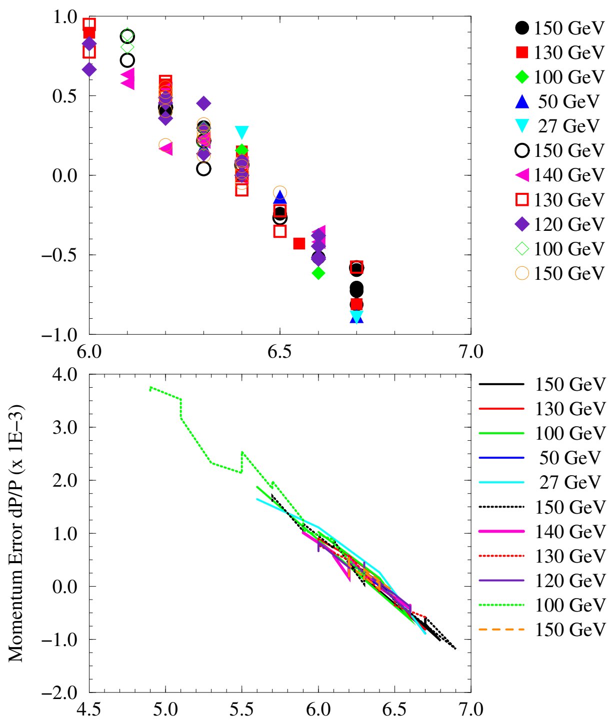

Figure 4: Fractional momentum error of following 120 GeV ramp *vs.* reset for various peak momenta. Final 150 GeV set used slow downramp. Offset at 6.4 GeV reset subtracted.

CONCLUSIONS

We have shown that Main Injector dipole fields at the standard injection current vary in the expected (approximately linear) fashion as a function of a reset current on the previous ramp cycle. For conditions similar to the standard 150 GeV operation mixed into the 120 GeV antiproton production cycles, we find a regular pattern in which the the offset of dp/p for a 6.4 GeV/c reset changes by about 4×10^{-4} between 120 Gev and 150 GeV ramps. The 150 GeV ramps experience a more negative momentum offset than 120 GeV ramps. Interpreted as a change in the field this corresponds to 0.4 Gauss out of the 1000 Gauss injection field. The remanent field of Main Injector dipoles is about 22 Gauss so peak field changes modify the remanent by about 1.8%. We interpret this to indicate that the higher peak field sets a remanent field which is lower. This then requires a higher reset momentum (less of a transition required).

The consistency among measurements provides evidence that this control of the reset allows one to modify the hysteretic portion of the injection field. Nevertheless, the values obtained in this study are different than have been found optimal for operational ramps which we interpret to imply that additional details of the ramps (dI/dt, flattop time…) may also affect the hysteretic remanent field. At present, control of the reset value at the end of each ramp provides adequate control of the injection field in mixed 120 and 150 GeV operation.

It had been observed that timelines with only 150 GeV ramps required changes of $\approx$ 6 Mev/c in the injection field compared with those with only 120 GeV ramps. Resets for both ramps had been set to 6.7 GeV/c. In October 2002 the reset for the 120 GeV ramps was set to 6.4 GeV/c and injection was tuned up for that value. Examination of the results in Figure 4 would suggest this would create a change of about 8×10^{-4} (7 MeV/c). We note that these injection currents no longer have to be changed when making this timeline change.

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