# TUNE CONTROL IN THE FERMILAB MAIN INJECTOR

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## *Abstract*

We describe methods used to measure and control tunes in the Fermilab Main Injector (FMI). Emphasis is given to software implementation of the operator interface, to the front-end embedded computer system, and handling of hysteresis of main dipole and quadrupole magnets. Techniques are developed to permit control of tune of the Main Injector through several acceleration cycles: from 8.9 GeV/c to 120 GeV/c, from 8.9 GeV/c to 150 GeV/c, and from 150 GeV/c to 8.9 GeV/c. Systems which automate the complex interactions between tune measurement and the variety of ramping options are described. Some results of tune measurements and their comparison with the design model are presented.

## 1 INTRODUCTION

Many modes of operation are required of the Fermilab Main Injector[1] to permit the several tasks which it performs within the projected Fermilab physics program. Acceleration from 8.9 GeV/c to 150 GeV/c of both protons and antiprotons is required for injection into the superconducting Fermilab Tevatron. Acceleration of protons from 8.9 GeV/c to 120 GeV/c is required for production of antiprotons and for fixed target physics programs. The Fermilab Recycler ring will allow antiprotons which remain at the end of a proton-antiproton colliding beam run to be retained but this requires the Main Injector to decelerate beam from 150 GeV/c to 8.9 GeV/c. Software for current control in the main bending and focusing magnets must permit flexible and often changing mixtures of these ramping cycles.

The iron properties modify the linear relation between current and magnet strength expected for the electromagnet dipoles and quadrupoles. Hysteresis differences at low fields and saturation at high fields are both important. Control of the bending and focusing magnets is based on their current so the resulting fields must be calculated from a model based on magnetic measurements. The field which results for a given magnet current will depend upon the previous history. It depends strongly on the most recent sign reversal in dI/dt and weakly on prior sign reversals. The cycle time for the 120 GeV/c cycles is an important parameter so adjustment of the minimum (reset) current, which will affect the resulting magnetic fields, is an important software design feature.

Design requirements to provide these features have been discussed in a previous paper[2]. This report updates that work and describes the software implementation, some measured results and the status during the first months of Main Injector commissioning.

## 2 REQUIREMENTS AND HARDWARE

Following our previous work[2] we note that the momentum, $p$, is controlled by the magnetic field achieved in accordance with

$$p = \frac{e}{2\pi}\int_C B_y \, ds = e(B\rho) \qquad (1)$$

where $e$ is the elementary charge, and $B_y$ is the vertical component of the magnetic field. This expression defines $B\rho$ where $\rho$ is a characteristic bending radius. We have $p = (e/\theta_D)B_1 L_{eff}$ for an MI 6-m dipole which bends by $\theta_D = 2\pi/(301\ 1/3)$. We can express the function which relates the tunes, $\underline{\nu}$, (horizontal and vertical) and the quadrupole strengths, $\underline{k_1}$, using a linear expansion about the operating point. Choosing to solve for the normalized quadrupole strengths we have $\underline{k_1} = \underline{Q}^{-1}\,\underline{\nu} + \underline{k_1}_0$. Letting $\underline{K} = \underline{Q}^{-1}$, we express this more fully as

$$\begin{pmatrix} k_{1f} \\ k_{1d} \end{pmatrix} = \begin{pmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{pmatrix} \begin{pmatrix} \nu_x \\ \nu_y \end{pmatrix} + \begin{pmatrix} k0_{1f} \\ k0_{1d} \end{pmatrix}. \qquad (2)$$

Using MAD[3], a lattice model calculation was performed on the design lattice MI19 at a variety of tunes. The results were fit to this form yielding

$$\begin{pmatrix} k_{1f} \\ k_{1d} \end{pmatrix} = \begin{pmatrix} 0.001022 & 0.000185 \\ -0.000196 & -0.001008 \end{pmatrix} \begin{pmatrix} \nu_x \\ \nu_y \end{pmatrix} + \begin{pmatrix} 0.008973 \\ -0.00901 \end{pmatrix}. \qquad (3)$$

Note that since this quadrupole strength is normalized to $B\rho$, it already employs a relation between the dipole and quadrupole strengths. To improve tune control the quadrupole current is regulated with respect to the dipole current as described below. An analytic model for describing the magnetic field strength achieved for a specified magnetic current and current history is described in a companion paper[4].

The main dipoles and quadrupoles for the Main Injector are powered using a folded bus for the dipoles and two quadrupole buses with currents flowing in opposite directions. The power supply system[5] consists of 12 new dipole supplies and 6 quadrupole supplies moved from the Fermilab Main Ring.

Let us consider an operational cycle for the Main Injector. Beam will be injected into the machine with the magnets at a constant current chosen to provide the required momentum and tune properties. The magnet currents will

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then be ramped to match a specified momentum-time profile and a momentum-tune profile to the required peak current. The currents will then be ramped to a reset current below the injection current, to set the hysteretic fields and then the current will be returned to the injection level. A reset well below the injection field is required to minimize field variations due to variations in the reset current. The required precision increases exponentially as the reset current approaches the injection current. The desire to maximize the repetition rate of the machine encourages a high reset as does the natural limitations in regulating SCR supplies at a small fraction of their peak current.

The proposed physics program to be supported by the Main Injector will require the ability to flexibly mix a variety of ramp modes. Since a given ramp (say a 150 GeV Tevatron proton injection cycle) may follow any other ramp (say a 120 GeV $\bar{p}$ production cycle), each must leave the magnets in a similar magnetic state such that history dependent differences are not important. Clearly all injection currents must be the same. The tool we have identified for restoring the magnetic state at the end of each different cycle (ready for 8 GeV injection) is a specific reset current appropriate to each specific cycle. No assurance exists that this will be sufficient. Main Injector commissioning has included a brief study of the field achieved for injection following 120 GeV or 150 GeV ramps. The observed differences in injection dipole field ($4 \times 10^{-4}$) could be matched using changes in the reset current (from 358 A to 376.5 A). Based on the success of these studies and examination of special hysteresis studies of the measured magnetic field strength, we expect no serious problems in mixing different energy ramps.

## 3 SOFTWARE IMPLEMENTATION

Control of currents in the bending and focusing magnet circuits is performed by a control console program, I2, interacting with a real time controller, MECAR (Main injector Excitation Controller And Regulator)[6]. An operator uses I2 to define profiles of basic accelerator parameters such as momentum, tune and chromaticity as functions of time in a cycle. Different ramping modes are associated with specific clock reset events which are used to identify each ramp cycle. I2 converts the momentum and tune profiles to current profiles and sends them to MECAR.

From the momentum profile, I2 creates a profile of bending magnet (dipole) current *vs.* time using dipole properties of the lattice along with an analytic model of the history-dependent relation between the magnet current and the integrated field strength. The parameters for the model are extracted from fits[4] to magnet measurements. The profile of dipole current *vs.* time is calculated on a set of points whose time density is related to the current-time slope. This set of points is passed to MECAR.

The conversion from the tune profiles to quadrupole magnet current profiles is separated into two parts. The main contribution is calculated using a *calibration* table, $C(I_b)$, which contains a relation between tunes and the momentum and the current in the dipole and each quadrupole bus which can be determined directly from measurements. This relation is assumed the same for all ramp cycle types. It is prepared in I2 and made available to MECAR. The specified tune *vs.* momentum profile (*tune* table) is compared to the result of a linear interpolation in momentum and tune using the *calibration* table and the difference is found. The tune differences are converted to magnet strength differences using a sensitivity matrix $\underline{Q}^{-1}$ (see above) derived by fitting lattice calculations. The resulting quadrupole strength differences are converted to current changes, $\delta(t)$, using a model for quadrupole strength *vs.* current[4]. This calculation is also carried out on a sparse set of times chosen to match the requirements of the tune *vs.* momentum curve. Current difference curves for the horizontal and vertical focusing buses are passed to MECAR.

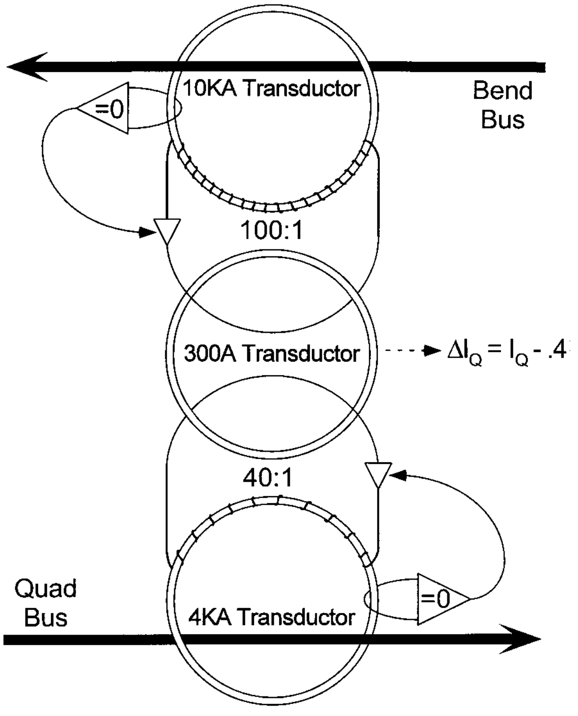

Figure 1: Schematic representation of a triple transductor for measuring the current in a quadrupole bus with respect to 40% of the dipole bus current.

MECAR reads the bend current *vs.* time points. A FIR filter is used to construct a gentle function, of bounded frequency, from the linear interpolation of these points to use as the dipole program function, $I_b'(t)$. MECAR regulates the dipole current, $I_b(t)$ measured using the dipole transductor[7], to match the program function.

Measurement of the quadrupole current uses a triple transductor differencing system as shown in Figure 1 which measures the quadrupole current $I_q(t)$ with respect to 40% of the bend current, $\Delta I_q(t) = I_q(t) - .4I_b(t)$. The desired program signal $\Delta I'_q(t)$ is created using inputs from the I2 program. The current difference curves $\delta(t)$ are read and a FIR filter applied to a linear interpolation in time of these points. Employing the differential quad current program, $\Delta I'_q(t) = C(I_b(t)) - .4I_b(t) + \delta(t)$, MECAR regulates the current yielding: $I_q(t) = C(I_b(t)) + \delta(t)$.

## 4 TUNE MEASUREMENT

Several tune measurement systems have been created and installed for the Main Injector, including previously described ones from the Fermilab Main Ring[8]. Commissioning of these systems is underway but not all yet provide convenient results in the Main Control Room so most of the measurements used employ the Turn-by-turn system (Console Application I42) which uses position measurements from the standard Main Injector beam position monitors. Transverse beam motion is excited with a pinger magnet whose time is varied to permit measurements at the required time. For most times, adjustments of the chromaticity are needed for coherent oscillations to be visible during a sufficient number of turns to allow a precise tune measurement.

## 5 RESULTS

Initial values for the calibration table were created from the preliminary hysteresis models and design lattice properties. Efforts will continue to provide a seamless way to integrate upramp and downramp tune control. For now, we believe that we can provide a calibration table for downramp operation which we will use when deceleration is required. Separate understanding was obtained by using the magnet measurements and lattice properties directly and predicting the ratios of bus currents which control tune properties. These quantities provide guidance for understanding power supply control requirements but also give sensitive tuning parameters for machine commissioning.

In Figure 2, data directly from magnet measurements and from machine tune calibration are shown. Measurements of dipole IDA114-0 and quadrupole IQB310-1 were analyzed using design properties of the lattice and linear interpolation of measured strength to predict the required currents and current ratios (points labeled Magnet Measurements). To provide the calibration table, the tunes were measured and the requested tune modified until values near the design values of (26.425, 25.415) were achieved. Currents were measured in this condition. Ratios labeled MI Measurement are from this data. The general shape is in reasonable agreement but the actual values for the vertical quadrupole ratio will require further examination.

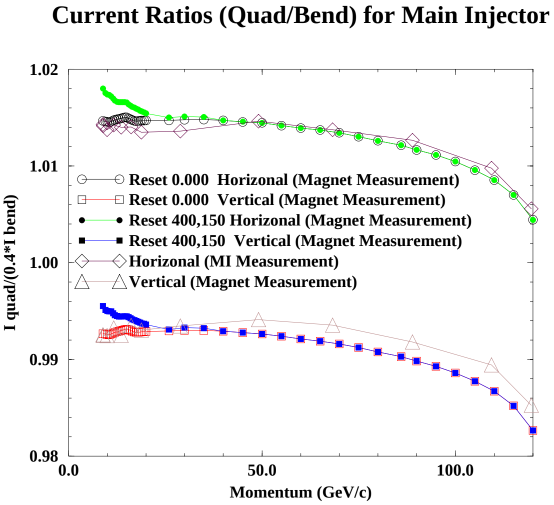

Figure 2: Ratios of quadrupole to dipole bus currents are shown as a function of momentum for the design tunes of $(\nu_H = 26.425, \nu_V = 25.415)$

## 6 SUMMARY

We have implemented a tune control scheme in the FMI using a real calibration table. Results of tune measurements have proved that the magnet model built upon the magnet measurement data works reasonably well. These efforts to describe the magnet performance continue in preparation for more complicated operation modes of the FMI.

## 7 REFERENCES

[1] The Fermilab Main Injector Technical Design Handbook. Fermilab, August 1994. Revised February 1997.

[2] B.C. Brown *et al.* Design for Fermilab Main Injector Magnet Ramps Which Account for Hysteresis. In *Proceedings of the 1997 Particle Accelerator Conference, Vancouver, B.C., Canada, 12-16 May 1997*, page 3245. IEEE, 1998.

[3] H. Grote and C. Iselin. The MAD Program Users Reference Guide. SL 90-13(AP), CERN, 1990.

[4] B. C. Brown. Hysteresis Study Techniques and Results for Accelerator Magnets with Unipolar Current Excitation. This Conference (PAC99).

[5] Steven Hays. A 5 Maga Watt Ramping Power Supply for the Fermilab Main Injector Dipole Bus. In *Conference Record of the 1993 IEEE Nuclear Science Symposium and Medical Imaging Conference*, page 390. IEEE, 1994.

[6] R. Flora *et al.* MECAR (Main Ring Excitation Controller and Regulator): A Real Time Learning Regulator For The Fermilab Main Ring Or The Main Injector Synchrotron. In *Proceedings of the 1995 Particle Accelerator Conference and Internation Copnference on High-Energy Accelerators*, page 2172. IEEE, Piscataway, N.J. 08855-1331, 1996.

[7] S. Hays, D. Wolff, and H. Pfeffer. Power Supply Regulation Systems Installed in the Femilab Accelerators. In *Conference Record of the 1991 IEEE Nuclear Science Symposium and Medical Imaging Conference*, page 957. IEEE, 1992.

[8] D. Still, I. Kourbanis, and D. Capista. Tune Measurement Methods in the Fermilab Main Ring. In *Proceedings of the 1997 Particle Accelerator Conference*, page 2061. IEEE, Piscataway, N.J. 08855-1331, 1998.