FERMILAB-Conf-99/096

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April 1999

Proceedings of the *1999 Particle Accelerator Conference*,
New York, New York, March 29-April 2, 1999

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Hysteresis Study Techniques and Results for Accelerator Magnets with Unipolar Current Excitation

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Abstract

Using an automated magnet measurement system employing a variety of current excitation ramps, extensive studies of the hysteretic behavior of magnet strength have been carried out. An analytic description which is accurate at better than 0.1% has been achieved. Prescriptions for setting field strength using these formulas will be adequate for multi-energy operation of the Fermilab Main Injector, for deceleration in the Main Injector and Accumulator and for multi-energy operation of various beamline magnets. An overview of this work is provided. Important regularities of the magnet behavior are identified.

1 INTRODUCTION

Accelerator and Beam Line systems at Fermilab have a variety of operating modes which require knowledge of the hysteretic behavior of magnet systems. Measurement strategies have been developed[1] to achieve the needed knowledge of the behavior of a variety of magnet systems. To prescribe the current *vs.* time profile which matches a required field strength *vs.* time requires further development. Interpolation schemes are made complex by the strong dependence of the field on current history in addition to the dependence on magnet current. A strategy of restricting operation to use only excitation histories which match measured histories would permit a simple interpolation but is considered unnecessarily restrictive. A scheme which attempts to properly interpolate in both preparation history and magnet current is assumed to be of sufficient complexity as to compromise algorithmic reliability. We choose to develop an analytic description of sufficient complexity and precision. Using this description, software which controls the magnet power supplies can calculate the field strength produced at all times along any prescribed magnet current history. The goal of this work was to achieve a relative strength error of a few parts in 10,000 at all strengths for a variety of ramping options which match all known requirements. The measurements were designed with the hope of characterizing any simplifying regularities over a range beyond any expected operational requirements.

2 RAMP PROFILES FOR MEASUREMENTS

Based on experience in characterizing various magnet systems, we have assumed that, for the magnets under study which have copper coils, iron-dominated field shapes and yokes comprised of thin laminations (1.5 mm typical thickness), the field is essentially static when the current is constant. Measurements are performed at constant current using a rotating full length cylindrical coil. Coil rotation times are characteristically about 1 second and the rotation begins many milliseconds after the completion of current changes. Eddy current and flux flow effects are largely complete following each current change before measurements begin.

We use the term *ramp* to characterize a portion of a larger ramp cycle[2] in which the sign of dI/dt is constant. The reset current for a ramp occurs at the beginning of the ramp where the sign of dI/dt has just changed. For this analysis we describe a preset current which is the reset current of the immediately preceding ramp. We believe that reversals of the sign of dI/dt prior to the preset current have small effects.

The current control has proven to be very precise, permitting repeated measurements at the same current setting to achieve the same value to $\approx 3 \times 10^{-5}$. However the current measurement involves additional electronics and has shown, for some of the studies, changes of more than 1 A. Some of the analysis will employ a recalibration of the requested current rather than using the measured current.

3 TYPICAL HYSTERESIS STUDY DATA

In Figure 1 we show the non-linear portion of the measured strength of a Main Injector dipole as measured on a pattern of current histories. We note a pattern which we describe by an upramp or downramp state. These states are approached approximately exponentially following a reversal of dI/dt. We identify these as upramp or downramp *hysteresis* curves. They may depend at most weakly on the reset and preset current. We identify the strength curve which connects from the down ramp *hysteresis* curve at reset and approaches the upramp curve as the *interjacent* curve.

Figures 2 and 3 explore limits to the algorithms we are developing. We see that the field remaining after a ramp depends weakly on the peak current to which it was driven (downramp reset current). After a reset, the magnetic state approaches the upramp or the downramp state closely but small differences remain.

This small effect becomes even smaller after the field is reversed again. We explored this with a different study in which the upramp response was examined after preset currents of 9500 A and 7100 A. The measurement was repeated six times for each preset current. The results in Figure 4 confirm that there is an effect. Ramping from 0 A to 500 A has greatly decreased the magnitude of this preset current dependence. We conclude that the difference in strength between 7100 A (120 GeV) preset currents and

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[†] Work supported by the U.S. Department of Energy under contract No. DE-AC02-76CHO3000.

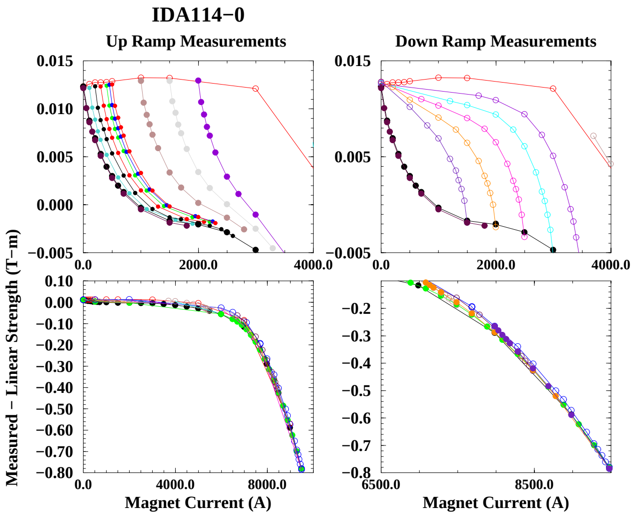

Figure 1: Measured non-linear strength for IDA114-0 with a variety of histories. The linear response is characterized by fitting the strength for currents below 2000 A (about 0.8 T) after excitation to about 9500 A. Each plot shows data at many currents on an upramp to 9500 A then on a down ramp to 0 A. Upramp data is shown using filled circles while downramp data uses open circles. On the upper right is also data on down ramps following a variety of peak currents. On the upper left data on up ramps following a variety of reset currents is shown. The lower left plot shows the complete data set. The lower right plot expands the data near the peak of the saturation.

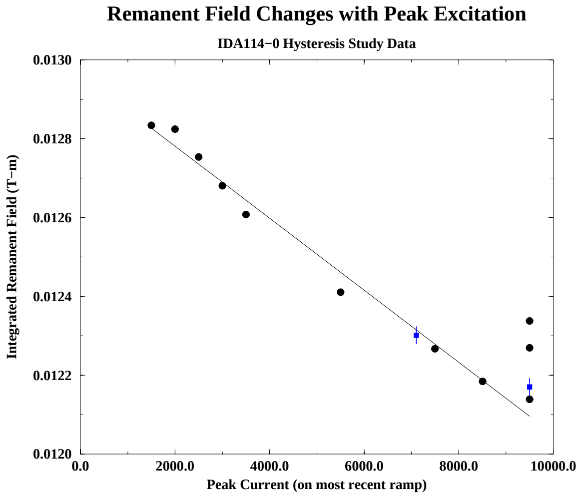

Figure 2: Remanent changes for IDA114-0.

9500 A (150 GeV) is $4.4 \pm 2.4 \times 10^{-5}$ T-m. Measurements at nearby currents determine the change in strength for a change in the preset current. At 500 A, we observe a change of 1.75×10^{-5} T-m/A. This predicts that a change of less than 3 A in the reset current would compensate differences between 120 GeV and 150 GeV ramp preset currents. Since the nature of these effects is not known, we are not surprised that measurements of related effects using the beam momentum to sense the field showed that nearly 20 A was needed in a preliminary measurement[3].

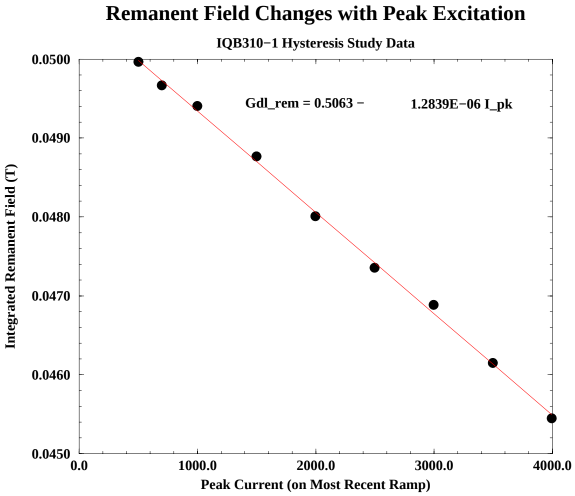

Figure 3: Remanent changes for IQB310-1.

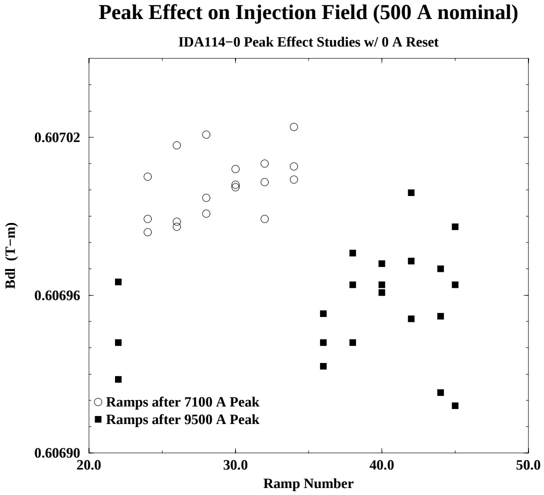

Figure 4: Studies of changes in Main Injector dipole injection field after 120 GeV and 150 GeV ramps.

4 ANALYTIC DESCRIPTION

To describe the data shown in Figure 1 above, we consider the magnet strength M ($\int B_1 dl, \int B_2 dl$ or $\int B_3 dl$) to be comprised of four terms, L (linear), R (remanent), H (hysteretic) and J (interjacent) . We continue to explore suitable expressions for these contributions but find that the goals stated above are met with the following functional relations:

$$M(I, I_r, I_p, D) = \\ L(I) + R(I_p, D) + H(I, D) + J(I, I_r, I_p, D)$$

where I is the magnet current during the measurement, I_r is the reset current, I_p is the preset current, and D is the ramp direction with +1 for upramps and -1 for downramps. We express the relations with normalized variables to provide consistency of representation among magnets. Use I_{scale} as a maximum current of interest (rounded) and I_S as a characteristic current for saturation.

$$x = \frac{I - I_S}{I_{scale}} \quad x_0 = \frac{-I_S}{I_{scale}} \quad L(I) = Slope * I$$

$$R(I_p, D) = RemStr_D + RemSlp_D * (I_p - I_{scale})$$

$$\begin{aligned} H(I, D) = & \\ & C_1 * I/I_{scale} \\ & - \sqrt[4]{h_4}x - \sqrt[4]{h_4x^4 + h_3x^3 + h_2x^2 + h_1x + h_0} \\ & + \sqrt[4]{h_4}x_0 + \sqrt[4]{h_4x_0^4 + h_3x_0^3 + h_2x_0^2 + h_1x_0 + h_0}. \end{aligned}$$

Note that H is defined to have the value 0 at I = 0. Each parameter is distinct for the upramp or downramp curve and could be expressed as h_{iD} or C_{1D} . Two forms have been used for fitting J:

$$J(I, I_r, I_p, D) = A(I_r, I_p, D)(se^{-\frac{I-I_r}{I_{C1,D}}} + (1-s)e^{-\frac{I-I_r}{I_{C2,D}}})$$

$$J(I, I_r, I_p, D) = A(I_r, I_p, D)e^{-(\frac{I-I_r}{I_{C,D}})^N}$$

where N is a real number, typically less than 1. The amplitude function A is the difference in hysteresis curves at the reset current.

$$\begin{aligned} A(I_r, I_p, D) = & \\ & H(I_r, -D) - H(I_r, D) + R(I_p, -D) - R(I_p, D). \end{aligned}$$

A software system to extract data from the Sybase measurement database and fit the results using MINUIT[4] has been developed with Perl and FORTRAN. If all parameters are released for fitting, the system is usually not stable so a manual interaction is interposed to permit separate fitting of various subsets of the parameters.

Data from IDA114-0 and IQB310-1 have been fitted successfully. Residuals reveal a pattern (not random) suggesting that the structure of the data is yet to be fully accounted for with these fitting functions. However, the pattern remaining confirms that the parameters which control the shape of the interjacent curves are the same over a wide range of magnet excitation levels. The relative magnitude of the residuals is less than 3×10^{-4} at all currents for both of these data sets when compared to the full magnet strength at the same current. This is sufficient for existing accelerator control needs. Figure 5 shows portions of the fits at low fields to the non-linear portion of the strength along with the resisuals for all the data. We plan to characterize the full set of measurements for Main Injector dipoles and quadrupoles by fitting the available production measurements to determine the linear, hysteretic, and remanent terms, constraining the remanent slope and the interjactent terms from the special study data. Parameters used for the commissioning of the Main Injector[3] were determined from these two magnet measurements but with cruder fits to a simpler function, achieving residuals of about 0.1%.

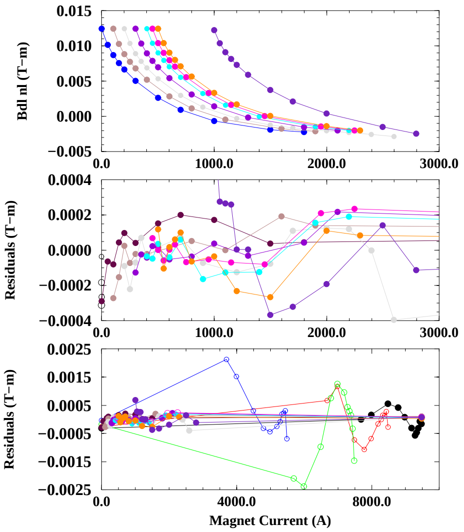

Figure 5: Selected data from the IDA114-0 hysteresis study were fit with the interjacent curve described by 2 exponentials. Top plot shows fits to the selected upramp data. Center and lower plots show residuals (measured - fitted) on scales which emphasize the low field and high field results.

5 SUMMARY

Measurement plans and analysis tools have been developed for studying the hysteretic magnetic strength of accelerator and beamline dipole, quadrupole and sextupole magnets which experience excitation currents of only one polarity. Guidance for changing currents during tuning or for multi-energy operation of beamline is obtained directly from plots of the non-linear strengths. For a more detailed understanding, we have developed a model, expressed in analytic fitting functions which describes the strength of electromagnets in terms of distinct hysteretic states for upramp and downramp operation, with transitions between these states which are described by interjactent curves. We suspect that an adequate description might become more complex for symmetric or asymmetric bipolar operation. However, sextupoles which have been measured with modest excitations with reversed current still show similar behavior.

6 REFERENCES

[1] B. C. Brown *et al.* Results on Fermilab Main Injector Dipole Measurements. *IEEE Trans. on Magnetics*, 32:2186, 1996.

[2] Bruce Brown, Dave Harding, and James W. Sim. Design of the **currents** Virtual Database. Technical Report MTF-92-0011 1.3, Fermilab, July 1992.

[3] G. WU *et al.* Tune Control in the Fermilab Main Injector. This Conference (PAC99).

[4] F. James. Minuit function minimization and error analysis. CERN Program Library Long Writeup D506, CERN, Geneva, Switzerland.