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Magnetic Field Measurements of Fermilab Main Injector Dipoles

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Abstract— **Measurements of the Fermilab Main Injector dipoles using a partially redundant system of integrated and point measurements were carried out for quality assurance. Additional special measurements studied the hysteretic field strength. Results from these measurements will be presented.**

I. Introduction

The Fermilab Main Injector[1] (FMI) was dedicated in June 1999 following a period of commissioning which began in September 1998. It is currently supporting a program of Fixed Target experiments with the Fermilab Tevatron, a high intensity target test, and transfers to storage rings. Support for Tevatron collider operation will follow. In previous years, the main dipole magnets were designed, prototyped, produced, measured, and installed. These efforts were supported by magnet measurements with existing[2] and newly commissioned[3][4][5] systems at the Fermilab Magnet Test Facility (MTF)[1]. A summary of these efforts with complete references was recently presented[6] which covers most magnet production and accelerator operation issues. We will concentrate on issues of magnet properties and measurement system characterization which have not been previously reported.

II. Measurement System

The measurements performed at MTF are grouped according to the data acquisition requirements into rotating coil HARMONICS, FLATCOIL[7], and POINTSCAN.

A. HARMONICS

For HARMONICS, a full length (6.7 m) probe of 19.39 mm diameter was constructed. It measures variations in the radial field strength using a dipole Morgan coil and a tangential coil . The dipole strength was recorded using the Morgan coil while the higher harmonic components were recorded with the two coils summed in opposition to buck out the dipole sensitivity while achieving good sensitivity to higher moments. The coil was rotated for two turns with data recorded at fixed magnet excitation. Measurements for dipole strength were followed immediately with harmonics measurements before the current was changed. Flux data was recorded at 256 points/revolution with two revolutions plus overlap points requiring <2 seconds. The flux changes were recorded with a V/f based digital integrator[2] which stored data for one measurement. Harmonic flux components were obtained from this data using a Fast Fourier Transform (FFT) and the results converted to field properties using the probe geometry. Measurements were carried out before beam pipe installation, permitting the probe mounting hardware to reference features of the pole tip. The probe was mounted with its rotation axis along the horizontal and vertical center of the magnet aperture, following the curvature of the magnet (sagitta of 16 mm). The probe was sufficiently flexible to be rotated smoothly despite being curved. This system measured normal and skew harmonic components in a region at the center of the aperture.

B. FLATCOIL

The FLATCOIL system has been described previously[7]. A full length (7.315 m), 6.35 mm wide, 16 turn curved coil, with geometry designed to reduce sensitivity to field derivatives, was mounted so it was at the center of the aperture for strength measurements. It was scanned horizontally over a $\pm$ 45.7 mm range to record changes in B_y on the midplane. Magnet strength changes with current were recorded by integrating the flux changes as a function of the current. The flux was recorded by the PDI integrator on command from the data acquisition program with the magnet at constant current. The current was then ramped to a new value and the flux again measured. The absolute measurements of strength changes (relative to the strength at remanent field) were supplemented with measurements using a coil installed in a separate magnet which was powered in series with the magnet under measurement. The reference coil voltage was subtracted from the voltage from the test coil for relative measurements that provide a reliable measure of relative magnet strength which is nearly independent of current measurement precision. The field shape (B_y *vs* x) was recorded at fixed excitation by recording flux changes as a function of position and converting to field changes using the probe geometry. This measurement is sensitive to normal harmonic components along the x axis but does not measure skew fields.

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[1]MTF is operated currently as part of the Development and Test Group of the Fermilab Technical Division

[2]PDI model 5035 from Metrolab

C. POINTSCAN

The POINTSCAN measurement system records fields at specified points using a combination of an NMR for measurements in the uniform portions (body field) and a Hall Probe for end field measurements. Field values and probe position are recorded on command from the POINTSCAN program. For production measurements of FMI dipoles, a motion control system was created which moved the probe with a toothed belt along the curved centerline of the dipole, recording the position changes with a separate belt attached to an encoder. The NMR probe was mounted in the center of the transverse aperture with the Hall probe mounted slightly higher. Data was recorded at intervals of ~6 mm (0.25″) in the end field regions and 25.4 mm (1.0″) in the body field regions.

D. Current Control and Readout

For these measurements, the magnet is powered by a parallel-connected dual 150 kW power supply system configured to supply up to 10,000 A. For all production measurements, the hysteretic state of the magnet is set by three ramps from 0 A to 9500 A and back to 0 A. The programs request a specified current ramp through a ramp generator and the power supply achieves that current using feedback from a Holec 10 kA transductor. The same signal is provided to a DVM for recording the current, but through isolation amplifiers. Current control is very precise. For example, repeated magnetic field measurements at 500 A demonstrate current control stability with RMS deviations of not more than 20 mA. Unidentified problems have reduced the precision of the current readout such that the RMS current measurement precision is greater than 150 mA.

III. Measured Magnet Properties

A. POINTSCAN Results

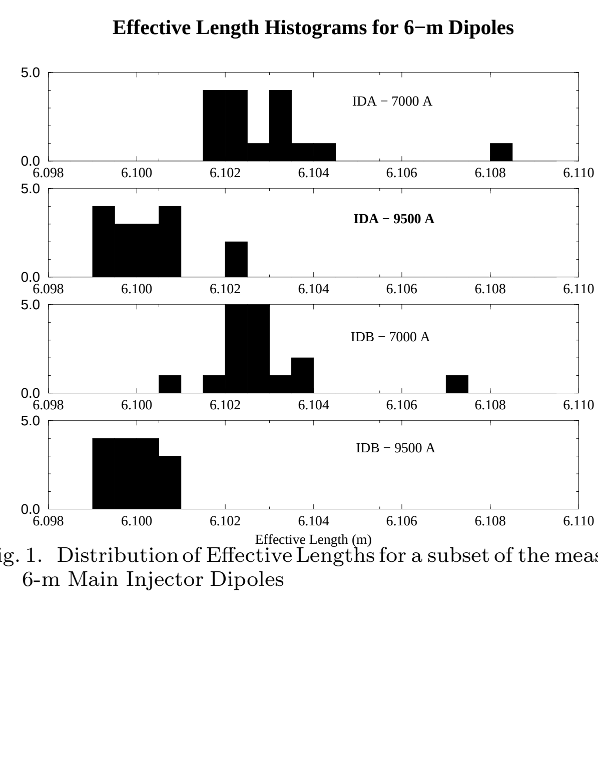

Fig. 1. Distribution of Effective Lengths for a subset of the measured 6-m Main Injector Dipoles

	7000 A		9500 A	
Series	$< L_eff >$	σ	$< L_eff >$	σ
	m	mm	m	mm
IDA	6.103	1.485	6.1003	0.9141
IDB	6.1029	1.3152	6.1	0.50295
IDC	4.0716	1.6792	4.07	2.0079
IDD	4.0715	0.7025	4.0691	0.52068

TABLE I

The effective length data from the POINTSCAN measurement of various design series of Main Injector Dipoles. RMS length deviations (σ) are dominated by a few measurements with large deviations. Results for IDD may actually be more characteristic of the production.

The POINTSCAN measurements were carried out at 7000 and 9500 A for every 4th FMI dipole. It provided a check of the gap uniformity by examination of the longitudinal profile. The effective magnetic length was obtained for each measurement by dividing the measured integrated strength by an average body field. In Figure 1 we show the measured distribution of effective lengths for 6-m dipoles. Statistical properties of these measurements are shown in Table I. We note that the laminations are 1.5 mm thick.

Main Injector dipoles are on a single current bus so it is important that the field integrals track. By design the 6-m (IDA and IDB) series are 1.5 times the length of the 4-m (IDC and IDD) series. To achieve this, the end saturation must be controlled. Averaging the two series we have an effective length at 7000 A (9500 A) of 6.10295 m (6.10015 m) for 6-m magnets and 4.07155 m (4.06955 m) for 4-m magnets. The ratio of effective lengths is 1.4989 at both excitation levels indicating that the 4-m magnets are about 7×10^{-4} or 2.4 mm too long.

B. Dipole Strength Hysteresis

The variety of acceleration and deceleration cycles required for Main Injector operation makes the hysteretic effects important despite the high injection field (~ 0.1 T). Since we mix various operational modes, we seek a detailed understanding of these effects. Analytic fits of special hysteresis studies have been presented recently[8]. A typical hysteresis study is shown in Figure 2 where we have subtracted the strength which is linear in current (corresponding to an electromagnet with infinitely permeable iron).

C. Field Shape Changes with Energy

The transverse field shape in the gap for a magnet with infinitely permeable iron is determined entirely by the pole shape since the pole is an equipotential. Remanent fields, saturation near the pole tip and saturation in the back leg (or elsewhere along flux lines) will change the potential at the pole and modify the field shape. For most magnets,

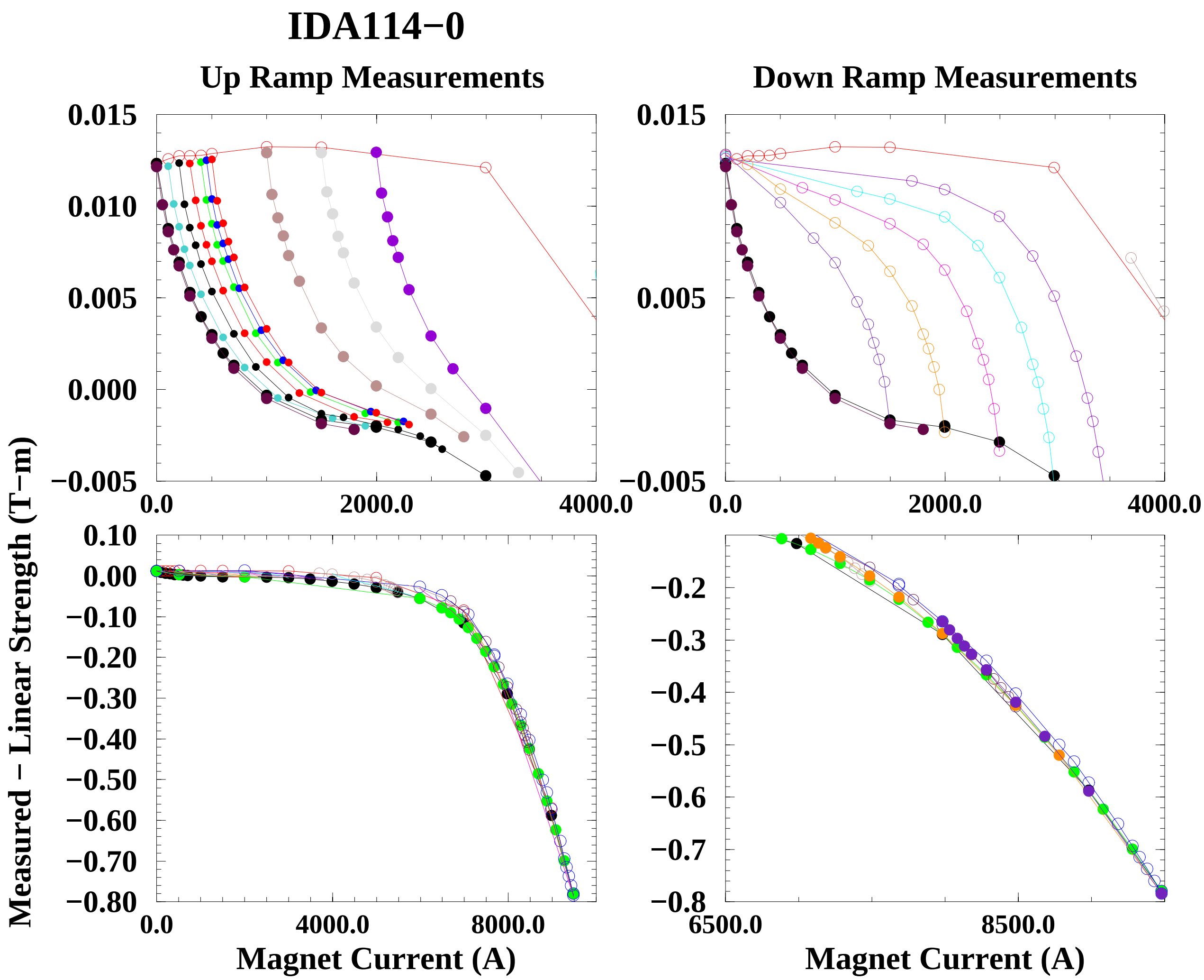

Fig. 2. Measured non-linear strength for IDA114-0 with a variety of histories. The linear response is characterized by fitting the strength for currents below 2000 A (about 0.4 T) after excitation to about 9500 A. Each plot shows data at many currents on an upramp to 9500 A then on a down ramp to 0 A. 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.

the pole is nearly an equipotential at mid-field excitation and the field shape is governed by geometry. The FLATCOIL shape measurements of a Main Injector dipole are displayed as $[B_y(x) - B_y(0)]/B_y(0)$ at several excitation levels in Figure 3. At injection fields (500 A or 0.1 T), the field shape is nearly the same as at mid-field, indicating that the remanent field effects do not modify the field shape for this design. As shown in Figure 4, correcting the high field shape for sextupole and decapole components, one has again a shape dominated by geometry. These saturation components are mostly produced by potential differences across the pole created by different saturation of the various flux lines through the back leg of the yoke.

IV. Summary

With a modern measurement system, it is possible to make extensive, precise measurements of magnets in a production environment. The Main Injector Dipoles meet the operational requirements for the Fermilab Main Injector. Measurements results are accessible via database queries. In addition reports of some significant strength and shape information is available on the World Wide Web (http://www-ap.fnal.gov/MagnetData) for use in accelerator modeling.

V. Acknowledgments

We would like to thank the measurement and support staff of MTF for building and operating the measure-

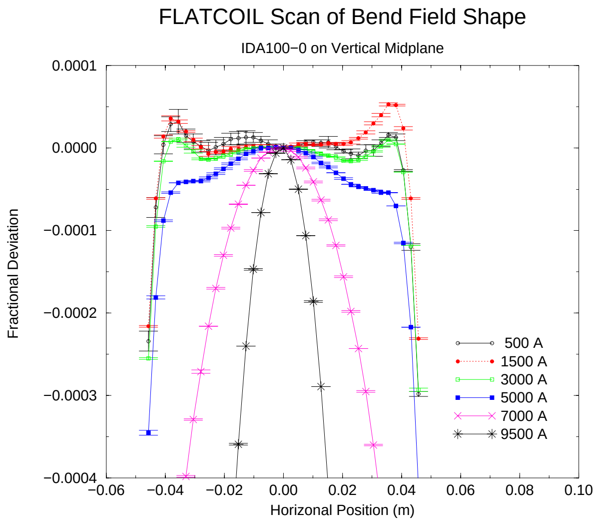

Fig. 3. Field shape deviations (normalized) at several currents.

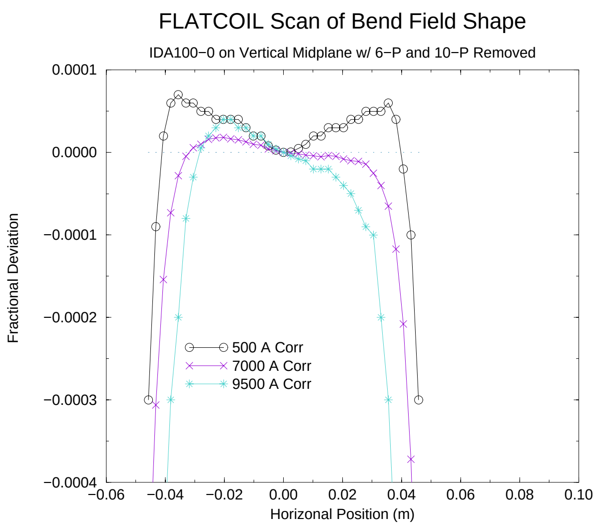

Fig. 4. Field shape deviations (normalized) at several currents after subtraction of sextupole and decapole field.

ment system used for the Main Injector Project. We also thank the staff of the Main Injector Project and especially project leader, Steve Holmes. They provided essential resources but also expressed ongoing interest. Project reviewers, including especially Klaus Halbach, provided useful insights.

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