



Fermi National Accelerator Laboratory

FERMILAB-Conf-95/143

Flatcoil Systems for Measurements of Fermilab Magnets

H.D. Glass, B.C. Brown, J. DiMarco, D.J. Harding, P.O. Mazur, C.S. Mishra,
A. Mokhtarani, D.F. Orris, C.M. Reid, J.W. Sim, J.C. Tompkins, D.G.C. Walbridge

*Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510*

June 1995

Presented at the *Fourteenth International Conference on Magnet Technology*, Tampere, Finland, June 11-16, 1995.

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Flatcoil Systems for Measurements of Fermilab Magnets

H.D. Glass, B.C. Brown, J. DiMarco, D.J. Harding, P.O. Mazur, C.S. Mishra, A. Mokhtarani,
D.F. Orris, C.M. Reid, J.W. Sim, J.C. Tompkins, D.G.C. Walbridge
Fermi National Accelerator Laboratory, Batavia, Illinois, USA

Abstract—A flux measurement system has been developed for measuring the integrated strength and relative shape of the magnetic field of Fermilab Main Injector dipoles. Improved field shape measurements have been obtained by constructing coil geometries which reduce the flux contribution from unwanted field derivatives. A bucking coil scheme employing reference coils in both the test magnet and a reference magnet reduce the sensitivity to power supply fluctuations. Design strategies for various measurement requirements are described, along with the details of implementing an assembly to measure curved 6 m and 4 m dipoles. Some representative results and comparison with redundant measurement systems are presented.

I. INTRODUCTION

The Fermilab Magnet Test Facility (MTF) is performing measurements of conventional magnets for the Main Injector, a new accelerator which is designed to accelerate protons and antiprotons to 150 GeV [1]. A new dipole has been designed for the Main Injector, and it comes in two lengths, approximately 4 m and 6 m. The magnet is designed to be powered to 9500 A and have a maximum central field of 1.75 T. The magnet body is curved, with the 6-m magnet having a sagitta of 1.6 cm [2].

MTF is responsible for measuring every production dipole. We have adopted a strategy of measuring magnetic properties with redundant measurement systems. For the dipoles, we are employing three systems: a combined Hall/NMR probe which is used for longitudinally scanning the field profile, a rotating coil harmonics probe, and a nonrotating coil which we call a *flatcoil*. This paper describes the design and experience we have had with the various types of flatcoils built for the Main Injector dipole measurements.

The flatcoil system is required to measure the total integrated field strength $\int B dl$, and the relative variation of this strength as a function of transverse position. The shape is measured along a horizontal line

traversing the midplane of the magnet aperture. The strength precision goals, relative to a standard magnet, are $dB/B = 2.0 \times 10^{-4}$ at low field (< 0.4 T), and better than 1.0×10^{-4} for $B > 1.0$ T. For the field shape, we desire a precision of $dB(x)/B_0 < 0.5 \times 10^{-4}$ at low field, and 0.2×10^{-4} at high field.

II. SYSTEM DESIGN

A flatcoil style probe consists of N turns of wire wound around a rigid bar of width w and length L . In principle, the bar should be nonconducting to avoid eddy currents, but we have obtained good results using an aluminum bar. For our system, we use $N = 16$, $w = 6.35$ mm, and $L = 7.315$ m.

A. Probe Mechanical Assembly

A cross-section of the mechanical assembly is shown in Fig. 1. An aluminum baseplate rests on the lamination surfaces of the lower pole face. In the center of the magnet there is a G-10 block which is subsequently used to position and maintain the curvature of the stainless steel beam tube. Prior to installation of the beam tube, the flatcoil uses the G-10 block as a centering guide: a brass locating pin extending from the flatcoil baseplate is inserted into a hole in the G-10 block. On both ends of the magnet, the flatcoil is manually positioned horizontally using an alignment fixture (gunsight) on the flatcoil probe. The locating pin also serves to center the probe longitudinally.

The lower reference coil is screwed down to the baseplate. Above the baseplate is an aluminum plate that rides on rollers placed along the length of the baseplate. Attached to one end of the moving plate is a linear actuator driven by a stepping motor. The extension of the cylinder is monitored by an encoder mounted on the stepping motor housing. Two limit switches, mounted on either end of the assembly, constrain the motion of the movable plate.

Sitting atop the moving plate is the main coil. The moving plate has a set of 9 diagonal slots equidistant along its length, and the main coil has a set of rollers which fit into these slots. A guide bar prevents the main coil from moving in z , but allows it to move freely in x . Thus, as

Manuscript received June 12, 1995.

Work supported by the U.S. Department of Energy under contract No. DE-AC02-76CH03000.

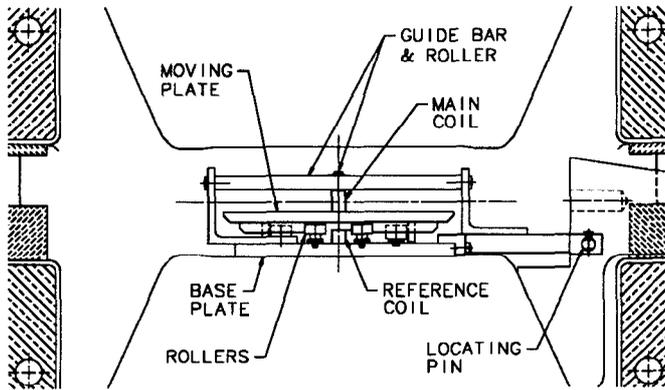


Fig. 1. Cross section of the flatcoil assembly as it is installed in the MI dipole.

the cylinder pushes (or pulls) the movable plate in z , the main coil is driven sideways to positive (or negative) x .

1) *Sextupole suppression scheme*: It is desired to have the total flux through the coil area proportional to the integrated field along the center of the coil. This can be nearly achieved by spacing the individual turns so that the sensitivity of the coil to low-order harmonics is suppressed. For our geometry, suppression of sensitivity to the gradient (quadrupole term) and even-order harmonics is achieved by symmetry. However, it takes some care to suppress the sextupole component. In a $2n$ turn coil, this can be achieved by introducing a vertical gap between turns n and $n + 1$. One cannot simultaneously suppress both the sextupole and decapole components with our simple geometry, but for fields we are considering, the decapole and higher-order harmonics are of lesser importance.

The suppression is achieved by minimizing the coil geometry factor [3], [4]

$$\eta_j = \frac{1}{j} \sum_{k=1}^n \{ (t + iy_k)^j - (-t + iy_k)^j \}, \quad (1)$$

where $t = w/2$ is half the coil width, $y_k = y_0 + kh$ is the height above the midplane of the k -th turn. By making suitable choices for n and w , one is left with the midplane half-gap y_0 as the free parameter.

For a 16-turn coil using 10-mil wire (254 μm diameter), the best sextupole suppression (minimizing (1) for $j = 3$) occurs for a midplane gap of 1.78 mm between the 8th and 9th turns. All other turns are adjacent to each other, as seen in Fig. 2.

2) *Reference magnet*: To aid in monitoring the long term stability of the measurement system, we had a 1.0 meter reference dipole built. It is installed to run in series with the magnet on the test stand. Two reference

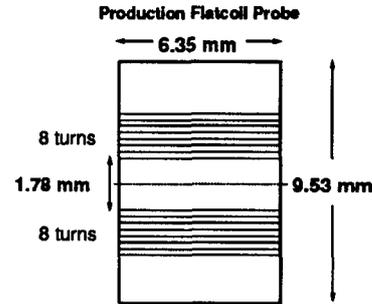


Fig. 2. Winding diagram for main coil. The gap in the midplane serves to suppress sextupole contributions to the total flux.

coils, wound on a single bar, monitor the body field of this reference magnet.

B. Coils

Four coils are used in the dipole flatcoil system:

dmeas: The 16-turn moving coil, capable of scanning over the horizontal range $|x| < 4.57$ cm. The coil is wound in accordance with the sextupole suppression scheme outlined above.

drref: This has the same dimensions and number of turns as the *dmeas* coil, but it is stationary.

drref1: This coil and *drref2* are located in the reference magnet. They are wound on a 2.54 cm wide G-10 bar of length 69.85 cm. The length is chosen so that the entire coil sits within the body field region of the reference magnet. There are 24 turns on this coil. The product NLw for this coil is chosen so that the flux it measures is approximately equal to the flux measured by the *dmeas* coil in a 4-m dipole.

drref2: This coil has 12 turns. When summed with *drref1*, the combined flux approximates the flux seen by the *dmeas* coil in a 6-m dipole.

III. DATA ACQUISITION AND SIGNAL PROCESSING

Each coil in the flatcoil system is connected to a separate channel in a coil configuration module (built by Fermilab) which selects, under computer control, the combination of coils to read out. It also performs analog bucking or summing of the signals. The resulting signal is then fed into a Metrolab Precision Digital Integrator (PDI Model 5035), which digitizes the time-integrated signal.¹ The PDI provides a calibrated flux in units of volt-seconds.

A. Operational Modes

We designed our flatcoil probe to be used in two operational modes called excitation and scan:

¹Metrolab Instruments SA, 110 Chemin du Pont-du-Centenaire, CH-1228 Geneva, Switzerland.

excitation: In this mode, the coil remains stationary while the magnet current is ramped. This measures the flux as a function of current, excluding any remnant flux. Two submodes are employed: 1) *meas* mode, which uses the main coil alone to measure the absolute flux in the test magnet; and 2) *buck* mode, in which the flux through a stationary coil in the reference magnet is subtracted from the main coil flux to provide a relative flux measurement. This is done by connecting the two coils in series but with opposite polarities.

scan: The main coil is moved horizontally across the magnet aperture, and its signal is bucked against the flux through a stationary reference coil located between the baseplate and moving plate. This is done while the magnet is at constant current.

In the excitation mode, we initially read out the flux at zero magnet current, and then step the magnet current up through a predetermined list of currents. We stop at each current, allowing about 20–25 seconds for the current to stabilize, and then read out the PDI. Once the flux at the maximum current is measured, we step back down and make our final measurement at zero current. The initial and final zero current measurements are used for correcting the PDI signal for drift due to the offset voltage.

For the scanning mode, the coil is moved to the $-x$ limit and then stepped every 2.54 mm until the $+x$ limit is reached. The direction of motion is then reversed. Two complete passes in each direction are made, and the results averaged together to cancel the systematic effects caused by the mechanics of probe motion. The flux measured for each pass at $x = 0$ is used to make the drift correction. In both the excitation and scanning modes, the coil geometry parameters are used to convert flux to integrated field strength (in Tesla-meters), and the results recorded in our measurement database.

The probe motion is controlled via computer program [5] that reads a checklist of commands to set magnet current and select measurement coil configurations. The raw and reduced data are recorded in a database organized in a hierarchy of measurement sequences, runs, and individual points [6].

Fig. 3 show typical scans at various currents. If we denote the integrated strength through the entire magnet length by $J(x) = \int B(x)dl$, then the figure shows the relative shape defined by $s(x) = \{J(x) - J(0)\}/J(0)$. The normalization, $J(0)$, is taken from an excitation run at a current nominally equal to the scan current.

B. Calibration

The most important source of systematic uncertainty in determining the absolute strength using the flatcoil is our knowledge of the coil width. By direct measurement, we can determine the width to at best a precision of $1 \times$

IDA010-0, Flatcoil scans

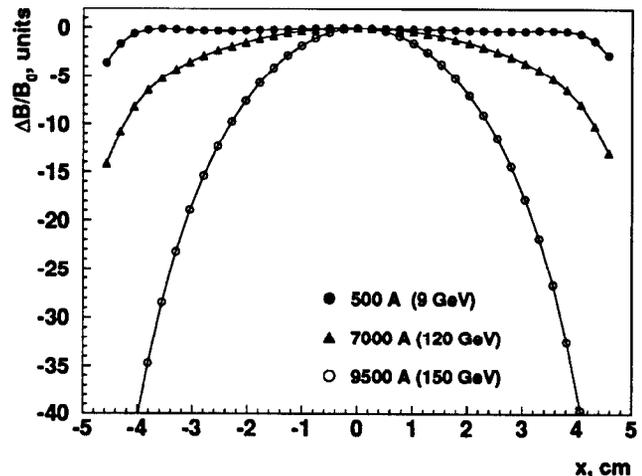


Fig. 3. Flatcoil scans for a typical magnet at a range of currents corresponding to injection (500 A) through extraction (9500 A).

10^{-3} . This can be improved by comparing the strengths measured by the rotating coil harmonics probe and the flatcoil over the range of excitation currents; we also cross-calibrate with a Hall/NMR longitudinal scan at a more limited set of currents. We have done this for a sample of dipoles and have obtained a consistent value of coil width, allowing us to get absolute strength measurements to a precision of 1–2 parts in 10^4 .

IV. EXPERIENCE WITH MI PRODUCTION DIPOLES

We have now used the flatcoil system to measure more than 60 production dipoles [7]. A typical scan at 500 A is shown in Fig. 4. Superimposed is a reconstructed scan based on the rotating coil measurement. Because of the curved magnet geometry, and the fact that the end laminations of the magnet are parallel to each other (and not perpendicular to the beam axis), the flatcoil does not measure the quadrupole introduced by the end geometry. The rotating coil, for which the axis of rotation is everywhere coincident with the beam axis, does properly account for the end quadrupole term. When this term is subtracted from the harmonics data, as seen in Fig. 4, the harmonics and flatcoil shapes agree to better than 0.15×10^{-4} (or 0.15 units). The error bars on the flatcoil data are derived from the variation in signal on each of the four passes. The maximum error is typically 0.2 units at this current; the error improves as the current is increased. In any event, the precision goal is more than adequately achieved.

The strengths measured by flatcoil and harmonics probes are compared in Fig. 5. The agreement is only 6.6 units rms at 500 A, but improves to 2 units at 9500 A. We have been observing a standard deviation of ~ 10 units in magnet to magnet variation, caused mainly by differences

IDA010-0, Flatcoil vs Harmonics, 500 A

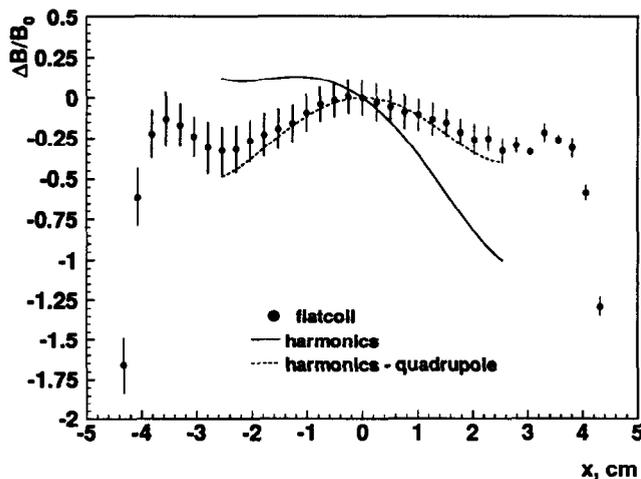


Fig. 4. Comparison of flatcoil transverse scan at 500 A with field shape reconstructed from rotating coil data, including (solid curve) and excluding (dashed) the quadrupole term.

in steel properties [7].

We periodically (every few weeks) monitor the stability of the measurement system by remeasuring a dipole with the flatcoil and other systems. In general, we have observed a repeatability in the strength using the bucked excitation mode of 1.0 units or better over the range of operating currents.

V. AUXILIARY SYSTEMS

The following probes share the same electronics and software controls, but are operated independently from the production flatcoil system:

A. Endfield Flatcoil

To study the behavior of the dipole endfield, we built a 2.03 m coil on a 6.35 cm wide Al body. This probe is attached to a positioning assembly that sits external to the magnet, and can move the probe in both x and z . In practice, we have used this probe to measure the integrated strength from far outside the magnet to a specific depth within the magnet. By collecting the strength as a function of penetration depth, we can cleanly separate body field from end effects, and also determine the effective magnetic length due to the end. This technique was used in designing the MI dipole endpack [8].

B. Stretched Wire

For studies of magnets having straight apertures, we have used a stretched wire technique consisting of a wire loop having a width of typically 2.54 cm. The stretched wire method has been used for measurements of Main Ring and beamline dipoles.

flatcoil - harmonics comparison

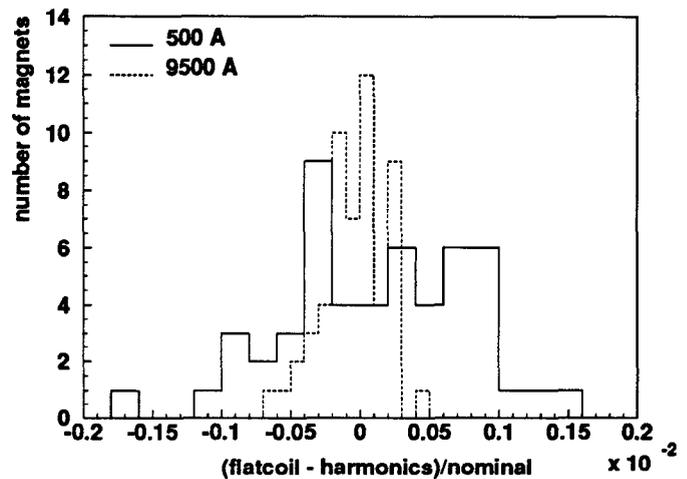


Fig. 5. Difference histogram showing strength as measured by flatcoil and harmonics probes at 500 and 9500 A.

ACKNOWLEDGMENT

We thank the MTF measurement technicians, D. Hartness, G. Kirschbaum, D. Massengill, M. Thompson, and F. Wilson and mechanical technicians A. Bianchi and D. Validis for helping to commission the production flatcoil system, and for making numerous valuable suggestions regarding robustness and reliability.

REFERENCES

- [1] Fermilab Main Injector Title I Design Report, Vol. 1, Fermi National Accelerator Laboratory, Aug. 1992.
- [2] D. J. Harding et al., "Design considerations and prototype performance of the Fermilab Main Injector dipole," in *Proceedings of the 1991 IEEE Particle Accelerator Conference*, pp. 2477-79, San Francisco, May 6-9, 1991.
- [3] B. C. Brown, "Using magnetic flux to determine magnetic fields," unpublished.
- [4] H. D. Glass, "Measurement of harmonic amplitudes and phases using rotating coils," Fermilab Magnet Test Facility, MTF-94-004, 1994.
- [5] J. W. Sim et al., "Software for a database-controlled measurement system at the Fermilab Magnet Test Facility," *Proceedings of the 1995 Particle Accelerator Conference* (in press), May 8-12, 1995, Dallas, TX.
- [6] J. W. Sim et al., "A relational database for magnets and measurement systems at the Fermilab Magnet Test Facility," *Proceedings of the 1995 Particle Accelerator Conference* (in press), May 8-12, 1995, Dallas, TX.
- [7] D. J. Harding et al., "Magnetic field measurements of the initial Fermilab Main Injector production dipoles," *Proceedings of the 1995 Particle Accelerator Conference* (in press), May 8-12, 1995, Dallas, TX.
- [8] D. J. Harding, et al., "Design and measurements of prototype Fermilab Main Injector dipole endpacks," in *Proceedings of the 1993 Particle Accelerator Conference*, May 17-20, 1993, Washington, DC.