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MEASUREMENTS OF BEAM PIPE EDDY CURRENT EFFECTS IN MAIN INJECTOR DIPOLE MAGNETS

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Abstract

The dipole magnets for the proposed Main Injector project at Fermilab are designed to ramp to maximum field (1.7 T) at rates over 2.5 T/s. These ramp rates will produce eddy current effects which degrade overall field quality. A harmonics probe was constructed for the purpose of measuring eddy current field components during the ramp cycle. Three separate ramp rates were employed ranging from 1.3 T/s to 2.7 T/s. Tests were performed using beam pipes with two different resistivities. The dominant multipole contribution resulting from eddy current effects in each beam pipe was sextupole. The sextupole component closely matched the calculated prediction.

1 Introduction

The Main Injector Project will replace the Fermilab Main Ring[1]. This accelerator will be composed of recycled magnets taken from the Main Ring and a series of new magnets. The dipoles will be of a new design. Specifications and preliminary measurement results for prototype dipoles have been presented elsewhere[2][3]. A theoretical study was performed to investigate the significance of eddy currents induced in the beam pipe walls and their effect on the field quality of the magnet[4]. The dipole, sextupole, decapole, and 14-pole effects were calculated as a function of beam pipe width. The effect of dipole and sextupole contributions were found to be significant. A measurement system was assembled for the task of verifying the eddy current field effects.

2 AC Harmonics Measurement System

The time-dependent flux through a set of stationary coils was monitored while the magnet was ramped. One AC harmonics measurement step consisted of: 1) position the probe, 2) simultaneously ramp the magnet, sample the current, and sample the probe signal, 3) record the sampled data and the probe angle, and 4) check the probe angle. Steps 1 through 4 were repeated until the probe completed one rotation. Once all data for a measurement had been obtained it was possible to extract the harmonic coefficients. Data was acquired in this way for all ramp rates, beam pipes, and probe coil selections.

Figure 1 outlines the primary hardware components used in these measurements. Several devices are worth noting. A hybrid probe consisting of sextupole and decapole Morgan coils[5] and tangential, belly band[6], normal and skew dipole coils was constructed. The outer diameter was 4.43 cm. Each coil was 44.9 cm long. The Morgan coils were wound with seven turns each. The tangential and belly band geometries were designed to provide equal but opposite dipole sensitivities. This probe was sufficiently short so as to be insensitive to the curvature of the magnet while still maintaining a high degree of signal sensitivity.

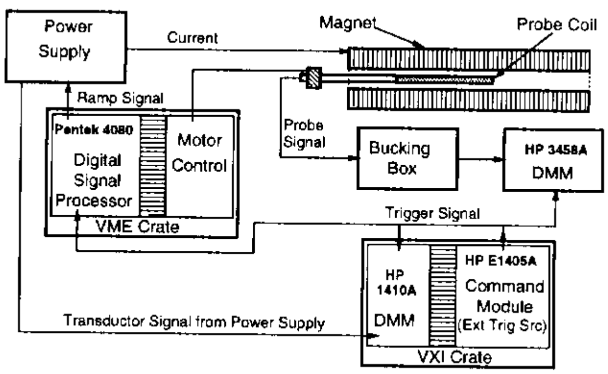

Figure 1: AC Harmonics hardware components.

The probe signal and the magnet current were measured simultaneously with two digital multimeters (DMM's). A Hewlett Packard[1] 3458A read raw probe voltage. An HP 1410A VXI DMM recorded the power supply transductor signal. Both DMM's were set to 1KHz sampling rates. The probe signal was sampled at $6\frac{1}{2}$ digits of precision with sensitivity set at either $1 \cdot 10^{-6}$ or $1 \cdot 10^{-7}$ volts. A Pentek[2] 4080 Digital Signal

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[1] Hewlett Packard Co., 1501 Page Mill Road, Palo Alto, CA, 94304, USA.

[2] Pentek, 10 Volvo Drive, Rockleigh, NJ, 07647, USA.

Processor generated the ramp functions. Data acquisition and ramp generation were started simultaneously with an electronic trigger pulse.

3 Measurement Conditions

Two 150 KW power supplies operating in series provided magnet excitation. Measurements were made with linear ramps of 7500, 10000, and 15000 A/s (1.34, 1.79, and 2.68 T/s) over the range 0.0 to 3000 A (0.0 to 0.54 T) for all ramps. Ramp stability was verified after each measurement.

Each beam pipe had dimensions 11.6 cm wide by 5 cm high by 122 cm long with a corner radius of 1.2 cm. The wall thickness was 0.15 cm for each pipe. Beam pipes constructed of two materials, type 316 Stainless Steel ($\rho = 0.73\ \mu\Omega$m[7]) and type 330 Stainless Steel ($\rho = 1.02\ \mu\Omega$m[8]), were used. Each beam pipe was tested in the lead end of the magnet. The pipe was positioned with its outer edge flush to the magnet coil, leaving 109 cm of the pipe inside the laminations.

All measurements were performed on the second prototype Main Injector dipole (IDM002). The probe was inserted in the pipe or between the pole faces with no pipe. The coils were placed 30 cm from the lead end, putting the probe within the body field of the magnet. A bucking box was used to select the coil(s) of interest for each measurement. The tangential and belly band coils were used in anti-series to suppress the dipole signal and allow observation of the sextupole and decapole. The dipole signal was recorded with the belly band coil. Data was taken at 64 uniformly spaced angles.

4 Data Analysis

The power supplies produced a current signal with observable ripple. Fast sampling of the transductor signal revealed nearly 4 A of 720Hz noise superimposed upon the requested current. This noise was magnified in the probe signal and was amplified further when the probe was in a beam pipe (see Panel A of Figure 2). Data from the sextupole Morgan Coil are shown in Figure 2. Panel *A* shows the probe voltage data, proportional to $d\Phi/dt$. Flux as a function of time was obtained by numerical integration (trapezoidal method). An example is shown in Panel *B*. Harmonics information was extracted from the integrated probe signals. The integrals were decomposed into time slices, transposing the data from time to angular position (see Panel *C*). Time slicing was done from 0.01 seconds to 0.5 seconds at each millisecond interval for each measurement. The data in Panel *C* exhibits the characteristic signature of a sextupole field

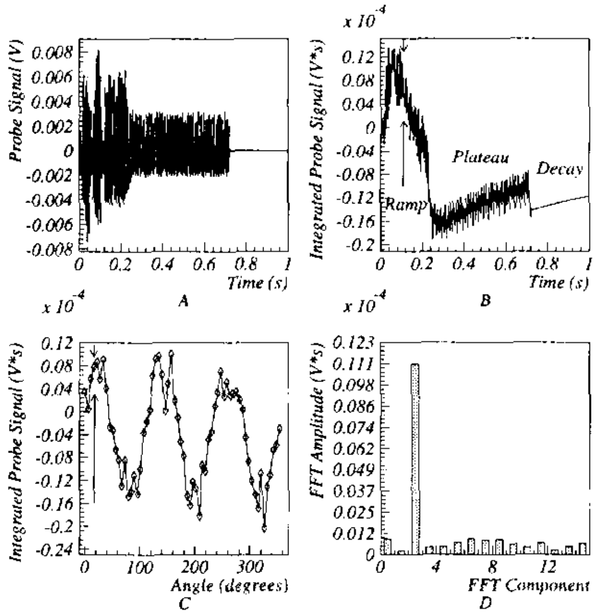

Figure 2: A: Probe signal for the type 316 Stainless Steel beam pipe, angle = 16.875 degrees, sextupole Morgan Coil; B: Integrated signal; C: Integrated signal at 0.11 seconds for all angular positions; D: FFT amplitudes for the data shown in Panel C). The arrows in B and C point to the same data value. Ramp rate = 15000 A/s.

and was typical of all measurements taken with the sextupole Morgan coil. Panel *D* gives the FFT amplitude results for the data in Panel C. The sextupole component dominates. FFT results for all measurements were transposed back to the time axis and compared with current. Figure 3 shows a plot of flux amplitudes (Φ_2) vs current for sextupole Morgan coil data at a ramp rate of 15000 A/s. Data is shown for no beam pipe, the type 330 Stainless beam pipe, and the type 316 Stainless beam pipe. Similar analyses were performed on the dipole and decapole data.

5 Results

The behaviour shown in Figure 3 is typical of all sextupole data taken during the ramp. It is observed at each ramp rate and with both the Morgan and tangential coils. With no beam pipe the sextupole strength rises linearly with current. With a beam pipe there is a constant contribution to the sextupole from the eddy currents which is proportional to dB/dt and inversely proportional to the resistivity of the beam pipe material.

Figure 4 shows the normalized sextupole harmonic coefficient b_2, the fractional deviation of the field from a pure dipole at 2.54 cm due to the sextupole component,

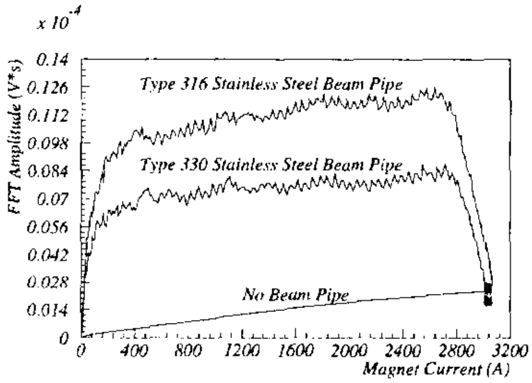

Figure 3: FFT Amplitudes for type 316 Stainless Steel, type 330 Stainless Steel, and no beam pipes. Ramp = 15000 A/s.

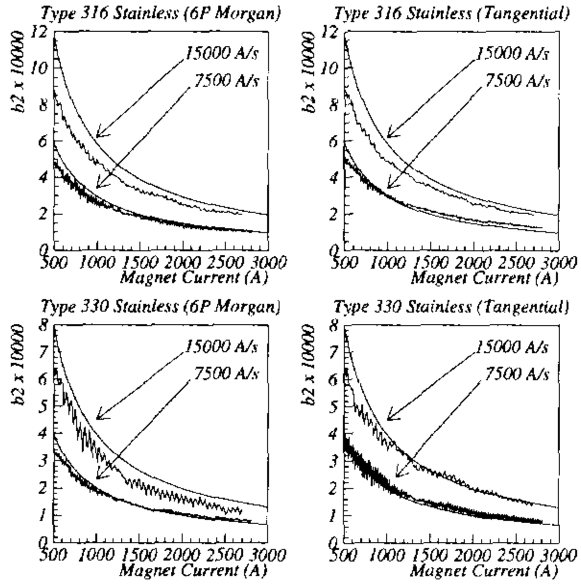

Figure 4: Eddy current b_2 field components calculated from sextupole Morgan coil and tangential coil measurements. The smooth curves are the predicted values.

as a function of magnet current. Measurements and calculations are plotted for various probes, beam pipe materials, and ramp rates.

6 Conclusions

Despite the significant power supply ripple on the data, sextupole eddy current signals were clearly observed with both Morgan and tangential coils. These effects were present at all ramp rates and with both beam pipes. The sextupole results compared well with the predicted values. No decapole signal that could be directly attributable to eddy currents was observed. Since the theoretical estimation of the magnitude of decapole was barely 1% that of the sextupole (at this beam pipe width)[4] the measurement system may not have the sensitivity required to detect the decapole signal.

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References

[1] S. D. Holmes, "Achieving high luminosity in the Fermilab Tevatron", in *Conference Record of the 1991 IEEE Particle Accelerator Conference*, San Francisco, May 6-9, 1991, p. 2896.

[2] D. J. Harding *et. al.*, "Design considerations and prototype performance of the Fermilab Main Injector dipole", in *Conference Record of the 1991 IEEE Particle Accelerator Conference* San Francisco, May 6-9, 1991 p. 2477.

[3] M. E. Bleadon *et. al.*, "The Fermilab Main Injector dipole construction techniques and prototype magnet measurements", in *Proceedings of the 12th International Conference on Magnet Technology*, Leningrad, USSR, June 24-28, 1991, (to be published).

[4] J. F. Ostiguy, "Eddy current induced multipoles in the Main Injector", *Technical report, Fermilab Main Injector Note* , October 1990, MI0037 (1990).

[5] G. H. Morgan, "Stationary Coil for Measuring the Harmonics in Pulsed Transport Magnets", in *Fourth Int. Conf. on Magnet Technology*, Brookhaven, (1974) p. 787.

[6] B. C. Brown, "Fundamentals of Magnetic Measurements with Illustrations from Fermilab Experience", in *Proceedings of the ICFA Workshop on Superconducting Magnets and Cryogenics*, Brookhaven National Lab, (1986) p. 297.

[7] Engineering Alloys Digest, Inc. *AISI Type 316*, Filing Code SS-114, Feb, 1991.

[8] *Alloy HA-330*, Huntingdon Alloys, Inc.