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Abstract – **The Fermilab Main Injector ramps from 8 GeV to 120 GeV in about half a second. The rapidly changing magnetic field induces eddy currents in the stainless steel vacuum tubes, which in turn produce error fields that can affect the beam. Field calculations and measurements are presented for the dipole and quadrupole magnets.**

I INTRODUCTION

A study was done in 1991 and 1992 to measure the effects of eddy currents in the beam tube of a Main Injector dipole[1][2] magnet while ramping the magnet at rates up to and exceeding 2.5 T/s (15000 A/s)[3]. At the time a theoretical study had been done to calculate the eddy current contributions to the sextupole, decapole, and 14-pole harmonics during ramps in Main Injector Dipole Magnets[4]. These early efforts to characterize the eddy current effects were done using a beam tubes of two different stainless steel alloys. Both types of beam tube were identical in their size and geometry and had rectangular cross-sections with rounded corners[3]. A special rotating coil probe was built to examine the sextupole and decapole eddy current contributions. The sextupole contribution was easily measured and compared well with the theoretical value. However, a decapole component was not observed and may not have been measurable by the measurement system.

The original measurements were done in a prototype Main Injector Dipole magnet. Since that time there has been interest in the examining eddy current effects generated by rapidly ramping Main Injector quadrupole magnets. The quadrupole magnets[5] will have two stainless steel tubes extending through the aperture and will ramp up to rates of 42.5 T/m/s (7500 A/S). Repeat measurements were requested on another dipole magnet as the shape of the beam tube has changed. The new tube is approximately elliptical in its cross-section[1] whereas the original tube was rectangular with rounded corners. Additionally, the power supplies used during the original measurements exhibited considerable 720 hz noise. The power supply regulation to these supplies has subsequently been improved, so there was interest in seeing if the new measurement exhibited reduced noise on the probe signals.

The repeat measurements on a dipole magnet were done using both the rectangular and elliptical beam tubes as well as no beam tube. Measurements on the quadrupole magnet were done with and without the elliptical beam tube inserted in the "star" shaped tube in the aperture of the magnet.

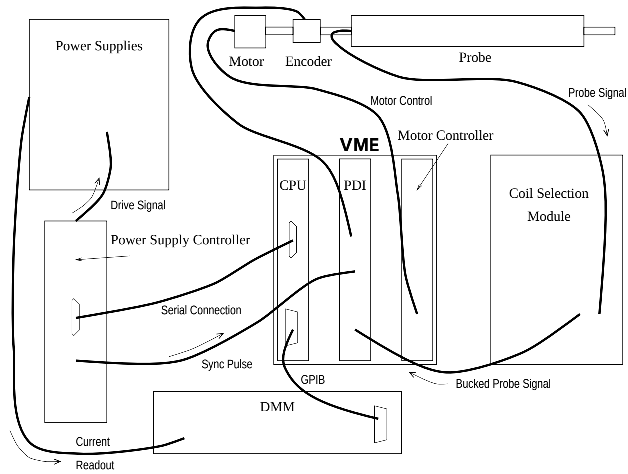

Figure 1: Measurement Hardware. The coil selection module is a manual switch bucking box for the quadrupole measurements. It is a VXI based configurations module for the dipole measurements.

II MEASUREMENT SYSTEM

Measurements were performed by using an AC Harmonics technique. This method monitors the change in magnetic flux with a stationary coil while the magnet is being ramped. Although the sequence of steps describing these types of measurements have been presented elsewhere[3] it will be repeated here for the sake of clarity. A coil or combination of coils is selected. The measurement sequence then proceeds as follows: 1) position the probe to an angular position, 2) ramp the current in the magnet while sampling the current and the probe signal, 3) save the data to computer disk, and 4) check the probe angle. If the angle is not the last position in the sequence, the probe is moved to the next position and steps 1 through 4 are repeated. Otherwise, the measurement is completed. This procedure is done for all coils of interest on the probe.

Dipole measurements were done using a probe built specifically to do AC harmonics measurements on Main Injector dipoles. This was the probe used for the measurements done in 1991 and 1992 [1]. It includes sextupole and decapole Morgan coils made with Litz (multi-stranded) wire as well as a tangential coil, dipole coil (belly band) combination. Since the sextupole and decapole Morgan coils were wound with 7 stranded Litz wire, these coils were made with 7 turns each. Use of the tangential coil as well as the Morgan coils provides two ways to measure the sextupole and decapole components. The diameter

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[1] The new beam tube is 11.38 cm wide and 5.31 cm high. Its shape is defined by the arcs of two circles. The top an bottom of the tube trace a circle of radius of 11.13 cm whereas the sides trace a circle of radius 1.42 cm.

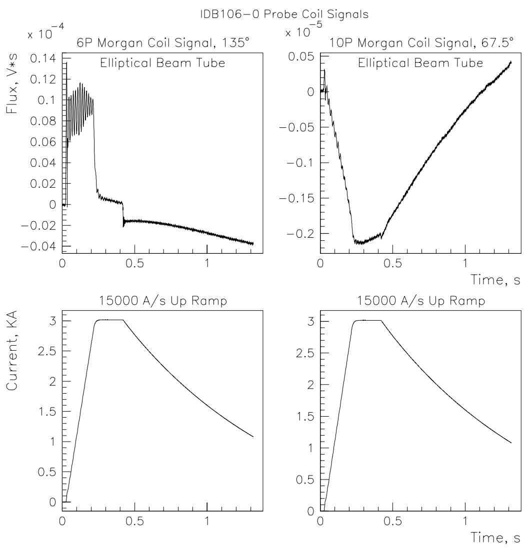

Figure 2: Raw probe signals for the sextupole and decapole Morgan coils as measured on IDB106-0 along with the corresponding current ramps. These signals were obtained at 15000 A/s ramp rates (on the up ramp) with the elliptical beam tube inserted in the aperture of the magnet.

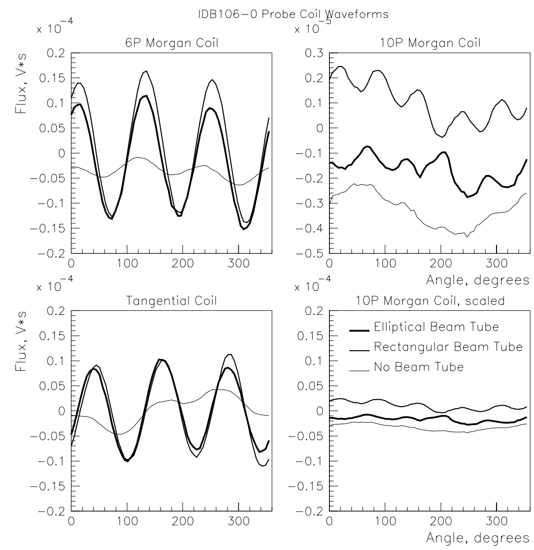

Figure 3: Probe coil waveforms obtained from the time slices of the data measured at all 64 angular positions in the probe rotation. These "slices" occur halfway up the ramp at 1500 A. The data is shown for all coils used in measurements on IDB106-0. The two decapole Morgan coil plots are the same data. The bottom graph is on the same scale as the sextupole Morgan coil and the tangential coil plots. The thick lines, the medium lines, and the thin lines are for the elliptical beam tube, the rectangular beam tube, and no beam tube respectively.

of the probe is 4.43 cm, with each coil being 44.9 cm in length.

Quadrupole measurements were done using a Morgan coil probe with dipole, quadrupole, sextupole, octupole, decapole, 12-pole, and 14-pole coils. Each coil is single stranded. This is a probe which was chosen for these tests due to its size and geometry. Since the theoretical study did not include eddy current calculations for a quadrupole magnet, it was not known which, if any, of the harmonics resulting from eddy currents would be significant. Thus, all coils on the Morgan coil probe were chosen for measurements in these tests. The probe has a radius of 1.511 cm and a length of 91.44 cm.

A schematic of the measurement hardware is shown in Figure 1. The measurement hardware components are the same or similar to those described for the original measurements[3]. There are some notable exceptions. Figure 1 shows the primary components used for these measurements. The power supplies for all measurements were controlled by a power supply controller which was developed at Fermilab[6]. The original measurements on the prototype dipole magnet used a Digital Multimeter (DMM) to record the signal voltage. That data was later integrated off-line to get the magnetic flux. The new data was obtained by using a PDI5035 Precision Digital Integrator[2] to obtain magnetic flux directly. Ramp information was sampled with an HP3458A DMM [3]. Both the probe signal and the current were sampled at a rate of 1440 Hz.

[2]Metrolab Instruments SA, 110 ch.du Pont-du-Centenaire, Geneva, Switzerland

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

III MEASUREMENT CONDITIONS

Quadrupole AC harmonics tests were done on a test stand powered by one 150 KW power supply. A Main Ring quadrupole which had been refurbished for use in the Main Injector (IQB214-1) was used for the quadrupole tests. This magnet had not yet been fitted with the Main Injector beam tube. It is 2.134 m in length. The quadrupole magnets for the Main Injector come with a permanently installed "star" shaped tube running through the aperture. Measurements with no beam tube inserted were done with the probe mounted in this star shaped tube. Measurements with the Main Injector beam tube were done with a 1.22 m section of the beam tube inserted sufficiently far in the aperture of the quadrupole so that the probe would be entirely contained within the body field region of the magnet. The Morgan coil probe was then placed in the center this tube. Measurements for the quadrupole magnet were done at two ramp rates, 0 to 1500 A at 7500 A/s, and 0 to 750 A at 3750 A/s.

Dipole tests were done on a test stand powered by two 150 KW power supplies in series. The magnet tested was one of the production Main Injector dipoles (IDB106-0) before insertion of the final beam tube. This is a 6 m dipole. Measurements were done with no beam tube, with the original rectangular beam tube (length 1.22m), and with a section of the Main Injector beam tube (length 1.22 m). In each case the probe or probe and beam tube were inserted so that the probe would be in the body field region of the magnet. AC Harmonics measurements for the dipole magnet were done at two ramp rates, 0 to 3000 A at 15000 A/s, and 0 to 3000 A at 7500 A/s.

Each of the beam pipe sections was made from type 316 Stainless Steel. The wall thickness for each was 0.15 cm. ρ for type 316 Stainless is 0.73 $\mu\Omega$m[7]. These values were used in calculating the theoretical eddy current harmonics components.

IV DATA ANALYSIS

Data was taken at 64 evenly spaced angular positions for each measurement. Examples of signals at specific angular positions are shown in Figure 2. Drift can be seen in most of the raw signals. The analysis attempts to minimize the drift when processing the data. When all 64 positions have been measured the complete set of data can be "sliced" to select the flux information at a specific time in to the ramp. Examples of these time slices can be seen in Figure 3. The time slices can then be analyzed using an FFT in order to obtain the harmonics components. Amplitude and phase information was obtained in this way for each of the time slices in the complete sets of data. This information was used to calculate a vector difference between the beam tube measurement and the corresponding no beam tube measurement. The results were then normalized to the fundamental component.

V RESULTS

Data taken on both test stands (for both magnets) exhibited a strong 60 Hz noise. This differs from five years ago where 720 Hz noise was a problem. Improvements to the power supplies, plus selecting a sampling at a rate which averaged out 720 Hz seems to have eliminated this problem. The 60 Hz noise does not prevent the analysis from obtaining usable results.

Quadrupole AC harmonics data was obtained using the dipole through 14-pole coils. A vector difference was taken between the beam tube and no beam tube measurements, and each was normalized with respect to the quadrupole signal. The data are shown in Figure 4.

The plots in Figure 4 start at injection current. Normalized amplitudes for the beam tube, no beam tube, and vector difference cases are shown. It is evident from these results that there does not seem to be any significant trend due to eddy currents in any of the components, regardless of ramp rate.

Eddy current effects are more noteworthy in the dipole data. The sextupole results for both the rectangular and elliptical beam tubes are shown in Figure 5. Morgan coil and tangential coil data are presented. Decapole results for both beam tubes is shown in Figure 6.

The sextupole results actually compare quite well to the expected theoretical calculated for the rectangular beam tube at both ramp rates, especially as seen for the Morgan coil data. The tangential coil data is a bit higher than expected, a result which differs slightly from the original measurements[3]. It is not yet clear why this is the case. Data for the elliptical beam is slightly less than that obtained for the rectangular tube. Since the sextupole field error is generated in a flat conductor perpendicular to the time varying magnetic field, and since the elliptical tube is not really flat, this is an expected result.

The decapole results show that the decapole component *may* be measurable in the elliptical beam tube, but it is small. Although the waveform implies that a decapole component is present in the rectangular beam tube, the final analysis indicates that it is smaller than the effect in the elliptical tube. It is also noteworthy that the sign of the theoretical values for the decapole are opposite to those obtained from the measurement, and that the measured values are considerably smaller in magnitude. If the decapole field components seen in the measurements are the result of eddy currents it is not clear why we see this sign change.

In conclusion, eddy current effects were not observed in measurements on a Main Injector quadrupole magnet. The sextupole component was observed in measurements on the dipole magnet, and it compares well with the expected result. These measurements also reveal the presence of a slight decapole component in the elliptical beam tube.

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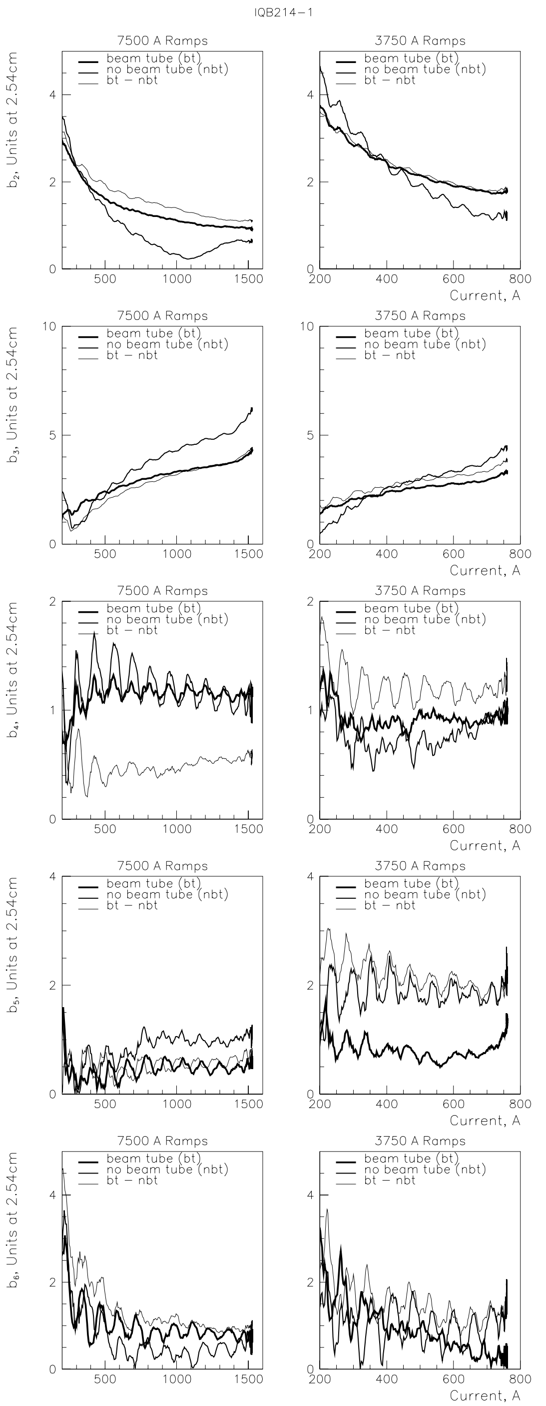

Figure 4: Normalized harmonics for the Main Injector Quadrupole magnet. Data for the beam tube, no beam tube, and the vector difference are shown. The top row show the sextupole data, the second row the octupole data, and so on to the 14-pole data.

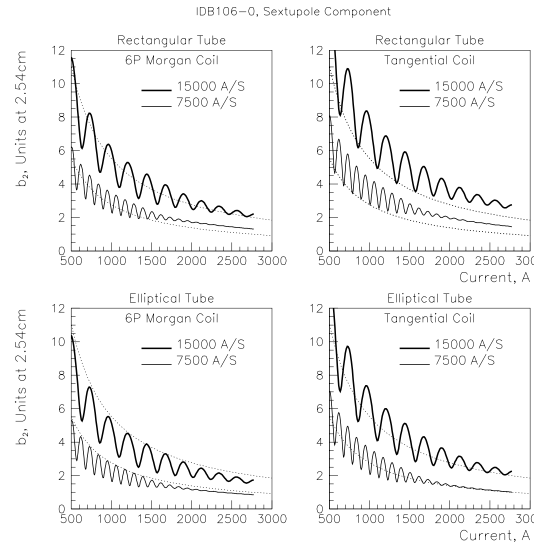

Figure 5: Beam tube sextupole eddy current field errors for the Main Injector dipole magnet IDB106-0. The dotted lines are the calculated theoretical sextupole values for the rectangular beam tube at the two measured ramp rates.

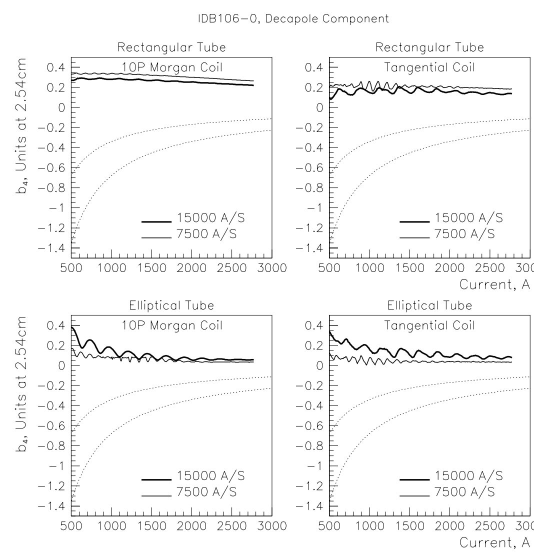

Figure 6: Beam tube decapole eddy current field errors for the Main Injector dipole magnet IDB106-0. The dotted lines are the calculated theoretical decapole values for the rectangular beam tube at the two measured ramp rates.