TEST RESULTS OF THE AC FIELD MEASUREMENTS OF FERMILAB BOOSTER CORRECTOR MAGNETS*

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Abstract

Multi-element corrector magnets are being produced at Fermilab that enable correction of orbits and tunes through the entire cycle of the Booster, not just at injection. The corrector package includes six different corrector elements - normal and skew orientations of dipole, quadrupole, and sextupole - each independently powered. The magnets have been tested during typical AC ramping cycles at 15Hz using a fixed coil system to measure the dynamic field strength and field quality. The fixed coil is comprised of an array of inductive pick-up coils around the perimeter of a cylinder which are sampled simultaneously at 100 kHz with 24-bit ADC's. The performance of the measurement system and a summary of the field results are presented and discussed.

INTRODUCTION

New corrector magnets are being built at Fermilab for the Booster ring in order to correct orbits and tunes through the entire Booster cycle and so maximize proton delivery for neutrino experiments. The corrector package includes six different corrector elements, providing normal and skew orientations of dipole, quadrupole, and sextupole. Each of these elements can be independently powered. The magnets operate in the Fermilab Booster ring, cycling at a rate of 15 Hz. A total of 63 magnets will be tested and characterized to obtain strength and harmonics data for beam simulations. The magnets require measurements at sampling rates of at least 10 kHz through the first allowed harmonics of each element. A detailed description of the magnet design is given in [1].

To measure the multipole fields of these relatively weak, fast-ramping corrector magnets, a fixed (i.e. non-rotating) coil system was developed, with multiple identical probes distributed at various angles that are sampled simultaneously by high-speed electronics during the current cycle.

MEASUREMENT TECHNIQUE

Probe Description

The Fixed-Coil Probe Array (FCPA) consists of 32 inductive pick-up coils fabricated on printed circuit boards and positioned on a cylindrical form. The circuit boards are 1.016 m (40 in.) in length and have 22 layers. The probe has unbucked windings as well as windings which buck dipole (DBuck), dipole and quadrupole (DQBuck), and dipole, quadrupole and sextupole fields (DQSBuck). The probe signals are amplified with gain 10 and simultaneously sampled at 100 kHz with 24-bit National Instruments NI PXI-4472B ADC modules. The probe, data acquisition and analysis are described in greater detail in [2].

The FCPA proved robust during production measurements. There was an instance in which a circuit board of the probe was damaged during insertion into the magnet. This board was replaced with a ready spare quickly (a couple of hours). Subsequently a protection plate was added at the end of the probe to guard against similar incident in the future.

Data Analysis

The multi-vertex probe data yields flux as a function of angle. With the assumption that the probes are quasi-identical (i.e. effectively the same probe is at the various angular positions), data are treated as simply coming from a single rotating circuit board probe. Though the winding geometry of each circuit board is complex, the analysis is straightforward and defined explicitly in [2].

Though the pick-up coils have the ability to buck fundamental fields, it was found that the 9-turn, single layer unbucked low-gain (UBL) windings on the probe were sufficient to extract strength and harmonics information.

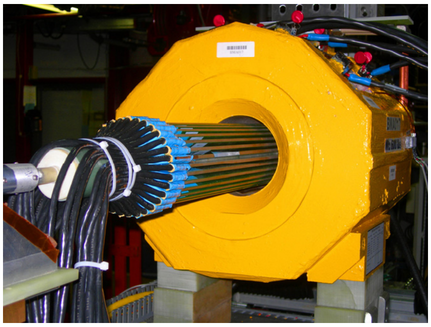

Figure 1: Fixed coil measurement probe array in BMA corrector magnet.

This required a calibration procedure in which data were acquired with the probe rotated to various angles. Analyzing the results from each of the measurements with the probe rotated over 360 degrees allowed a determination of the false harmonics generated by placement errors in the positions of the boards during FCPA fabrication. These errors tended to be

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predominantly caused by angular positioning errors of the boards on the cylinder perimeter. The largest corrections were in lower order terms and were less than about 25 units.

PRODUCTION RESULTS

Production measurements were planned for the Booster Corrector (BMA series) magnets to occur after fabrication but prior to a final potting process. This would confirm magnet performance before the final production step which impregnates the coils in a mixture of epoxy and glass filler beads. However, changes were observed in field measurements before and after potting, and it was decided that measurements should be done both before and after potting in order to monitor the magnitude and uniformity of the changes. The measurements consisted of standard ramp profiles which were to be similar to those used in the actual operation of the Booster. A picture of the probe and magnet is shown in Figure 1.

The average and standard deviation of integrated strength transfer functions over the ensemble of 50 tested magnets are given in Table 1. Note that the strength data in the table are determined during the 10 ms flattop of the 60 ms cycle. The power supplies presently in use have some current over-shoot and so the 'flattop' has current drift which may contribute to some of the spread observed in the data.

Table 1: Average Measured AC Strength Transfer Function over 50 Booster Corrector Magnets

Corrector	Ave. Strength TF (T-m/A at R=1m)	s.d. (percent)
Horiz. Dipole	**0.000366**	**0.66**
Vertical Dipole	**0.000365**	**0.58**
Normal Quad	**0.002489**	**0.43**
Skew Quad	**0.003924**	**0.36**
Norm. Sextupole	**0.045831**	**0.38**
Skew Sextupole	**0.045477**	**0.42**

Figure 2 shows quadrupole strength data as a function of magnet serial number. The behavior observed is typical of all six corrector types over the production run of magnets. The 'pre-potting' results are quite stable (except for the latest magnet which has coils that are shorter). The overall shift downward from pre- to post- potting strengths is apparent and is about 1 percent on average.

This shift is caused by expansion of the magnet aperture, which occurs during potting, and which results in a shift in the position of the steel laminations after the epoxy has set. To verify this, 3 magnets had their aperture size compared before and after potting. Since there is an epoxy coating on the post-potting laminations of the aperture, this must be scraped away in several regions to properly attain the aperture dimension on the lamination. The measurements showed an increase in aperture size during potting of ~200 μm on average.

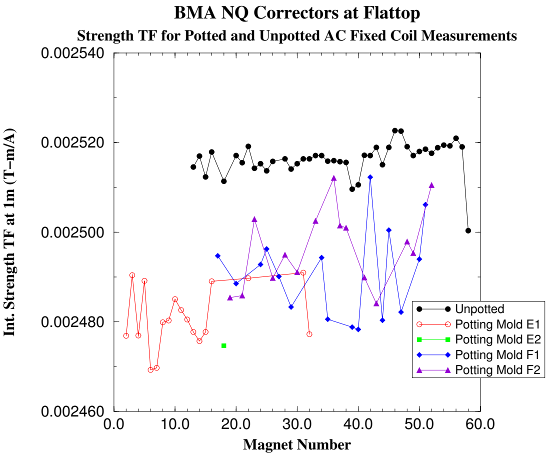

Figure 2: Quadrupole strength transfer function before and after potting for the series production.

Though there may be local trending in the series and within potting fixtures used, clearly there is a very large random component which dominates the strength shift and magnet to magnet variability.

Figure 3 is an example of a measurement made within the Beam Position Monitor (BPM) that will be inserted into these correctors. The effects of substantial eddy currents are evident, and introduce a delay in the field of about 300 μs. The delay can be compensated for during Booster operations.

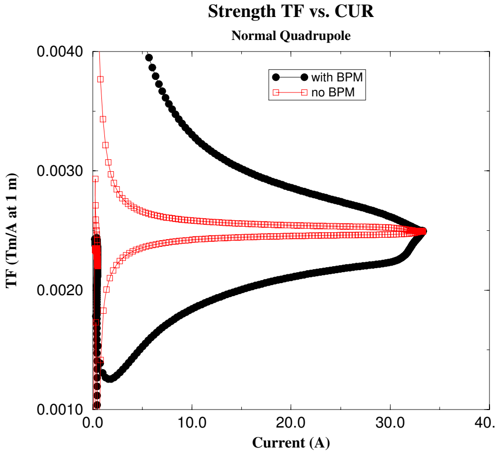

Figure 3: Quadrupole TF with and without the BPM that will be present in the magnet.

Additional tests were performed in the presence of steel laminations and a portion of support girder to measure the effects of having external iron near the magnet, similar to what will be present in the tunnel environment. The effects of the external iron were quite small – only the dipole corrector saw a minimal effect - and should not be a substantial issue for the BMA magnets in the tunnel.

The testing of the magnet series has so far found two magnets which were substandard. Magnets BMA031 and BMA047, were found to have anomalous AC behavior after potting. Measurements before potting were typical and showed no suggestion of the problem. The effect is predominantly in the normal dipole, quadrupole and sextupole correctors. An example of the unusual AC response for normal dipole is shown in Figure 4 comparing a typical magnet (BMA017 regular) against BMA047.

Measurements with the main fields bucked show that a field anomaly exists at the 180 deg. measurement position during AC ramping in both magnets. Eddy currents were suspected as a source of these problems, and to explore this possibility, two turns of heavy gauge copper were looped through a potted magnet aperture. As can be seen from Figure 4, the field response of BMA017 with the 2 loops present is much like the behavior seen in BMA047.

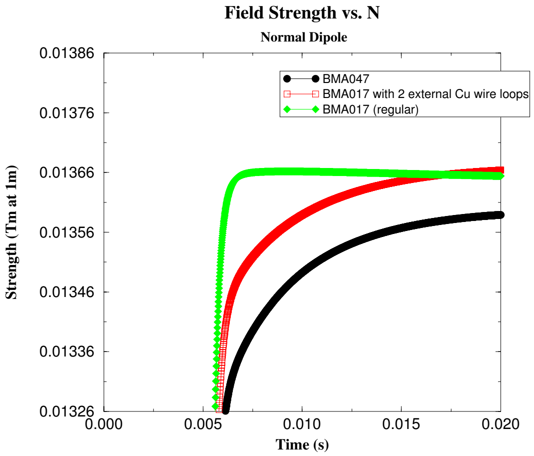

Figure 4: Anomalous ramping behavior observed in the normal correctors of 2 magnets. Shown for dipole.

Repeating these measurements with a series resistance of 2 Ohms added to the loops effectively extinguished the effect, so that whatever loop is presumably present within the magnet, it seems it must be highly conductive. The source of this effect is still being investigated. The cooling tubes were a candidate as a source of the effect, but tests on pre-potted magnets with these tubes intentionally shorted did not show an effect of the same magnitude. Puzzling is the fact that the problem develops during the potting process and, for the two magnets which have had this effect, occurs at the same angular location. Note that for the large eddy currents induced in the BPM, the shape on approach to flat-top current is observed to be the same as the regular BMA017 data in Figure 4, but simply shifted in time. Presumably this is because the BPM eddy currents have a cylindrical symmetry rather than being localized at one angular position in the magnet.

Reconstructed field shapes across the aperture show that the magnets have error fields of less than 1e-04 T-m at the specified good field region of ±37.5 mm for all corrector elements during their ramps. Figure 5 shows an example of the field shape for a normal quadrupole corrector element. In the figure, data are shown every 2ms of the cycle for clarity.

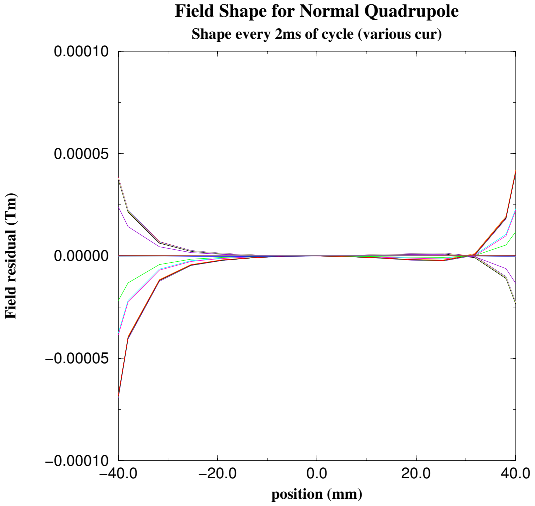

Figure 5: Field shape reconstructed from measured harmonics for a normal quadrupole corrector.

SUMMARY

To date, production measurements have been made on 50 of the 63 BMA Corrector magnets for the upgrade of the Fermilab Booster. The AC behavior of the magnets has been well characterized by a high speed stationary pick-up coil system. The results show very consistent field strength and harmonics over the set of magnets, well within the performance requirements for the Booster. A reduction in the transfer function of the correctors on the order of 1% was observed during the potting process. This is apparently from a small increase in the aperture size during the epoxy curing. A couple of exceptional magnets were found to have what appears to be large localized eddy currents.

REFERENCES

[1] V.S. Kashikhin, et al., “A New Correction Magnet Package for the Fermilab Booster Synchrotron,” PAC’05, May 2005

[2] J. DiMarco et al., “A Fast-Sampling, Fixed Coil Array for Measuring the AC Field of Fermilab Booster Corrector Magnets”, IEEE Trans. on Applied Superconductivity, Vol. 18, No. 2, June 2008.