FABRICATION AND PRODUCTION TEST RESULTS OF MULTI-ELEMENT CORRECTOR MAGNETS FOR THE FERMILAB BOOSTER SYNCHROTRON*

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Abstract

The fabrication of the multi-element corrector magnets for the Fermilab Booster synchrotron has just been completed. These water-cooled packages include six different corrector types - normal and skew dipole, quadrupole and sextupole elements. They will provide full orbit, tune and chromaticity control of the beam over the whole range of Booster energies, from 0.4 GeV to 8 GeV. During production, a set of quality assurance measurements were performed, including special thermal tests. This paper summarizes the results from these measurements as well as discussing some specific steps of the magnet fabrication process.

INTRODUCTION

In the next decade, high intensity accelerator-based neutrino experiments will be the central part of the Fermilab physics program [1]. Consequently, the demand for high intensity proton beams will be greatly increased. This demand requires new operational criteria for the Fermilab accelerator complex, especially for the Fermilab Booster Synchrotron, where the beam losses are increasing due to the strength limitations of the existing corrector system, which dates back to the beginning of Booster operation in 1970.

New stronger water-cooled corrector magnets (designated BMA) were recently built at Fermilab for the Booster ring. Every magnet consists of six independently powered corrector elements including normal and skew orientations of dipole, quadrupole, and sextupole. By design, these correctors are superior in comparison to the current ones and will provide full control over the beam orbit from the injection to extraction energy (0.4-8.0 GeV), including the ability for the normal quadrupole and sextupoles elements to swing through the full current range in ~1 ms during the transition crossing.

This paper describes some aspects of the production process, as well as providing a summary of the quality assurance magnetic measurements and specific tests for magnet thermal protection.

MAGNET PRODUCTION

the production of corrector packages was started in the summer of 2007, after successfully testing two prototypes,. Though the initial request was to produce 60 magnets, 63 were eventually manufactured. In September 2008, the last three magnets were built from the contingency cores and coils, establishing a production rate of approximately a magnet per week. Figure 1 shows BMA064: the last production magnet from the series.

Figure 1: BMA064 - the last production magnet from the series.

Forty-eight of these magnets will be installed in the Booster ring during the accelerator complex maintenance shutdowns: 12 of them were installed during the fall 2007 shutdown, 36 are going be installed this summer.

Table 1 (column 2) summarizes the design strength requirements for these correctors. Additional information on the design and operational specifications of this corrector magnet may be found elsewhere [2].

During production, several modifications of the tooling and manufacturing process were implemented. At the beginning, a small R&D project was started to determine the right filler to prevent the epoxy from cracking during magnet impregnation (potting). After checking various substances, glass beads filler [3] was selected. The next step was an optimization of the potting fixtures, which gave us the ability to better control coil position and moreover, to decrease the time for pre- and post-potting preparation by 50%. These modifications, along with having enough magnet assembly stations, made it possible to meet the schedule requirement and produce one unit per week.

Due to the wiring complexity of these new correctors (104 electrical connections between the coils), a polarity checker probe using 12 low cost industrial (~ $2 per element) Hall elements was built. This system proved to be very useful during the construction of the magnets

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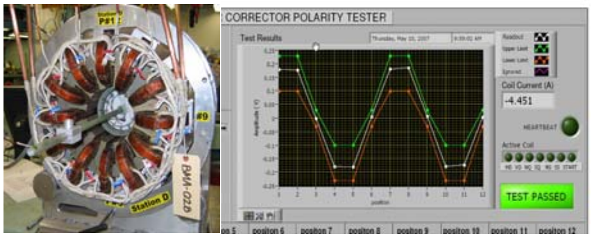

Figure 2: Polarity checker: hall probe array inserted in the production magnet aperture (left) and results of the measurements (right). The green and red curves indicate the upper and lower measurement limits.

by verifying that the polarities and wire connections were correct (Fig. 2). A detailed description of the system design and application is given in [4].

MAGNETIC MEASUREMENTS

At the beginning of the production, the 15 Hz test of the correctors was done by using a slowly rotating tangential coil system. This method, described in greater detail in [5], has the benefit of using a conventional measurement system with some limitation coming from the need to synchronize the probe rotational speed with the signal triggering. A new fixed-coil probe array, consisting of 32 inductive pick-up coils was developed and deployed exclusively for performing the AC characterization of the magnets. The signals from the probe array were amplified and simultaneously sampled at 100 kHz with 24-bit ADC modules. The probe, data acquisition and analysis are described in detail in [6].

Originally, one set of quality assurance magnetic measurements was planned for magnet production. These were to take place before magnet potting. However, since some deviation in the magnet parameters was observed due to the impregnation process,, a decision was made to perform measurements both before and after potting to monitor the magnitude of these changes.

Figure 3 shows the normal sextupole transfer function (strength normalized to the current) versus BMA serial number. The data are shown in several categories. Pre-potted (i.e. unpotted) measurements for the magnets at the beginning of production (BMA001-12,17,19) are given by the grey curve. Thereafter, pre-potted measurements were taken with the AC probe (black curve). One can see that the pre-potted results are quite stable, tending to imply good quality control during magnet assembly. BMA058-059 are an exception: they have been assembled with shorter coils.

The coloured curves in Fig. 3 correspond to the post-potting measurements, with the different colours representing magnets impregnated with different potting fixtures (molds). The post-potted results show a large random component (~ 5%) and no clear systematic trends. Such a random variation is expected due to the deviation of the epoxy curing temperature conditions during the production.

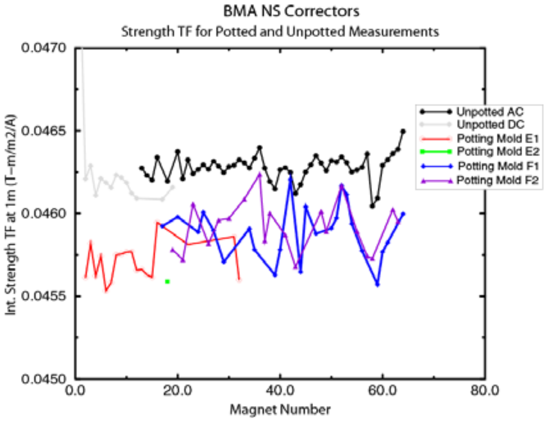

Figure 3: Sextupole strength transfer function versus the BMA production number.

An approximately 1.5 % shift downward from pre- to post-potting strengths is observed in all correctors. The cause of the shift is associated with the expansion of the magnet aperture during the temperature treatment of the epoxy. This treatment results in a permanent radial shift of the steel laminations, which do not return to their pre-potted positions after the epoxy has set.

Table 1 summarizes the average measured values over the full production line. The measured TF values are 2%-6% lower than calculated. This deficiency can be easily compensated by increasing the maximum operating currents by the required fractions as needed. The production power supplies have the ability to provide at least 10% more than the maximum operational currents.

At the beginning of the BMA production, only prototype versions of the corrector power supplies (PS) were available. For measurement consistency of the quality assurance tests, these power supplies were utilized during the entire magnet manufacturing process. Recently, we substituted the PS units with a new, production set [7]. To cross-check the magnet performance with the new supplies, a sample of 8 BMA magnets were re-measured.

A comparison between the dipole TFs in BMA017 with the production (black) and prototype (red) PSs is shown in Fig. 4. An obvious observation is that the current loop with the production PS set is much narrower compared to the loop with the prototype ones.

TABLE 1 Average Measured Transfer Functions over 63 Booster Corrector Magnets

Corrector	**Design Strength TF x10^{-3} (T-m/A)**	**Ave. AC Meas. Strength TF x10^{-3} (T-m/A)**
Horiz. Dipole	**0.39**	**0.37 ±0.002**
Vertical Dipole	**0.39**	**0.37± 0.002**
Normal Quad	**2.67**	**2.49± 0.010**
Skew Quad	**4.00**	**3.93± 0.013**
Norm. Sextupole	**47.0**	**45.5± 0.028**
Skew Sextupole	**47.0**	**45.5± 0.020**

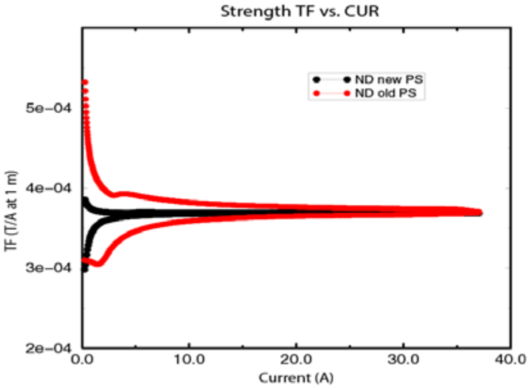

Figure 4: Dipole TF with production (black) and prototype (red) power supplies.

This is likely because the new PSs have faster current load monitors, which provide a better time synchronization between the field and current measurements.

THERMAL MEASUREMENTS

To protect the magnet from possible cooling problems, two Resistance Temperature Detectors (RTD) and one klixon were mounted to the upper half of the correctors. In case of a water flow restriction or blockage, the magnet will be protected from the extensive heat by switching off the power supplies before its core temperature reaches ~350 F, where the bonding epoxy starts to liquify.

By design, these magnets have independent cooling paths for the upper and lower halves. Soon after starting the production, it was suspected that in the case of a blockage of only the lower path, the temperature of the upper half might not reach the limit to activate the magnet protection system. Moreover, in this case, the temperature of the lower half might exceed the safe limits for structural integrity of the epoxy.

To test this possibility, magnet BMA033 was manufactured with two more RTDs, embedded in the epoxy of the lower half of the unit. Figure 5 shows the result of thermal tests with different water flow rates through the upper and lower cooling paths when the correctors are powered with DC current equal to the RMS of the operational AC profile. One can conclude that even with a restricted flow rate of 0.1 gallon per minute (gpm) in both paths - 0.6 gpm is the operational requirement - the magnet is still safe. The problem starts when the water flow in the lower path is blocked and the upper path is still open. After 4 hours, e.g. see the dark green and red curves between 7 and 11 pm, the temperature of the lower half exceeds 147 F and will continue to rise if the cooling is not restored.

Based on these data, a decision to equip the magnets with one extra klixon and RTD, glued to the bottom of the units was taken. Recently, all the magnets, not installed in the Booster were upgraded; the installed ones will be modified during the upcoming shutdown.

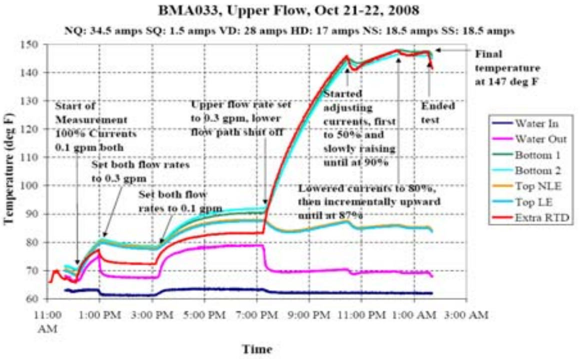

Figure 5: BMA033 thermal measurements with different water flow conditions.

SUMMARY

The production of the BMA corrector magnets for the upgrade of the Fermilab Booster is finished. In total, 63 magnets were assembled, 12 were installed in the 2007 accelerator shutdown and successfully operate. 36 more magnets are prepared for installation during the upcoming 2009 shutdown. The quality assurance measurements show very consistent field strength and homogeneity over the entire set of magnets, well within the Booster performance requirements. The tests of the new power supplies demonstrated a performance which is better than the prototype units. Several thermal tests revealed a potential problem with the magnet protection in the case of severe restriction of the lower water path. To prevent such accidents, a new klixon and RTD were added to the lower half of the magnets.

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