Design and Fabrication of a Multi-element Corrector Magnet for the Fermilab Booster

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***Abstract*— A new package of six corrector elements has been designed to better control the beam position, tune, and chromaticity in the Fermilab Booster synchrotron. It incorporates both normal and skew orientations of dipole, quadrupole, and sextupole magnets. These new corrector magnets will be installed in the Fermilab Booster ring in place of old style corrector elements. A severe space restriction and rapid slew rate have posed special challenges. The magnet design, construction, and performance are presented.**

***Index Terms*— Accelerator magnets, Corrector, Dipole, Quadrupole, Sextupole**

I. INTRODUCTION

The magnet specifications for the 48 new corrector magnets for the Fermilab Booster synchrotron were driven by the accelerator requirements, geometrical constraints, and power supply considerations, which are discussed elsewhere [1] - [4]. This paper presents the current status of corrector package design, fabrication, magnetic field measurements and thermal tests results.

Two prototype magnets were built and tested to verify the design and tooling functionality, and magnet power losses dissipation capability at different power and water flow regimes. Over 24 production magnets have already been fabricated and tested. Some of them will be installed in the Fermilab Booster Ring in 2007, with the remaining magnets being installed in 2008.

II. CORRECTOR PACKAGE DESIGN

The new Fermilab Booster corrector package includes six different types of magnets (Table 1). Each magnet is powered from an independent power supply, providing independent normal and skew orientations of dipole, quadrupole, and sextupole field correction. The field quality in the good field region of 50.8 mm diameter is better then 1%. Beyond tracking the excitation of the main Booster bus 15 Hz cycle, the corrector elements are specified [2] to correct more rapid variations, with a capability of switching from a full positive field to a full negative field within ~2 ms for quadrupoles and sextupoles.

TABLE 1 CORRECTOR PACKAGE FIELD CAPABILITY

Magnet Type	Achievable Integrated Field or Gradient	Max Operating Current Required for the Field
Horizontal Dipole	0.015 T-m	41 A
Vertical Dipole	0.015 T-m	41 A
Normal Quadrupole	0.16 T	64 A
Skew Quadrupole	0.008 T	2.1 A
Normal Sextupole	1.41 T/m	31 A
Skew Sextupole	1.41 T/m	31 A

To implement the integrated field strength and the flexibility required, we have designed a 12 pole, iron dominated magnet with coils that approximate a cos(nΘ) current distribution around the aperture, where n is equal to 1, 2, and 3 for dipole, quadrupole and sextupole windings respectively (Fig. 1). The magnet pole tip diameter is 138mm. The pole length is 267 mm and the overall magnet length is 425 mm. The core consists of 12 identical laminated segments. Two types of coils are used to form 6 different sets of magnet windings (8 of 12 coils contain 5 sections, and 4 coils contain 3 sections). The sections in the package are connected in such a way to achieve the desired current distribution. Two water cooling loops in each of the 12 coils are connected into two parallel water circuits (upper and lower) and provide the heat dissipation from the package.

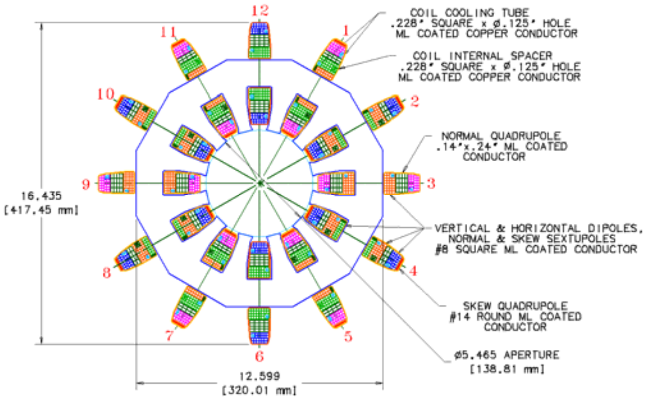

Fig. 1. Corrector package cross section.

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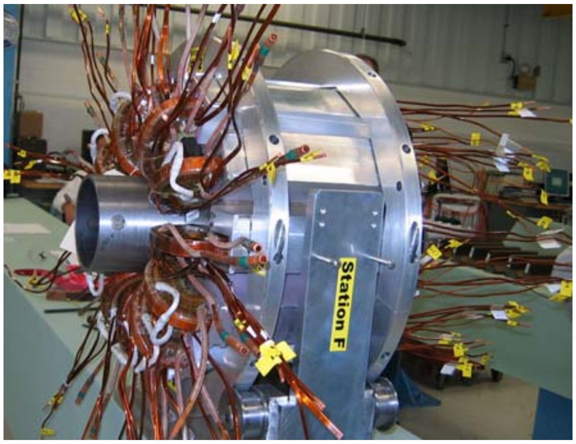
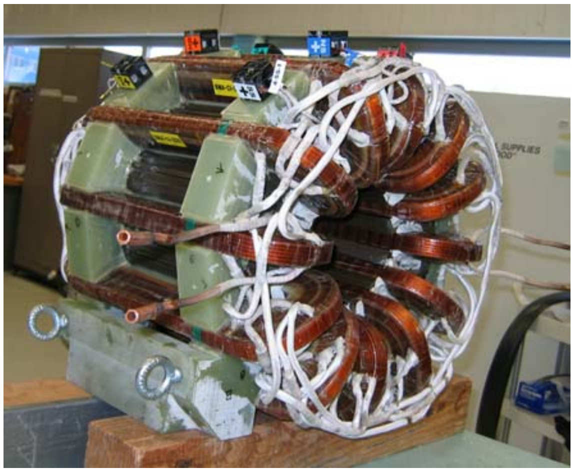
III. CORRECTOR PACKAGE FABRICATION

The fabrication of the corrector package was the main challenge of the project. It required using complicated tooling at every stage of magnet assembly to ensure achievement of the strict assembly tolerances.

Fig. 2. Corrector package at the different stages of fabrication:



a) Before coil leads were cut…



b) After coil leads were cut and connected…

c) The final magnet appearance with a BPM installed into the magnet gap...

Three different stages of the magnet fabrication are shown in Fig. 2.

The overall intricacy of the design was complicated by the severe space restriction imposed by the requirement to squeeze the magnets into the existing Booster ring while adding two additional correction elements and increasing the strength of the others. The new package has 104 coil leads and 48 water leads to be properly and reliably connected within the specified magnet size. The magnet ends were potted after the final field measurements to secure the coil leads and protect them from the possibility of being damaged at the magnets handling and service. Each corrector package is furnished with a beam position monitor (BPM). Maintaining the magnet - BPM relative alignment and providing access to the BPM pick up connectors creates additional difficulties.

IV. COILS DESIGN AND FABRICATION

All six magnet windings are formed from two types of coils. Three different sizes of standard solid ML coated wire are used in the coils. A square hollow conductor is used for water cooling lines and for an internal spacer in the type #1 coil.

The type #1 coil design is presented in Fig. 3, and the coil assembly appearance after the potting is shown in Fig. 4. The coil contains five independent sections. Each successive section is wound over the previous one. Two water cooling loops are buried between sections to ensure the heat dissipation with a minimal temperature gradient across the coil. Two additional spacers are buried in the coil to ensure the required number of turns in each section. Sections are electrically insulated from each other, from the water cooling loops, and from the internal spacers with additional layers of fiberglass tape. The entire coil body wrapped with several layers of fiberglass tape. The coils are vacuum impregnated with epoxy and cured using a special coil curing fixture.

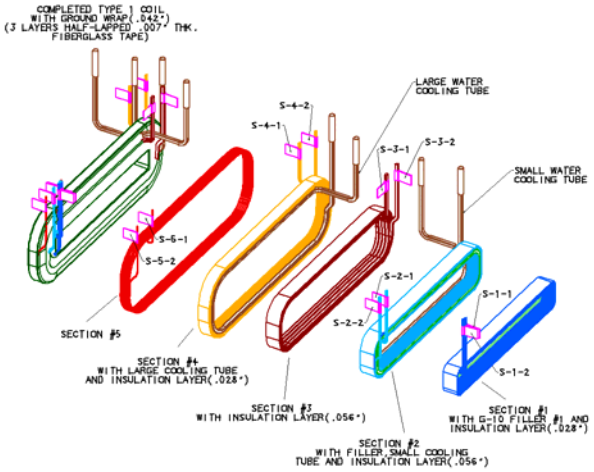


Fig. 3. Type #1 coil design.

The type #2 coil is similar to the type #1, but contains only three sections. There are also two water cooling loops buried between sections in the type #2 coils, but no internal spacers.

Each coil was electrically, hydraulically, and dimensionally tested prior to installation in the magnet.

Fig. 4. Type #1 coil assembly appearance after the potting.

V. Core Design and Fabrication

The 12 identical core segments, 267 mm (10.5”) long, are stacked from ~1000 laminations 0.25 mm (0.010”) thick. A special coating insulates laminations each from other and bonds them together after core segment curing.

Two types of lamination (the second type is a mirror reflection of the first one) were used in the core segments. Laminations were alternated at the stacking to minimize the burr effect and avoid extensive eddy currents.

Fig. 5. Core segment assembly.

VI. Thermal Tests

Since the temperature distribution across the magnet is very critical for the magnets with indirect water cooling, several thermal tests were done at different stages of magnet design and fabrication, including fabrication and extensive testing of two full scale prototypes.

The results of one of the thermal tests are shown in Fig.6.

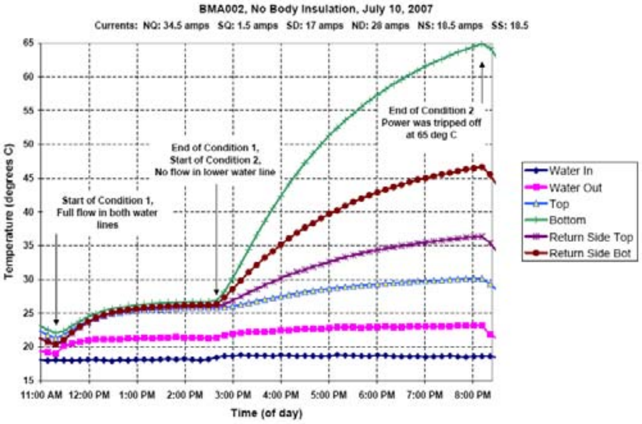


Fig. 6. The magnet test results at nominal currents in all windings and with full or 50% restricted water flow.

The first magnet prototype has provided most of the thermal test data. Two thermocouples were installed in the presumably hottest spots of each of 12 magnet coils, and two more thermocouples were attached to the magnet core. These thermocouples allowed monitoring of temperature distribution in the correction package during the test at different magnet operation regimes, including regimes with restricted (up to completely shut off) water flow in one or both magnet water cooling lines. The water temperature on the magnet supply and return lines was also recorded.

The prototype tests results demonstrated an acceptable temperature distribution within the magnet cross section and reliable heat dissipation from the coils with the water cooling lines at the magnet nominal power and water flow. They also provided us with some ideas of magnet capability at restricted water flow.

Production correction packages do not have thermocouples in the coils, but are furnished with two thermocouples and one thermo switch attached to the core.

VII. MAGNETIC PERFORMANCE

Field measurements of two prototype magnets were performed to validate the magnet design using several different available techniques. Most measurements were made using a rotating coil system [6]. Primary goals were to measure field strength and harmonics, measure the coupling between corrector elements, and demonstrate achievement of the desired slew rates. Field strength transfer functions were as or greater than expected. Coupling between package elements was small. Measurements during a set of nominal current cycles containing the specified slew rates showed the field following the measured current.

Fig. 7 demonstrates the results of the Normal Quadrupole strength measurement during a current cycle containing the nominal slew rate.

More field measurement results and further discussion can be found in [3].

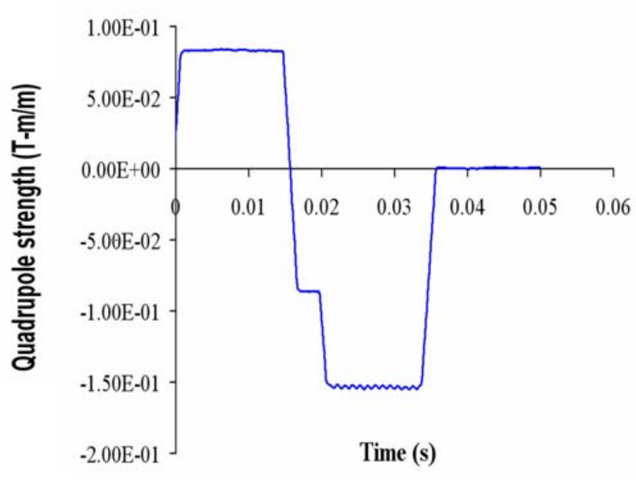


Fig. 7. Normal quadrupole strength measurement during a current cycle containing the nominal slew rate.

For production measurements, a fixed coil measurement array was built [5]. The array consists of 32 radial windings fabricated on individual circuit boards mounted on a cylindrical G10 tube. Unbucked signals are available for strength measurements as well as dipole, dipole-quadrupole, and dipole-quadrupole-sextupole bucked signals for harmonics measurement of the different elements. This system has now been commissioned, and an example of field measurements with this array is shown in Fig. 8 for four corrector packages. On the scale of this plot no difference in the field is observed. The variations of strength in the first 14 magnets measured were 0.1-0.2% for all elements except the skew quadrupole which has a variation of 0.4%. Note that the skew quadrupole has a much smaller field than the other elements and a larger variability can be expected. Comparing the field strength measurement results before and after the magnet potting, a systematic shift in strength of 1-2% was noticed. This magnet strength shift after the potting has yet to be understood.

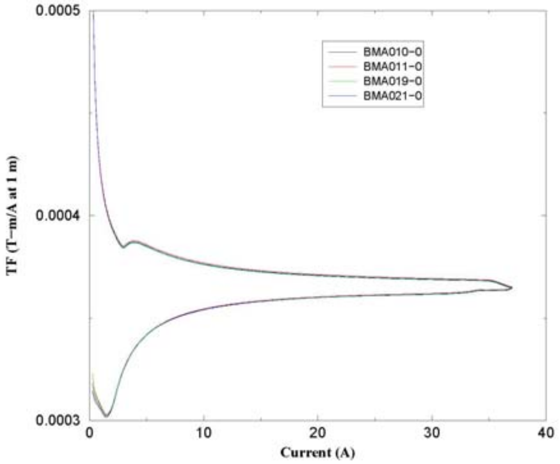


Fig. 8. Measurements of the normal dipole strength as a function of time.

VIII. CONCLUSION

The new Booster Corrector Package has been designed, fabricated and tested at Fermilab to replace the existing correctors. In addition to significantly stronger field in dipoles and quadrupoles, the new design includes normal and skew sextupoles, which allows better accelerator tuning.

48 new corrector packages will replace the old Booster Correction System in 2007-2008.

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