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DESIGN AND FABRICATION OF A MULTI-ELEMENT CORRECTOR MAGNET FOR THE FERMILAB BOOSTER SYNCHROTRON *

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Abstract

To better control the beam position, tune, and chromaticity in the Fermilab Booster synchrotron, a new package of six corrector elements has been designed, incorporating both normal and skew orientations of dipole, quadrupole, and sextupole magnets. The devices are under construction and installation at 48 locations is planned. The density of elements and the rapid slew rate have posed special challenges. The magnet construction is presented along with DC measurements of the magnetic field.

INTRODUCTION

The magnets described here will replace the existing corrector packages in the Fermilab Booster Synchrotron [1]. The goal is to control the beam position, tune, coupling, chromaticity, and resonances over the full acceleration cycle, slewing fast enough to maintain control in the face of the known variations in the accelerator.

Several groups [2-5] have been drawn by the attraction of a 12-pole geometry to squeeze multiple functions into a single package. In contrast with others, we have configured the coils so that we have a one-to-one map of power supplies to corrector elements. To simplify operations, we add the complexity of multiple windings in each coil package, appropriately wired in series across packages, so that each power supply for the magnet controls a single function: horizontal dipole, vertical dipole, normal quadrupole, skew quadrupole, normal sextupole, or skew sextupole.

We have constructed two prototype magnets and production is currently (June 2007) in progress on 24 magnets to be installed later in the year. Another 24 magnets will follow for installation in 2008, along with 12 spare magnets.

REQUIREMENTS

The requirements on the various elements are based on experience running the Booster, including observations of beam motion and tune variations through the acceleration cycle [6]. To maintain a constant closed obit we need dipole trims that are able to steer the beam by 10 mm in either direction at the highest beam energy and that can slew the position at 1 mm/ms up to the middle of the cycle. While the goal of the initial design [7] was to maintain the tune constant through the cycle, we have escalated the scope to require the ability to move the tune arbitrarily close to the integer resonance in the expectation that the larger working space there will improve acceleration efficiency. The normal quadrupole slewing rate is specified on the basis of requiring a full range swing at transition. The skew quadrupole strength is based on the strengths currently needed to decouple the tunes. The normal and skew sextupole strengths are based on the current system, though distributing them uniformly around the ring will allow better control of resonances than does the current configuration. The ability to flip the sign of the sextupoles during transition crossing, especially if the gamma-t jump system is implemented, drives the sextupole slew rate requirement. The magnet parameters to meet the beam-based requirements are listed in Table 1.

Table 1: Magnet Performance Specifications

Element	**Strength (approx)**	**Integrated Strength**	**Slew Rate**
Dipoles	0.357 T	0.015 T-m	3.24 T-m/s
Quad, normal	0.49 T/m	0.16 T-m/m	88 T-m/m/s
Quad, skew	0.031 T/m	0.008 T-m/m	0.8 T-m/m/s
Sextupoles	5.87 T/m^2	1.41 T-m/m^2	2350 T-m/m^2/s

The target good field region is 110 mm full width. The magnet pole tip diameter is 138 mm. The magnets must fit into the existing space, limiting their length and (on the bottom) transverse extent. By building new beam position monitor pickups that will fit inside the magnets we gained a few centimeters, so that the steel length can be 267 mm and the total length 425 mm.

MAGNET DESIGN

The basic magnet design is a 12-pole yoke with a coil around the back leg between each pair of poles to drive the flux, as shown in Figure 1. The 12 yoke assemblies are composed of 0.25 mm thick laminations. Each coil package includes either three or five windings, depending on its location.

The dipole elements, horizontal and vertical, each use windings from 10 coils. The normal quadrupole uses a winding from each of the 12 coils. The skew quadrupole uses 8 windings. And each of the sextupoles uses 6 windings to excite the desired field.

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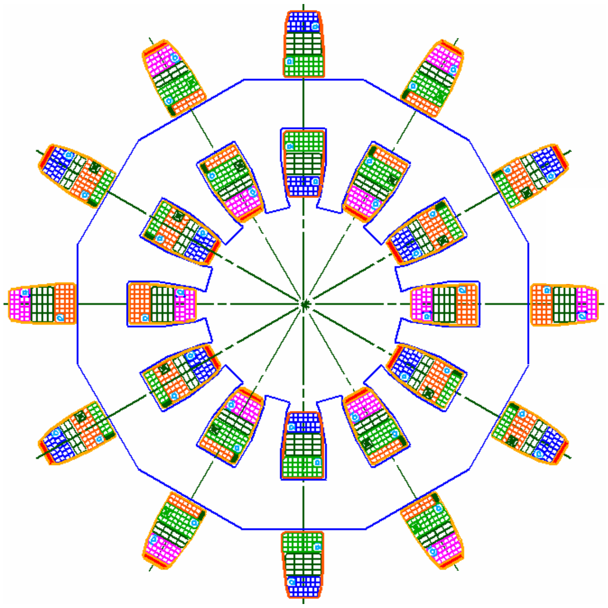

Figure 1: Cross section of Booster corrector package.
Orange – horizontal dipole
Bright green – vertical dipole
Open green – normal quadrupole
Red – skew quadrupole
Magenta – normal sextupole
Blue – skew sextupole

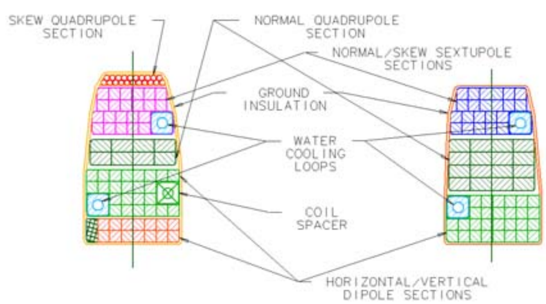

Figure 2: Cross section of five- and three-winding coils.

ELECTRICAL PROPERTIES

The resistance and inductance of the individual elements posed no problem for calculations. The mutual inductances of what appears at first glance to be a complex transformer required more careful consideration, as the voltage and regulation requirements on the power supplies can be affected. If all the field components are pure, symmetry arguments claim that there should be no coupling. In practice, the first prototype suffered from fabrication errors and poorly held tolerances, which were reflected in significant measured mutual inductances. The coupling was reduced in the second prototype and is further reduced in the production magnets to the point of not affecting the power supply performance. .

MAGNETIC PERFORMANCE

Measurements have been conducted on the two prototype magnets and are currently in progress on the production run of magnets. The main magnetic design issues have been addressed by DC measurements and are reported here. AC measurements of the fields at the full slew rates specified have also been made and are reported in a companion paper [8]. To date the primary measurement tool has been a rotating coil system, but we have recently commissioned an array of fixed coils that will be our production system.

Field Strength

Each element has been powered to its full design excitation (in both polarities) to verify the magnetic model. Figure 3 shows the deviation of the integrated field strength from linear as a function of current for each element. Saturation and remanent fields are minimal. Powering all elements simultaneously does not change the result.

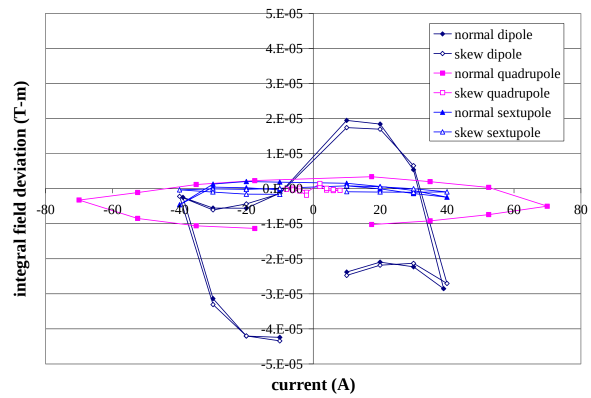

Figure 3: Deviation from the expected linear behavior of the integrated dipole, quadrupole, and sextupole fields at 25 mm as a function of current.

Field Uniformity

Each element is powered individually and the harmonic components of the field are measured. The harmonic coefficients can be compared and can also be used to reconstruct the field strength as a function of position. Figure 4 shows the deviation of the measured field from a perfect dipole, quadrupole, or sextupole field when only the corresponding element is powered to full current. The field uniformity is completely satisfactory. We have also measured the performance of the other elements with either a dipole or quadrupole element fully excited and have looked at all field components as all six elements are excited simultaneously. Figure 6 shows the last case. All elements have been powered to their maximum current, the field has been measured, and the residual is plotted after subtracting the expected dipole, quadrupole, and sextupole fields. In no case is there a significant interaction among the fields.

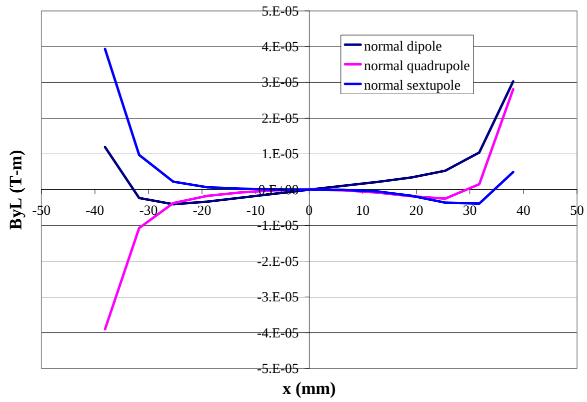

Figure 4: Deviation of the integrated dipole, quadrupole, and sextupole field shape from the nominal as a function of position when only the element of interest is powered to full current.

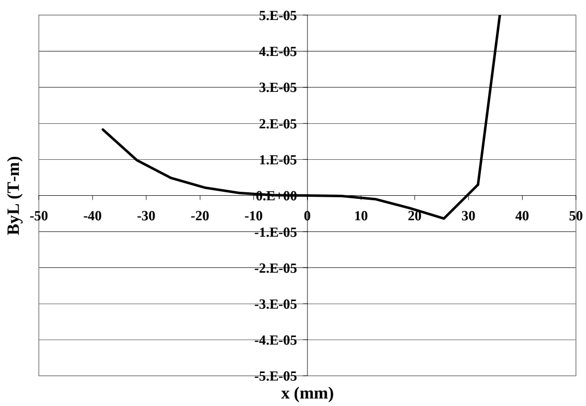

Figure 5: Deviation of the field shape from the nominal as a function of position when all the elements are powered to full current.

High Slew Rate Response

The ability of the magnet to follow the desired curve is also of concern. To measure the response of each element we have placed a stationary Morgan coil through the magnet and captured the waveform, sampling at 100 kHz, as each element was excited on a characteristic cycle. The output voltages could then be integrated to measure the integrated field of the principle harmonic. In Figure 6 we see examples of the fastest slew rates required. The quadrupole and sextupole signals are compared to the field calculated by applying the DC transfer constant to the current at each point.

SUMMARY

We have designed a multi-element correction package that meets the requirements of the Fermilab Booster Synchrotron. The magnets perform according to design, with magnetic strength and field uniformity measurements demonstrating the desired properties.

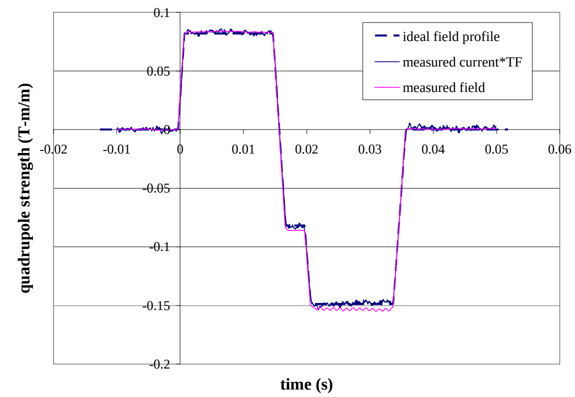

Figure 6a: Integrated normal quadrupole strength as a function of time..

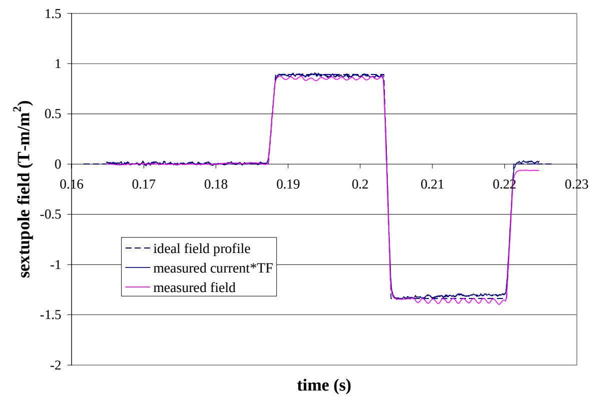

Figure 6b: Integrated sextupole strength as a function of time.

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