DESIGN, FABRICATION AND CHARACTERIZATION OF A LARGE-APERTURE QUADRUPOLE MAGNET FOR CESR-c *

M. A. Palmer, † J. A. Crittenden, J. Kandaswamy, T. O'Connell, A. Temnykh
LEPP, Cornell University, Ithaca, NY 14853-8001

Abstract

Installation of a radiative-Bhabha luminosity monitor for CESR-c operation in 2004 required replacing a 40-mm-aperture steel quadrupole magnet with one of aperture 75 mm while maintaining field-quality tolerances at the level of a few parts in 10^4. We present the design methodology using 2D- and 3D-finite-element field calculations, discuss the fabrication and mechanical tolerances, and present the results of flip-coil field measurements.

INTRODUCTION

During the summer of 2004, luminosity measurements for CESR-c operation were enhanced by installing a high-rate scintillator-based photon counter [1] sensitive to the flux of photons produced by Radiative Bhabha (RB) scattering at the interaction point. Space constraints required the placement of this detector downstream of a quadrupole magnet, 15m from the CLEO interaction point, with insufficient aperture to allow passage of the photon beam. It was thus necessary to design a replacement magnet with sufficient aperture to accommodate passage of the RB photons. After reviewing various options, we determined that the most efficient route to a magnet satisfying our requirements was to modify spare laminations from 40 mm bore, 4-piece quadrupoles presently installed at the injection points in CESR. By machining the pole tips and placing spacers between the 4 quarters, a design with sufficient aperture could be achieved as shown in Fig. 1.

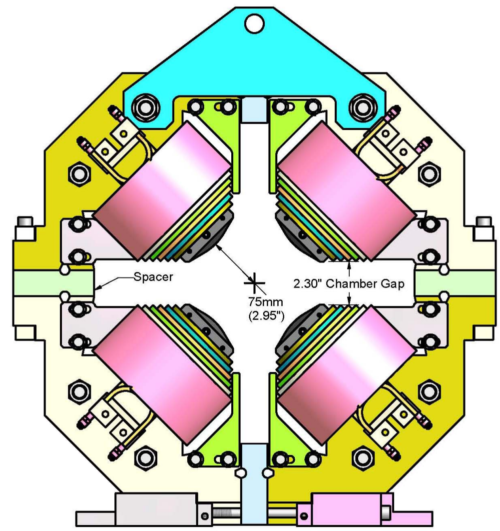

Figure 1: Design of a 4-piece quadrupole with sufficient bore and coil slot aperture to accommodate the beam pipe modifications needed for the luminosity monitor

DESIGN SEQUENCE AND FIELD MODELING

The design of the field-defining shape of the quadrupole iron proceeded in two steps. First, a 2D field model was developed which was used to calculate the transverse profile of the field on the central vertical mid-plane. The pole-tip profile consisted of a hyperbolic shape on the 45-degree axis of the quadrupole which transitioned to a tangential shimming region. The end of the shimming region was terminated in a flat to ensure a vertical gap of 5.8 cm between pole tips which was necessary to accommodate the new beam pipe. The distance of the pole-tip from the central axis was fixed at 75 mm. Thus only the length of the straight region was left as an adjustable parameter. It was chosen such that the maximum relative deviation from a perfect quadrupole field over ±4.5 cm was less than $\pm 3 \times 10^{-4}$. This 2D modeling was performed using the Poisson package [2] and then repeated, for the magnet's central vertical mid-plane, with the OPERA 3D package from Vector Fields [3]. With sufficient refinement of the finite-element mesh generation, consistency of the fields to a few parts in 10^5 was obtained between the two packages.

The second step of the design procedure was to calculate the field integral along the length of the magnet using the OPERA 3D algorithm. With no further modification of the pole-tips, the fringe fields sufficed to ruin the field integral beyond the original specification of $\pm 3 \times 10^{-4}$ relative deviation used during the design of CESR optics in the late 1970's [4]. This level of field uniformity was re-established by introducing a 45-degree bevel on the pole-tips at each end of the magnet. Judicious choice of the depth of the bevel resulted in a field quality within specification as shown in Fig. 2 (top plot).

Fig. 2 also shows the horizontal gradient of the vertical field component integrated over the 56-cm length of the magnet as a function of horizontal entrance position, i.e. the uniformity of the focusing strength. The field gradient is within $\pm 3 \times 10^{-4}$ of the central value over a ±4 cm region. The absolute gradient on the vertical mid-plane for CESR-c operation at 1.88 GeV is 209 gauss/cm. For the highest anticipated fields, corresponding to the use of round beam Möbius optics at 5.3 GeV, the gradient is 620 gauss/cm.

* Work supported by the National Science Foundation
† palmer@mail.lepp.cornell.edu

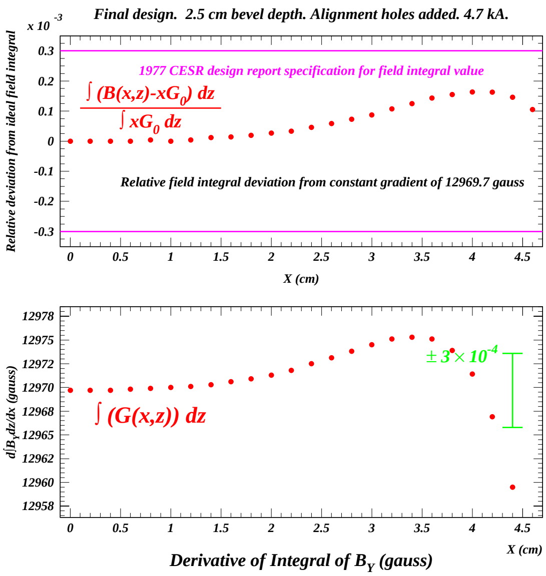

Figure 2: The horizontal gradient of the vertical field component integrated over the 56-cm length of the magnet as a function of horizontal position on the mid-plane. The upper plot shows the relative field deviation from a perfect quadrupole of uniform focusing strength. The lower plot shows the absolute integrated gradient.

CONSTRUCTION

Construction of the magnet proceeded in several steps. First, the existing 1/16" laminations (see Fig. 3) were shuffled and grouped into 5 sets to provide a complete magnet plus one spare pole. The laminations were machined, inspected, cleaned and then assembled into quarters. After mounting of the coils, 2 of the quarters were assembled into a bottom half and 2 into a top half for final installation.

Figure 3: The original 1/16-inch thick CESR quadrupole steel lamination.

The machining and mechanical inspection challenges involved repeatability of results at the 5×10^{-4} tolerance level. Ultimately, the 2 alignment flats ($45°$ wings) of the laminations, which provide the precision mounting surfaces between the quarters, had to receive a finish machine cut on an NC vertical mill which removed less than 0.005". These machined surfaces were then used to register the laminations with pins for pole-tip profile machining, Coordinate Measuring Machine (CMM) inspection and also to register the stacked magnet laminations together on a precision ground assembly table.

Once the pole-tip profile design was finalized, the OPERA 3D geometry was ported to the Inventor CAD package [5] via an exported ACIS (.sat) file. The CAD geometry was developed further to build a complete assembly model of the finished magnet. This CAD model was also used to port the 2D hyperbolic shape to the FeatureCAM package [6], allowing precise machining of the laminations to the specified tolerances, as well as providing a valuable inspection tool to cross reference CMM data.

The CMM process developed as the understanding of the limits of the available technology increased. Using the same jig plate for CMM inspection that was used in the NC machining process provided a known configuration in which to take measurements. Comparing ΔY values at predetermined X design values in the CAD model (see Fig. 4) across multiple samples of machined laminations led to the conclusion that the machined pole-tip profile was well within the desired design tolerances.

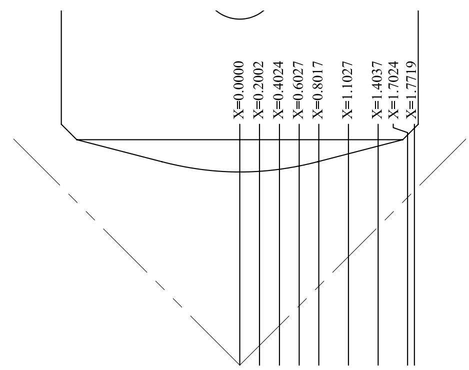

Figure 4: Lamination hyperbolic/flat pole-tip profile shape reference check points shown in inches.

Final assembly of each magnet quarter involved stacking 356 laminations to produce the 56-cm long magnet; the laminations were sorted into 27 groups, each with 13 or 14 laminations, in alternating orientations so that outside assembly tabs could be matched between the magnet quarters. In addition, 39 laminations at each end of a quarter were epoxied and pressed into end packs. These end packs were then machined to accommodate a solid nose piece insert with a bevel used to tune the magnet's 3D field integral.

While the magnet iron fabrication process was underway, preparation of coils and a power supply capable of providing the necessary excitation was also in progress. Table 1 lists the magnet operating parameters for the CESR-c (1.88 GeV) and high energy (5.3 GeV) modes of operation. The primary requirements for the coils were:

- Small enough package to provide clearance for the flared beam pipe passing through the coil slot
- Voltage drop compatible with the 60V CESR quadrupole magnet bus
- Reasonable thermal characteristics

It was determined that the space and voltage drop require-

Table 1: Operational Parameters

Parameter	**Value**		
	1.88 GeV	**5.3** GeV CHESS	**5.3** GeV Möbius
Field Gradient	209 G/cm	330 G/cm	620 G/cm
NI	4825 Amp-Turns	7235 Amp-Turns	13600 Amp-Turns
Turns per coil	72		
Conductor	1/4” x 1/4” with 0.125” dia. hole		
R_{coil}	0.062 Ω		
Current	67 A	100 A	188 A
Magnet Voltage Drop	17 V	26 V	49 V
Power/coil	290 W	650 W	2.3 kW
Water flow/coil @60 psi	0.45 Gal/min		
Coil temperature rise	2°C	5°C	18°C

ments could be met by constructing each coil out of 0.25” square conductor with a 0.125” diameter cooling hole. In order to provide sufficient cooling at the highest expected operating currents, given limitations in differential pressure available in the CESR cooling system, each coil had to be split into 3 separately cooled loops. Thermocouples and thermal switches were placed on each loop to protect against any possible cooling failure. Insulation for each coil consisted of an inner wrap of 0.003” kapton tape and an outer wrap of 0.0045” fiberglass impregnated with B-stage epoxy. The outside of each coil was then encapsulated with an alumina-doped epoxy layer in a wet layup process. Finally, a standard CESR 300A, 20kHz transistor switching module was assembled to power the magnet from the quadrupole bus.

FIELD MEASUREMENTS

A conventional flip-coil procedure was used to measure the field integral of the completed magnet. The results are shown in Fig. 5 for currents between 46 and 183 A. The standard operating currents are about 67 A at 1.9 GeV and 100 A at 5.3 GeV when providing X-ray beams to the Cornell High Energy Synchrotron Source (CHESS). A slight asymmetry of a few parts in 10^{-4} is observed which is within the range of measurements obtained from other quadrupoles around the CESR ring. The success in obtaining these results within design specifications without post-construction fine tuning of the bevel on the pole-tips testifies to the high degree of reliability of the design procedure.

CONCLUSIONS

We have successfully employed our 3D magnet modeling tools to design a magnet to the necessary specifications and, upon assembly, have it ready for immediate use. The final design of the magnet was obtained in June, 2004, while fabrication and assembly were completed in July. Field integral measurements were performed in August and indicated that no further field tuning was required. Installation occurred immediately thereafter. The magnet has been operating to specification since that time.

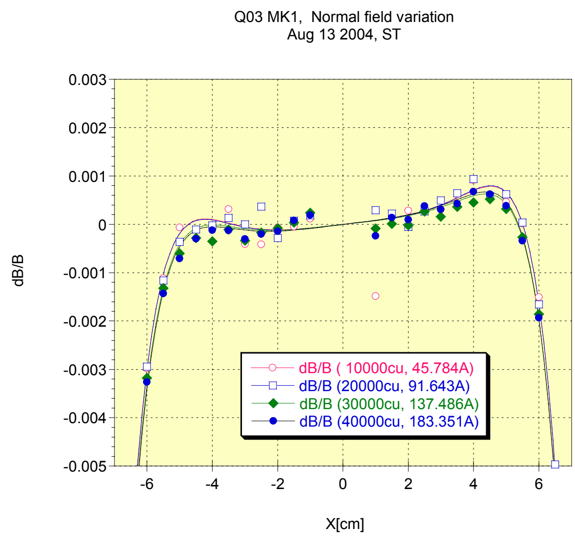

Figure 5: The relative variation of the field integral along the length of the magnet as measured with a flip coil for operating currents between 46 and 183 A.

ACKNOWLEDGMENTS

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