MAGNETIC DESIGN OF E-LENS SOLENOID AND CORRECTOR SYSTEM FOR RHIC*

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Abstract

As a part of the proposed electron lens system for the Relativistic Heavy Ion Collider (RHIC), two 6 T, 200 mm aperture, 2.5 meter long superconducting solenoids are being designed and built. Because of several demanding and unique requirements, this has become a very involved and technologically advanced magnet system. To deal with the large axial forces in the ends and large hoop stress along the length of the solenoid, a new structure has been developed. A new type of dipole corrector has been developed to satisfy the demanding requirements of field straightness inside the solenoid. To facilitate the unusual requirement of significant field outside the coldmass, fringe field coils have been added at the two ends. Moreover, anti-fringe field coils are also incorporated to maintain good field quality inside the main solenoid while the ratio of the fields between the main solenoid and the fringe field coils changes. This paper summarizes the development and optimization of the entire e-lens superconducting magnet system consisting of the main, the fringe field and the anti-fringe field solenoids together with the nested corrector package consisting of short and long horizontal and vertical dipoles.

INTRODUCTION

To increase the proton beam luminosity in RHIC, an electron lens (e-lens) magnet system is being built at Brookhaven National Laboratory (BNL) [1]. For the e-lens to function efficiently and facilitate the necessary cooling of the proton beam, the electron beam must be made similar in size and aligned parallel to the proton beam within 50 microns inside the 2.1 m long good field quality region of superconducting solenoid (Fig. 1). The electron beam size and trajectory are determined by the field in the solenoid. The straightness of the field is primarily determined by the straightness and thickness of the tube on which the coils are wound. Since 50 micron straightness is beyond what can be expected from normal construction techniques, a correction package becomes an integral part of the solenoid design.

Initially high current density, water-cooled copper correctors inside the superconducting solenoid were considered [2]. However, to reduce the stored energy and Lorentz forces, the inner diameter of the solenoid was reduced by making correctors superconducting and placing them at the outer surface of the superconducting solenoid. The solenoid yet remains a challenging magnet because of the still high Lorentz forces and stored energy (associated with the large aperture and high fields). For quench protection purpose, the main solenoid coil is divided into a number of double layers.

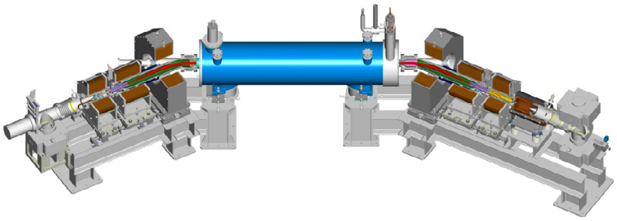

Figure 1: Superconducting (blue in middle) and copper (brown on either side) solenoids of the electron lens system. The electron beam (red) follows the copper solenoid whereas the proton beam goes straight through.

MAIN SOLENOID

Major design parameters of the main solenoid are listed in Table 1. The design was optimized to use many existing magnet components to minimize the overall cost.

Table 1: Major Design Parameters of the Main Solenoid

Parameters	Value
Wire, bare	1.78 mm X 1.14 mm
Wire, insulated	1.91 mm X 1.27 mm
Wire I_c specification (4.2 K, 7 T)	>700 A
Turn-to-turn spacing (axial)	1.98 mm
Turn-to-turn spacing (radial)	1.42 mm
Number of layers (main coil)	22 (11 double layers)
Additional trim layers in ends	4 (2 double layer)
Length of additional trim layers	173 mm on each end
Coil inner diameter	200 mm
Coil outer diameter	274 mm
Coil length	2360 mm
Yoke length	2450 mm
Maximum design field	6 T
Current for 6 T	~440 A
Peak Field on the conductor @ 6 T	~6.5 T
Computed Short Sample @4.2 K	~7.0 T
Stored energy @ 6 T	~1.4 MJ
Inductance	~14 Henry
Yoke inner diameter	330 mm
Yoke outer diameter	454 mm
Operating field (on the axis)	1 T to 6 T
Relative field errors on axis	$<6 \times 10^{-3}$

Computed quench performance (short sample field) with the wire specified in Table 1 is over 7 T at 4.2 K and over 6.6 T at 4.6 K. The radial component of the Lorentz force (causing hoop stress) is computed to be about 24 MN and is contained by the stainless steel sleeve, tapered for ease of insertion (Fig. 2). Axial Lorentz forces in the ends are large (~25 kN in each end) but are concentrated

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in a relatively small end section only. To avoid transmitting these forces to rest of the solenoid, an innovative structure consisting of a 10 mm thick disc is introduced. Coil winding must continue through this disk as dividing the coil in three sections would cause a large asymmetric axial force if one of the sections quenches.

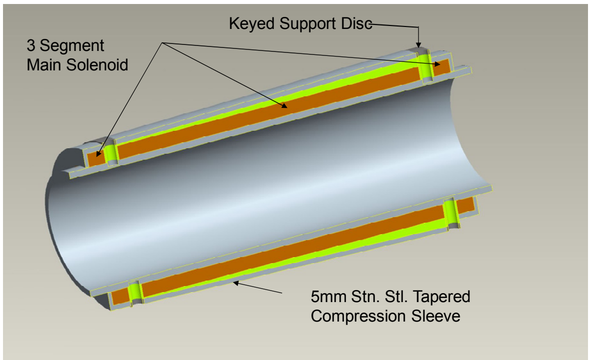

Figure 2: Schematics of the innovative magnet structure of the 6 T, ~2.5 meter e-lens superconducting solenoid.

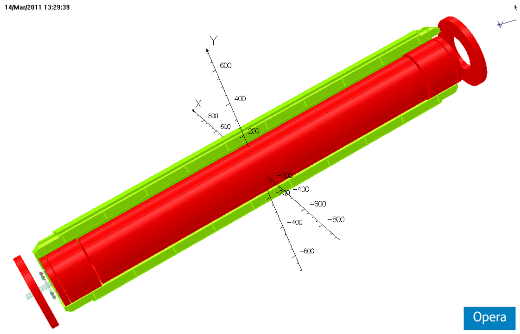

Figure 3: OPERA 3-d model of the e-lens superconducting solenoid magnet system. Only half of the yoke is shown to allow a better view of various coils, as labelled in Fig. 5.

Fig. 3 shows an OPERA 3-d model of the superconducting solenoid magnet system shown in Fig. 2. The solenoid primarily consists of 22 layers (11 double layers), except in the ends where it is increased to 26 layers (13 double layers) to expend the good field quality region in the ends. The relative field errors with respect to the central field remain below 5×10^{-3} along the axis in a good field region of ±1050 mm (Fig. 4) and within a cylinder having a 20 mm radius.

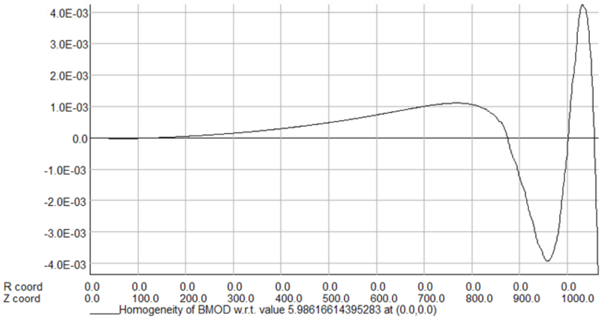

Figure 4: Computed relative errors along the magnet axis.

SUPERCONDUCTING MAGNET SYSTEM

A minimum of 0.3 T field is required [3] along the electron beam trajectory, including the space between the copper and superconducting solenoids (Fig. 1). Since such a high leakage (fringe) field could not be generated either by a copper solenoid or by the main superconducting solenoid alone, strong superconducting fringe field coils have been added on either end of the main solenoid (Fig. 5) but within the same cryostat. Since this 0.3 T minimum field is needed irrespective of the field in the main solenoid (1 T to 6 T), the current in fringe field coil cannot be a linear function of the current in main solenoid coil. In fact a higher value may be desired at low main fields. A change in the ratio of the current in the main coil to the current in the fringe field coil will impact the field uniformity (Fig. 4) inside the main solenoid. Anti-fringe field coils (with polarity reversed relative to the main coil and fringe field coils) were added to maintain good field quality inside the main solenoid. Computer simulations show that it is possible to achieve both high leakage outside the main solenoid and good field quality inside the main solenoid with the magnet system shown in Fig. 5. Parameters of the fringe field and anti-fringe field coils are given in Table 2. They use the same conductor as in the main solenoid (Table 1).

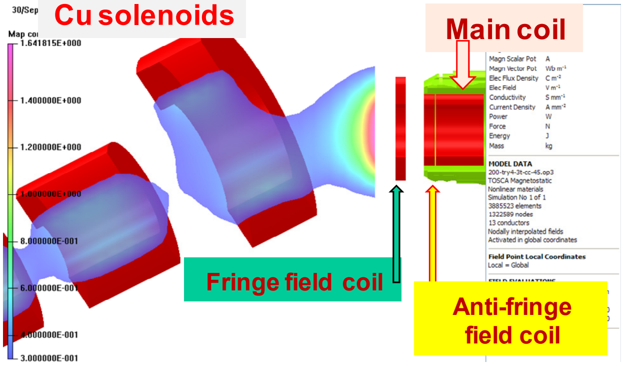

Figure 5: Section of OPERA 3-d model containing copper and various superconducting solenoid coils with magnitude of the field superimposed in critical region.

Table 2: Major Design Parameters of the Fringe Field and Anti-fringe Field Coils

Parameters	Fringe field coil	Anti-fringe coil
Coil inner diameter	206.4 mm	206.4 mm
Coil outer diameter	404.0 mm	274.0 mm
Coil length	37 mm	30 mm
Number of layers	70 layers	24 layers
Maximum design current	~470 A	~330 A

SOLENOID CORRECTOR SYSTEM

One of the most critical requirements in the e-lens solenoid is that field lines remain parallel to axis within 50 microns. Simulation of the normal mechanical errors in the tube on which coil is wound and their impact on the field show that the transverse field errors, that cause misalignment, can be corrected with the help of five 0.5

meter long independently powered horizontal and vertical dipole correctors (total ten) with a central field of 0.02 T [2]. In addition, 0.006 T full-length horizontal and vertical dipole correctors will be used to align the axis of the solenoid to the proton beam.

As mentioned earlier, the corrector magnets are made superconducting and placed outside the main solenoid coil to reduce the stored energy, Lorentz forces and size of the main solenoid. Another advantage of placing correctors outside, rather than inside, the solenoid coil is that the field (and hence Lorentz force) on them become much smaller. The use of radial space was further reduced by placing horizontal and vertical dipoles within the same radial space (Fig. 6), even though it requires more amp-turns for the same field. The figure shows the magnetic design of a horizontal and vertical pair of dipole correctors based on the optimum integral design [4].

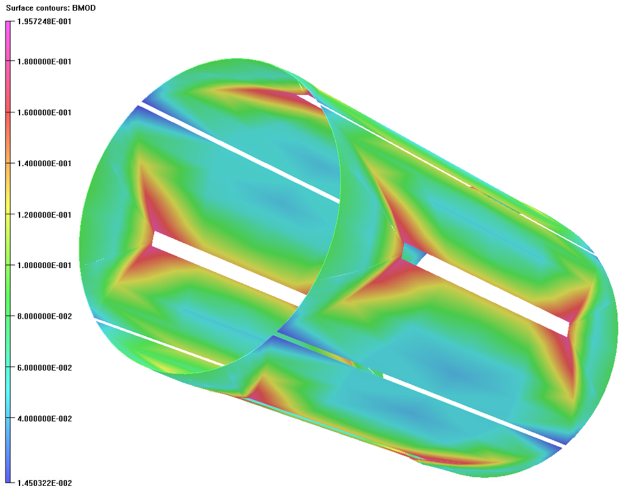

Figure 6: Thin coils with field superimposed on the dipole correctors. The left and right coils create a horizontal dipole and the top and bottom a vertical dipole.

The concept was further refined by reducing the angular extent of the winding (compare Fig. 6 and Fig. 7). The design is more efficient as more turns are closer to midplane in cross-section and less space is wasted in the ends. The new design requires multiple layers but creates a negligible drop in field between two adjacent dipoles due to shorter ends. In addition, it allows the use of lower cost slotted design which has been used earlier in helical magnets [5]. Slotted design requires machining slots in the aluminium tube where the superconducting wires are placed. Whereas a 6 mT, 2.5 m long dipole still requires only a single layer, 20 mT, 0.5 m short dipole requires four layers. Horizontal and vertical dipole correctors are still nested together in the same radial space.

The corrector magnets are constructed with 0.33 mm (0.013 inch) round wire with turn-to-turn spacing being 0.635 mm (0.025 inch). Smaller size wire (as compared to the solenoid wire specified in Table 1) makes the maximum operating current and hence the heat load smaller with ten short dipoles served by 30 A current leads and two long dipoles by 40 A current leads. Minimum specified critical current is 120 A (2 T, 4.2 K).

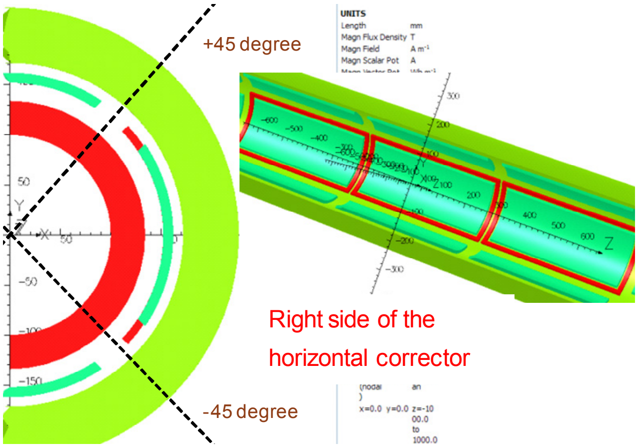

Figure 7: Right side of the horizontal corrector (s). Cross section is shown in the picture on the left and three such short length horizontal correctors on the right.

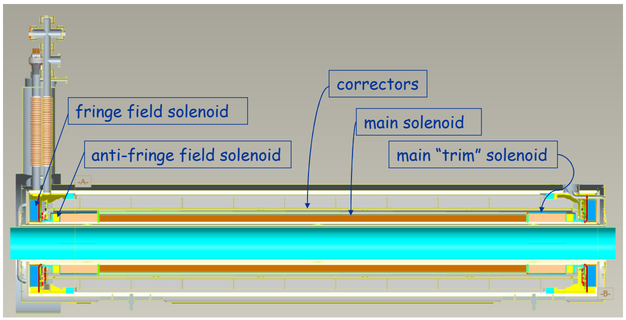

Figure 8: Schematic of the superconducting e-lens magnet system consisting of five superconducting solenoid coils and twelve superconducting dipole corrector coils.

SUMMARY

An electron lens system that satisfies a number of demanding and unique requirements has been designed. Superconducting horizontal and vertical dipole correctors are integrated with the main solenoid to correct transverse field errors. Fringe and anti-fringe field coils are added to generate desired field outside the solenoid while maintaining good field quality inside the solenoid. The complete superconducting magnet system is shown in Fig. 8. It uses several innovative design features implemented by using previously proven technologies.

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