

Mechanical Design and Construction of Superconducting e-Lens Solenoid Magnet System for RHIC Head-on Beam-Beam Compensation

M. Anerella, W. Fischer, R. Gupta, A. Jain, P. Joshi, P. Kovach, A. Marone, A. Pikin, S. Plate, J. Tuozzolo, P. Wanderer

Abstract—Each 2.6-meter long superconducting e-Lens magnet assembly consists of a main solenoid coil and corrector coils mounted concentric to the axis of the solenoid. Fringe field and “anti-fringe field” solenoid coils are also mounted coaxially at each end of the main solenoid. Due to the high magnetic field of 6T large interactive forces are generated in the assembly between and within the various magnetic elements. The central field uniformity requirement of $\pm 0.50\%$ and the strict field straightness requirement of ± 50 microns over 2.1 meters of length provide additional challenges. The coil construction details to meet the design requirements are presented and discussed. The e-Lens coil assemblies are installed in a pressure vessel cooled to 4.5K in a liquid helium bath. The design of the magnet adequately cools the superconducting coils and the power leads using the available cryogens supplied in the RHIC tunnel. The mechanical design of the magnet structure including thermal considerations is also presented.

Index Terms—Accelerator, electron lens, solenoids, superconducting magnets.

I. INTRODUCTION

To increase the polarized proton luminosity in RHIC, a superconducting electron lens (e-Lens) magnet system is being built at Brookhaven National Laboratory (BNL) [1-3]. 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 the superconducting solenoid and the central field strength uniformity must be within $\pm 0.50\%$. 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 the required straightness is beyond what can be guaranteed from normal construction techniques, a correction package is included as part of the solenoid design. The central component of each e-Lens is a superconducting magnet system, which is shown as a cold mass in its cryostat in Fig. 1.

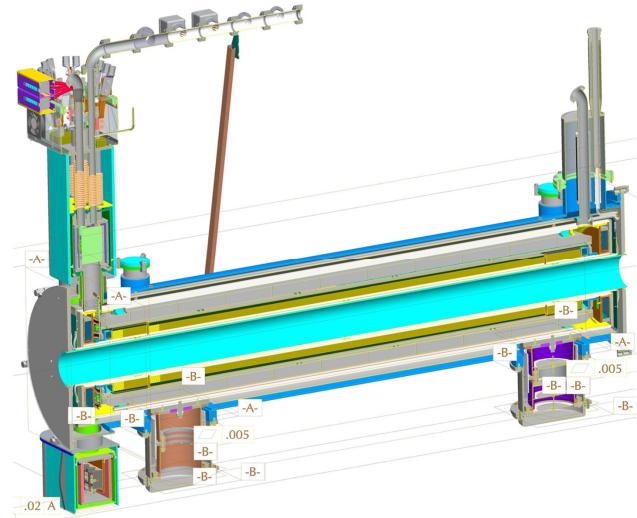


Fig. 1. Longitudinal section view of e-Lens solenoid

II. MAIN SOLENOID DESIGN

The main solenoid design is comprised of eleven “double layers” of rectangular monolithic conductor, 1.78 mm wide and 1.14 mm tall, with a 3:1 copper to superconductor ratio. Individual conductors are insulated with a 50% overlap of 25 μm Kapton insulation. To conserve radial space to reduce the stored energy and Lorentz forces of the main solenoid, and permit the use of surplus helium vessels and cryostat to save cost, coils are wound directly onto the stainless steel tube which also serves as the inner helium vessel, with 25 μm Kapton insulation first applied to the tube with a 66% overlap. Each double layer is wound from the lead end to the non-lead end of the magnet and back again, with start and end leads spliced to adjacent layers after all winding is completed. Before each layer is wound a layer of epoxy impregnated fiberglass is attached to the tube surface, and after each layer is wound fiberglass filled Styccast epoxy is applied to fill small gaps ($\sim 25 \mu\text{m}$) between the windings. Due to the high axial Lorentz forces ($\sim 600 \text{ kN}$) concentrated in the coil ends, stainless steel support discs are installed within the solenoid at each end and are keyed to both the inner helium vessel tube and the outer stainless steel support tube, preventing motion of the windings which could trigger a quench (see Fig. 2). In order to properly protect the coils in the event of a quench, the windings needed to be wound continuously in the resulting three sections of solenoid, necessitating gaps in the discs where conductors could pass through. To provide proper

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M. Anerella is with the Superconducting Magnet Division, Brookhaven National Laboratory, Upton, NY 11973-5000, USA (telephone: 631-344-7291, e-mail: mda@bnl.gov).

All other co-authors are also with Brookhaven National Laboratory, Upton, NY 11973-5000, USA.

mechanical support in these areas, insulated stainless steel inserts are fabricated and installed with each layer, which contain machined serpentine paths for the individual windings and axial support for adjacent windings (see Fig. 3). Finally, the last double layer includes “trim” windings at each end, which are comprised of an additional four layers of conductor continuously wound with the last layer (for a total of twenty six layers) at the outboard sides of the stainless steel support discs.

The motion due to outward radial pressure as a result of Lorentz forces (~ 12 MPa) is restrained by the installation of a stainless steel support sleeve. Again to conserve radial space, a smooth cylindrical sleeve is chosen over other clamping methods, although for ease of installation over the 2.5 m length an 8 mm taper is introduced into central portion of the sleeve. Separate cylindrical sections of support sleeve are used in the trim sections of the solenoid outboard of the stainless steel support discs. Prior to installation, the final conductor layer is overwrapped with epoxy impregnated fiberglass, the coil is cured in an oven and a precise matching taper with a 0.2 mm interference fit to the support sleeve is machined into the fiberglass (Fig. 3). The sleeve is then installed after heating to 180 °C to provide a running clearance to the coil at assembly.

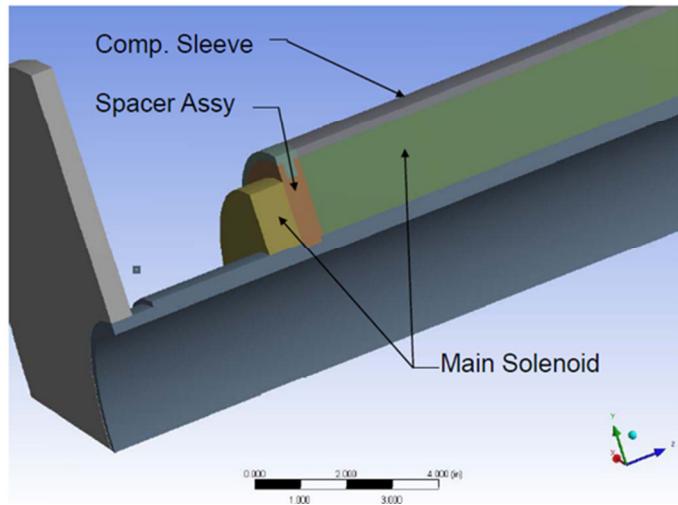


Fig. 2. Main solenoid coil axial support system

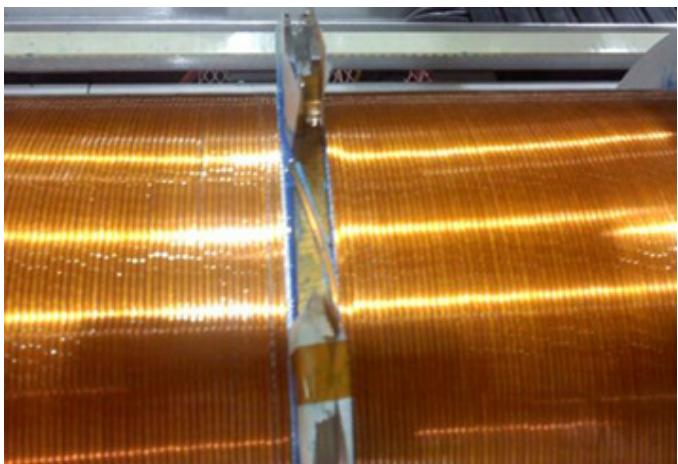


Fig. 3. Main solenoid coil serpentine conductor path through stainless steel support discs

III. FRINGE, ANTI-FRINGE FIELD COIL DESIGN

A fringe field solenoid (70 layers) is installed within the e-Lens helium vessel at each end, and an anti-fringe field coil (24 layers) is installed between the fringe field coil and the main solenoid at each end. Fringe field and anti-fringe field coil designs use the same conductor and other features as the main solenoid coil, with the exception that they are continuously wound from start to finish. The axial forces of the anti-fringe field coils (70 kN) are supported by the inner helium vessel and the larger axial forces of the fringe field coils (180 kN) are supported by both the inner helium vessel and the outer helium vessel. The outward radial pressures of the fringe field coils (14 MPa) are supported by stainless steel support sleeves, machined to precise interference fits with fiberglass wrap over the coil as in the main solenoid. The radial pressures of the anti-fringe field coil are inward and do not need external support.

IV. CORRECTOR COIL DESIGN

Superconducting corrector coils are comprised of five short (0.5 meter long) independently powered horizontal and vertical dipole correctors (total ten) and one full-length horizontal and vertical dipole corrector (total two). Placing corrector coils outside the main solenoid further reduces the stored energy and Lorentz forces of the main solenoid by about a factor of two. Radial space is further reduced by placing horizontal and vertical dipoles within the same radial space (coils occupied ~ 90° instead of the more traditional 180°).

The conductor is a 0.33 mm diameter round monolithic wire, 1.8:1 copper to superconductor ratio, insulated with a 50% overlap of 25 µm Kapton insulation. The wire is wound into precision machined grooves in an aluminum support tube. Short and full length correctors share common grooves in the aluminum tube. Short correctors, wound first, use four layers of windings and subsequent full length correctors require a single layer. Before winding each coil grooves are insulated with Kapton, and before winding each layer epoxy impregnated fiberglass strips are placed within the grooves. Transfer tape (double sided adhesive strips) is used to assist in temporarily securing wires. After the final coil winding is complete G-10 pusher/insulator blocks are installed, and the coil is overwrapped with tensioned epoxy impregnated fiberglass roving to resist motion due to Lorentz forces.

V. MAGNET DESIGN

All coils with the exception of the fringe field coil are contained radially within a solid iron yoke. All coils and yoke are connected to the helium vessel in a four-way keying manner which holds components concentric while allowing for differential axial and radial contraction of the iron, stainless steel and aluminum parts. Outside of the helium vessel a double walled stainless steel heat shield is installed,

with embossed passages for helium flow. This outer heat shield is bolted to aluminum heat shield end plates, which in turn are bolted through flexible couplings to an aluminum inner heat shield tube. Beyond the inner and outer heat shields and heat shield end plates are cryostat tubes and end plates. Multi-layer aluminized Mylar insulation (MLI) is used between cold mass and heat shield and between heat shield and cryostat in all locations. Inner cryostat and cryostat end plates are made of stainless steel so as to not interfere with operation of the solenoid magnet system. The cold mass to cryostat support posts are standard RHIC polyetherimide flanged cylinders, two at each of two locations, with heat stationing to the heat shield between support cylinders. Unlike RHIC, due to radial constraints the support posts are located in external cryostat spool pieces.

All exiting leads for the seventeen coil elements, associated wiring for instrumentation, quench protection, etc. and helium supply and vent lines are routed through the lead end of the cold mass and cryostat, with the exception of an additional helium vent and helium return line at the non-lead end.

VI. THERMAL DESIGN

The superconducting coils are cooled by a 4.5 K liquid helium bath provided in the helium vessel. Liquid level is maintained above all coils including the fringe field coils using level probes. Helium envelopes the various coil structures and cools the coils by conduction through the support structure, insulation and coil layers. Gas flow from helium that is vaporized from the 4.5 K heat load is used in part to cool the ten vapor cooled leads which provide power to the main solenoid coil and the fringe and anti-fringe field coils, and to cool the corrector lead assembly and instrumentation leads which are contained in two central vapor towers. Vaporized helium is also flowed through the outer heat shield passages before exiting the magnet at the non-lead end. Helium relief ports are provided at both ends of the magnet to permit the safe, rapid release of vaporized helium in the event of a magnet quench. The heat load assumed in the thermal design includes radiation from the warmer surfaces and conduction through the magnet supports and exiting leads. Magnet supports are heat stationed at the outer heat shield temperature. Multiple layers of aluminized Mylar separated by polyester fabric are installed between surfaces as described in Table I to reduce radiation heat flow.

TABLE I
INSULATION LAYERS

Vacuum vessel – outer heat shield	32
Outer heat shield – cold mass O.D.	50
Cold Mass I.D. – inner heat shield	12
Inner heat shield – inner cryostat	10

The resulting calculated heat load of the magnet is summarized in Table II. Note that heat loads are typically reported separately at cold mass and heat shield temperatures. Here they are also combined since there is a single helium

circuit providing cooling at both stages. Also note that calculations were iterated after testing began to include the measured results of a 40 K average heat shield temperature and a 5 K average inner helium vessel inner surface temperature.

TABLE II
HEAT LOAD SUMMARY

Item	Heat load (W)
<i>To outer heat shield and end caps from 300K</i>	
Radiation, conduction through MLI	5.8
Conduction through shield support wires	0.2
Radiation to support post shields	0.5
Conduction to support post intercept	2.2
Conduction to lead tower shield	1.1
<i>To inner heat shield from 300K</i>	
Radiation, conduction through MLI	2.7
<i>subtotal</i>	12.5
<i>To 4K cold mass and coil support tube</i>	
Radiation, conduction through MLI	1.0
Conduction through support posts	0.1
Gas cooled leads	10.8
Lead tower bellows	1.4
Lead tower inner chamber	0.1
Instrumentation wiring	1.5
<i>subtotal</i>	14.8
Total	27.4

Of particular interest is the temperature profile of the inner helium vessel, since the inner layers are where the main solenoid coil magnetic field is highest and therefore the temperature margin is lowest. Also, cooling of the main solenoid windings occurs from the outer radius inward by conduction, making the inner layer the least efficiently cooled. Analysis indicated that the temperature at the axial center of the cold mass (where the inner heat shield is warmest) is acceptable, with an increase of only 0.03 K.

VII. CONSTRUCTION ISSUES

The design and construction of the e-Lens Solenoid was challenged by tight funding and schedule time. Therefore, construction began as soon as possible in parallel with the continuing engineering and design efforts, and without the benefit of a prototype. As a result, changes, compromises and repairs were instituted as construction proceeded.

The first significant issue to arise during construction was the difficulty in winding the main solenoid coil. A semiautomatic winding machine with coordinated computer controlled gantry translation, tube rotation and conductor payout was modified for use in winding the main solenoid. Successful winding depended on providing a precise pitch to the windings. Control of the various motors proved difficult initially and several of the first few layers of the first magnet contained errors in the numbers of windings in the central

portion of the coil or the trim sections or both. After giving consideration to the problem it was concluded that as long as the as-built condition of the main solenoid was known it could be properly balanced by small corrections in the nearby anti-fringe field and fringe field coils.

Another significant issue to surface involved the quench protection diodes. Due to the large induction of the main solenoid, coil diodes were specified to be installed between each of the double layers of the coil. Qualification testing of the specified diodes was delayed until after construction began. Said testing revealed that the intended diodes did not have sufficient capacity to protect the coils. An alternate diode was subsequently selected and successfully qualified for use but this diode was too large to enable the ten required to be located within the available helium vessel end space, and so parts fabrication was placed on hold, and a new diode helium vessel extension was designed and fabricated below the lead end of the magnet.

Later in construction during the vertical cold test of the first cold mass it was discovered that in certain circumstances the fringe field coil could experience a significant outward axial force. The specification for the fringe field coil previously was for support only in the inward axial direction, and so during testing the fringe field coil separated from the main coil structure. The coil was independently cold tested to ensure that no damage existed, and re-assembled onto the main structure. Provisions were then made in the design of the coil support to add restraint in the outward direction during vertical cold testing and operation in the RHIC ring.

Also during vertical testing of the first cold mass an electrical short occurred. It was isolated to be in the very first coil layer, most likely in the serpentine region where conductor passes through the stainless steel support discs (this area was problematic initially, and clear improvements in installation technique were made as construction continued). By the good fortune of the design which included each double layer being spliced to the next external to the windings in the end of the cold mass, the first double layer was simply unwired from the rest and the cold mass was returned to cold test, where it achieved the needed 110% of 6 T field (6.6 T total) using appropriately higher current [3].

The most recent issue to arise, which is still under investigation at this time, is the coil performance limitation due to temperature rise as installed in the cryostat. Although the thermal analysis indicated that the use of the inner helium vessel as the coil support tube was acceptable, temperature sensors mounted to the inner (vacuum) side of the inner helium vessel measure temperatures approximately 0.5K higher than anticipated. Moreover, those same temperature sensors indicate that coil temperature increases during current ramping due to unanticipated hysteresis or other effects. A repair to eliminate this issue is possible, by reclaiming the radial space occupied by the inner heat shield and installing an inner helium vessel instead (thereby improving magnet performance at the expense of an increase to the 4K heat load or a decrease in the magnet aperture) but as installation in the ring is imminent and both magnets have exceeded 5T operation which was the minimum requirement, no plans for repair have been initiated at this time.

VIII. FIELD STRAIGHTNESS MEASUREMENT

In order to measure the straightness of the solenoid field so as to tune the corrector coils a system needed to be developed which was able to be used *in situ* in the RHIC ring. To accomplish this, a “magnetic needle-and-mirror” system was designed and built, which included a laser interferometer to send and receive signals, a carriage to house the needle-and-mirror, and a precision track to drive the carriage through the length of the 2.1 m solenoid field. This system is designed to be used in the RHIC ring but is presently being commissioned with the magnet in the test bay. Early results indicate that the performance of the system and the straightness of the solenoid field are acceptable in both the vertical and horizontal directions.

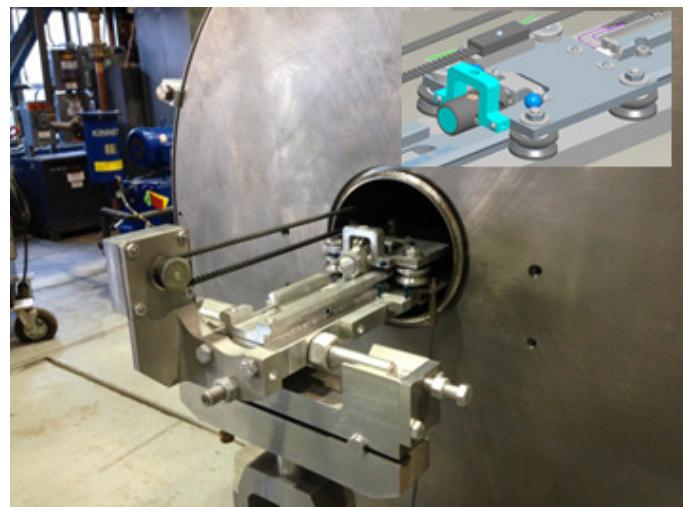


Fig. 4. Magnetic needle and mirror system installed inside e-Lens solenoid magnet; carriage highlighted in insert.

IX. CONCLUSIONS

The electron lens superconducting magnet system is a unique and complex assembly of 17 superconducting magnets, and its operation in RHIC is critical for a planned luminosity upgrade. Despite the pressures of funding and time, and the myriad of issues associated with building without a prototype, a unique, technically demanding device, two magnets have been designed and built. All magnetic elements of both magnets have been successfully tested to 110% of the operating field (6 T) in a liquid helium vertical dewar [3]. The main solenoid fields of both magnets have been tested to the minimum acceptable field (5 T). Early indications are that the magnetic field straightness and the system designed and built to measure field straightness are acceptable.

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