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Test Results for the Electron Lens Superconducting Magnets at RHIC

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***Abstract*—In order to partially compensate for head-on beam-beam effects from polarized proton collisions in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), two electron lenses (e-Lens) have been manufactured at BNL. For each e-Lens, one for each of the two RHIC rings, a low energy electron beam and the high energy proton beam will interact in a 2.5 m long superconducting solenoid, which is also accompanied by four other smaller solenoids and twelve corrector dipoles, all of which are superconducting and provide various tuning and corrective functions during operations. The design of this multi-coil assembly is a unique and complex one, and likewise, the simultaneous operation of the coils at 4.5 K is also challenging, due to high inductance and individual magnetic fields which interact with each other. This paper reports on the results from extensive ramp and quench tests at 4.5 K, and the proper operating procedures determined from these tests.**

***Index Terms*—Accelerator, electron lens, magnetic measurements, solenoids, superconducting magnets.**

I. Introduction

A future luminosity upgrade at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) will be limited by the head-on beam-beam effect due to polarized proton collisions at the interaction points IP6 and IP8. In order to compensate for this effect at IP8, two electron lenses (e-Lens) have been constructed and will be installed at IP10, with one in each ring of RHIC. Details of the e-Lens design and construction have been given elsewhere [1]-[3]. 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. For each e-Lens, a low energy (7.8 keV) electron beam and one of the proton beams (250 GeV) will interact in a 2.5 m long main superconducting solenoid, which guides and focuses the electron beam in its interaction with the polarized proton beam. In order to properly accomplish this, the field lines in the solenoid aperture must be straight to within ±50 μm and the beam width must be equal to that of the proton beam, 310 μm. The main solenoid is assembled with four other smaller solenoids and twelve corrector dipoles, all of which are superconducting and provide various tuning and corrective functions during e-Lens operation. A fringe field solenoid is installed at each end of the main solenoid with the purpose of providing a 0.3 T or greater field external to the main solenoid at each end, in order to transport the electrons into and out of the main solenoid, from and to e-Lens room temperature copper solenoids. In addition, an anti-fringe field solenoid is installed near and interior to each fringe solenoid to correct for the effect of the fringe solenoid on the main field so as to maintain the required 2.1 m uniform field region inside the main solenoid. They must be operated in reverse polarity to the main and fringe solenoids. 10 short (0.5 m) vertical and horizontal corrector dipoles and 2 long (2.5 m) vertical and horizontal corrector dipoles are mounted on a separate coil form outside the main solenoid. The short correctors keep the electron beam straight to within ±50 μm by correcting construction errors in the main solenoid that cause deviation of the field lines from straightness. The long correctors are angle correctors that help to align the electron beam with the proton beam. In total, there are 17 magnets with 17 separate power supplies in the e-Lens superconducting magnet system. Table I gives the magnet system parameters relevant to the 4.5 K testing to be described in this report. Table II gives the dimensions of the solenoid coils.

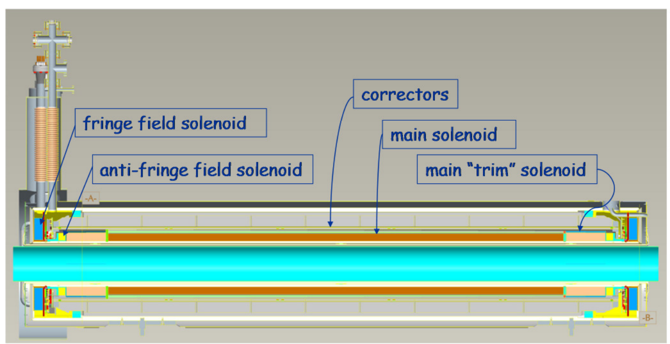

Fig. 1. Cut-away drawing of the e-Lens superconducting magnet system.

Due to the unique and complex nature of the e-Lens superconducting magnet assembly, it was necessary to design a test program not only to verify acceptable mechanical and electrical integrity and magnetic field quality at 4.5 K, but also to determine the proper procedures to operate the magnets simultaneously in RHIC without quenches and false quench detector (QD) trips. The testing of the two e-Lens cold masses at 4.5 K was done at the Vertical Test Facility (VTF) of the Superconducting Magnet Division (SMD) at BNL. This report presents the results of the SMD vertical cold mass quench and ramp tests.

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TABLE I E-LENS SUPERCONDUCTING MAGNET SYSTEM PARAMETERS

Magnet Type	Number of each	L (H)	I_{op} (A)	E_{op} (kJ)	I_{max} (A)	E_{max} (kJ)
Main Solenoid (e-Lens2)	1	14	430	1294	473	1566
Main Solenoid (e-Lens1)	1	12.7	473	1397	520	1691
Fringe Solenoid	2	0.515	470	56.9	517	68.8
Anti-Fringe Solenoid	2	0.0393	330	2.14	363	2.59
Long Vert Corrector	1	0.0053	±47.6	0.0061	±53	0.0075
Long Horiz Corrector	1	0.0053	±47.6	0.0061	±53	0.0075
Short Vert Corrector	5	0.0192	±39.5	0.0150	±44	0.0186
Short Horiz Corrector	5	0.0192	±39.5	0.0150	±44	0.0186

The main solenoids in e-Lenses 1 and 2 have different parameters because 2 uses all 11 double layers and 1 uses only 10; this is explained later in the text.

TABLE II E-LENS SUPERCONDUCTING SOLENOID COIL DIMENSIONS

Parameters	Main	Fringe	Anti-Fringe
Inner diameter	200.0	206.4	206.4
Outer diameter	274.0	404.0	274.0
Length	2360	37.0	30.0
Number of layers	22	70	24

Units are mm.

II. QUENCH PROTECTION ANALYSIS

Before testing at 4.5 K, it was necessary to determine the parameters needed to insure quench protection of the superconducting solenoids. This was done by performing quench propagation calculations using the program QUENCHS, which uses an iterative calculation algorithm based on a heat balance equation that assumes adiabaticity, usually a good assumption during the initial part of the quench propagation [4]:

$$J^2(t)\,\rho(T)\,dt = D\,C(T)\,dT, \tag{1}$$

where J is the current density, D the mass density, and $C(T)$ and $\rho(T)$ are the temperature-dependent specific heat and resistivity, respectively, which are represented by averages over the conductor cross-section of all the materials in the conductor, and are modeled by coefficients in temperature region-specific power law equations. Details of the usage and input parameters of the QUENCHS program can be found in [5], [6]. All the solenoids were wound with a NbTi/Cu rectangular monolithic wire (Cu:SC = 3:1). Due to its high inductance of 14 H and relatively high operating field, the main solenoid was the main concern for protection during quenches. The quench hot spot temperature can be determined from the current and the quench integral $\int I^2 dt$ (in units of MIITs = $10^6 \cdot A^2 \cdot s$). The relationship between MIITs and hot spot temperature is given by the equation

$$\int_0^t I(t)^2\,dt \;=A^2\int_{T_0}^{T}\frac{DC(T)}{\rho(T)}\,dT, \tag{2}$$

which is derived from (1), and where A is the conductor cross-section and $I(t)$ is the time-varying current at quench. The time integral is taken from the quench start at t = 0 to the time when the current has decayed to 0. The temperature integral is taken from the initial temperature T_0, nominally 4.5 K, to the maximum (hot spot) temperature T reached at the quench start location. The results of the quench propagation calculations determined that, in order to keep the quench hot spot temperature below 350 K, the value of the quench integral must be limited to 0.5 MIITs. Fig. 2 shows a plot of temperature vs. quench integral in MIITs as calculated with QUENCHS. The calculated data have been fitted to a fourth order polynomial equation, shown in Fig. 2 and used to determine the temperature for intermediate measured values of the quench integral.

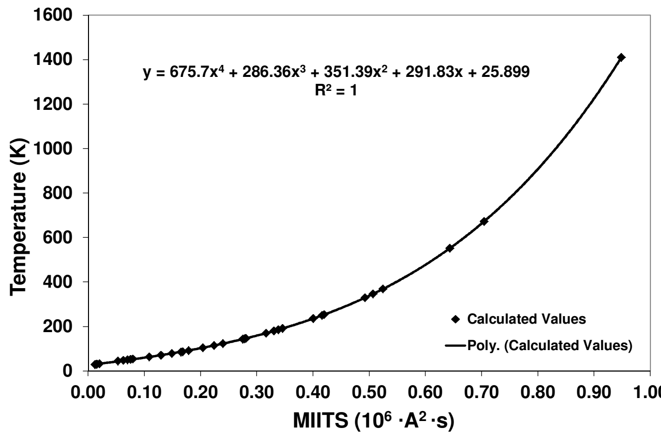

Fig. 2. Plot of hot spot temperature vs. MIITs for main solenoid.

Due to the results of the quench propagation analysis, it was decided to use cold protection diodes, pre-tested in liquid He by SMD personnel and shown to start conducting at 6 V at 4.2 K, to protect the main solenoid during a quench [7]. The main solenoid is wound in 11 double layers, with a cold diode installed in parallel to each double layer. An energy extraction circuit was also added to protect the main solenoid, and the external dump resistor was chosen to be 1.2 Ω in order to limit total voltage across the magnet to 600 V (300 V to ground with center tap) at the maximum test current. With this value of resistance, it can be shown that the time constant for current decay in the main solenoid after a quench at 500 A will result in 1.5 MIITs. To reduce the total MIITs in the coil to less than 0.5, extra copper was added to the bus work of the cold diodes. Therefore most of the stored energy of the main solenoid during a quench will dissipate as heat in one or more diodes, copper buses, and the dump resistor.

Similar calculations for quench propagation in the fringe field and anti-fringe field solenoids were done, and it was shown that no added protection other than the energy extraction circuit was necessary. Again, the value of the dump resistance was chosen so as to limit voltage to ground to 300 V. The corrector dipoles were wound with a round 0.33 mm diameter NbTi/Cu wire (Cu:SC = 2.5:1), which has been extensively used and tested at the SMD, and is well characterized. Also, since the correctors are outside the main field of the solenoids and have low inductance and stored energy, quench protection was not a concern with these, but energy extraction was installed for the correctors as well.

III. EXPERIMENTAL SETUP AND PROCEDURES

The main solenoid was equipped with voltage taps at the coil ends and between each of the 11 double layers. This allowed the monitoring of the individual double layer voltages during powering and quenches. The four smaller solenoids had end taps only. Each corrector had end taps and a center tap at the joint between the coil halves. Each superconducting lead was also monitored by adding a tap at the joint with the copper lead. The copper leads had room temperature taps which allowed them to be monitored as well. There were two silicon diode temperature sensors mounted at each end of the cold mass.

Quench detection was accomplished by monitoring the voltages of the coils during a quench. For the main solenoid, one of the inter-layer taps at the approximate center of the solenoid was used with the end taps to input the half coil voltage difference to the QD. For the fringe and anti-fringe solenoids, the difference between the lead end and non-lead end solenoid voltages for each solenoid type was used as input. For all the solenoids, the difference signal threshold voltage for tripping the QD was 125 mV. For the correctors, the QD input was the difference between the calculated $L\,(dI/dt)$ coil voltage during the ramp and the actual coil voltage. The threshold for this signal was 100 mV. The QD for the superconducting lead voltages was set to trip at 25 mV.

Each of the e-Lens cold masses was tested in a bath of liquid helium at 4.5 K and 0.131 MPa. This was done by suspending the cold mass in a hanging fixture from a stainless steel top plate that included feedthroughs for instrumentation wires, power leads, and helium input and return lines, and installing this assembly in a vertical 6 m-deep test dewar at the SMD. For the test, there were four power supplies used: the VTF 8.5 kA/20 V supply for the main solenoid, a Dynapower 600 A/20 V supply for the two fringe field solenoids in series, an identical Dynapower for the two anti-fringe field solenoids in series, and a 150 A/20 V Suncraft Model 440 bipolar power supply for all correctors in series or for individual correctors. As already mentioned, each power supply was equipped with an energy extraction circuit and an external dump resistor.

The actual test plan consisted of three basic parts. First, the main solenoid, the fringe solenoids in series, the anti-fringe solenoids in series, and all 12 correctors in series were to be individually ramped to 10% above their respective operating currents. The purpose was to verify acceptable quench-free operation for each and determine if any mechanical or electrical problems existed.

During actual operation in RHIC, the five solenoids are to be powered in combination, where the operating fields will depend on the main solenoid field strength. The fringe field solenoids are always to provide 0.3 T or greater for electron beam transport, but the fields of the anti-fringe field solenoids depend on the field strength of the main solenoid. The higher the main field, the lower is the anti-fringe field, which becomes 0 when the main is at 6 T. The correctors' operating fields will depend on the relative strengths needed to correct the main field and will of course always be operated simultaneously with the solenoids. Table III shows three primary operating scenarios, with the main solenoid field at 1, 3, and 6 T, that were used for testing purposes. After proper individual operation of all 17 component magnets was verified, simultaneous powering of the components to 110% of the operating currents, listed in the table, was to be performed according to the three scenarios in the table. The determination of the maximum allowable ramp rates and the order of powering of the component magnets needed to be done, so as to provide a guideline for successful operation in RHIC without false QD trips or quenches in any of the magnets.

The third part of the test plan was to perform magnetic field measurements of all 17 magnets. These results will be presented in a later report.

TABLE III Three Operating Scenarios Used in Testing

MAIN FIELD (T)	MAIN CURRENT (A)	FRINGE CURRENT (A)	ANTI-FRINGE CURRENT (A)
1	71/79	470	-330
3	216/238	470	-160
6	473/430	470	0

The main solenoids in e-Lenses 1 and 2 have different currents because 2 uses all 11 double layers and 1 uses only 10; this is explained later in the text.

IV. RESULTS

For each e-Lens test, the first task was to ramp the main solenoid to its maximum test current, 110% of the maximum operating point (6 T). The main solenoid was the component of most concern considering its large inductance, stored energy, and the smaller quench margin. Fig. 3 shows the quench history during training for both main solenoids. All quenches for both originated in the innermost double layer 1, and for most quenches, the coil voltage difference signal exhibited a precursor spike, evidence for conductor motion.

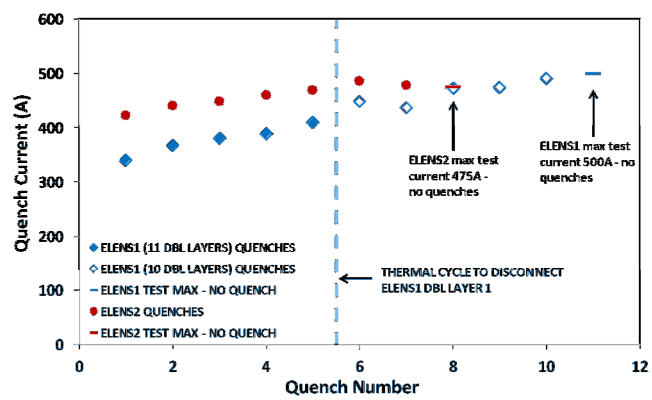

Fig. 3. Plot of quench performance for both main solenoids. Before the indicated thermal cycle, e-Lens1 had 11 double (dbl) layers, and afterwards, it had 10 dbl layers and therefore higher operating and maximum test currents than e-Lens2 (473 A instead of 430 A and 500 A instead of 475 A, respectively).

As can be seen, the e-Lens1 main solenoid exhibited relatively slower training and lower initial quench currents than the second e-Lens. At the fifth quench, a large (> 10 A) ground fault signal was seen at the power supply shutoff. The ground was not a hard ground but exhibited about 800 Ω. Electrical measurements showed that the short to ground was from double layer 1. The magnet was then warmed up and the shorted double layer was disconnected, leaving a 10 layer solenoid whose operating current had to be increased from 430 A to 473 A in order to generate the required 6 T maximum operating field. The resulting differences with e-Lens2 were detailed previously in Tables I and III.

After cooldown, quenches continued to start in the innermost double layer, now layer 2. This is consistent with the fact that the highest local field is at the inner surface of the innermost layer and at axial center [8]. After 5 more quenches, the solenoid trained to 500 A, giving a 6% margin over the 6 T operating point of 473 A. The slight fluctuations seen in quench current during training are not unexpected in a magnet assembly like e-Lens, where large forces can be generated. Repeated ramps to 500 A were done to verify stability at that level. The e-Lens2 main solenoid, benefitting from the experience of manufacturing the first one, proved to be more stable, as seen by its quench performance in Fig. 3, training in 7 quenches. In this case, repeated cycles to 475 A (110% of the 6 T current 430 A) proved to be stable.

For each quench, the quench integral in MIITs was calculated using the power supply current signal. The MIITs values ranged from 0.29 to 0.34 for e-Lens1 and 0.34 to 0.37 for e-Lens2. This is safely below the maximum 0.5 determined previously from quench calculations, as discussed earlier. Furthermore, the currents through the diodes and dump resistor were not subtracted out, so the calculated MIITs values actually represent an upper bound; temperatures were therefore significantly below the 350 K maximum allowed.

During main solenoid testing, it was determined that, due to its large inductance, the ramp rate had to be limited to 0.4 A/s or lower when being ramped upward in order to avoid generating troublesome high voltages. For down ramps, the maximum ramp rate was limited to 0.2 A/s. This was a consequence of the freewheeling diode in the power supply going into conduction at higher ramp voltages. If a faster current decay is required, a manual trip of the quench detector will switch in the energy extraction circuit and allow the current to go through the dump resistor thus bypassing the diode.

Ramp tests of the other solenoids in both e-Lens systems resulted in no quenches up to 110% of the maximum operating fields. Likewise, the dipole correctors were cycled to ±55 A without quench.

Combined operation of the solenoids comprised the next phase in testing, and initially an overly robust testing program was attempted, involving the powering of all solenoids simultaneously to 110% of their maximum operating fields. When first tried with e-Lens1, this proved to be problematic due to QD trips from large induced voltages generated by interactions between the coils and resulted in frequent trips of the anti-fringe solenoid QD and one quench of the main solenoid near 500 A. These problems were overcome by lowering the ramp rates from the initial values and ramping the three solenoid circuits alternately in steps equal to 10% of the maximum test currents. This worked well enough to successfully verify quench and trip free operation at the 1 T and 6 T field scenarios in Table III with 6% and 10% margins, respectively. For the 3T scenario, both the main and anti-fringe solenoids were at 200% of their operating fields, but the fringe was at its actual operating field. The correctors were also ramped to ± 55 A during some of these exercises without quench or false QD trips. Because of time constraints with the test of e-Lens1, it was decided that these tests were robust enough until the future retest in the full cryostat.

With e-Lens2, combination tests at the three field scenarios with 10% margin were free of quenches and QD trips. Table IV lists the ramp rates that were determined to provide stable simultaneous operations. In the case of the correctors, adjustments had to be made to QD thresholds and the value of resistance used in the calculation of the induced coil voltage being used for quench detection so as to insure QD trip-free operation to ± 55 A.

TABLE IV MAXIMUM RAMP RATES FOR STABLE OPERATION

STATUS MAGNET TYPE	ALONE A/s	COMBO A/s
MAIN SOLENOID (UP/DOWN)	0.4 / 0.2	0.2 / 0.2
FRINGE SOLENOID	2	1
ANTI-FRINGE SOLENOID	3	1
CORRECTORS	0.5	0.1

V. CONCLUSION

The electron lens superconducting magnet system is a unique and complex assembly of 17 superconducting magnets. Its operation in RHIC is critical for a planned luminosity upgrade and has to be specified by a set of procedures that allow simultaneous powering of the components without quenches and QD trips. The menu of 4.5 K tests that have been described here has determined the required procedures to successfully perform operations in RHIC and has also verified the mechanical and electrical integrity of the design and construction of both magnet assemblies and their capability to reach the required fields with margin. Both cold masses have now been installed in their stand-alone cryostats, which include a warm bore tube, multi-layer insulation, and inner and outer heat shields. Details of the full cryostat assembly and the cooling scheme can be found in [3]. Both fully cryostatted e-Lenses are now installed in RHIC and are being tested. The focus of these next tests is to repeat the tests on the cold masses in the new cryogenic environment of the cryostat to make sure that the cooling is adequate for the operations that have been described in this report, and also to perform precision measurements of the magnetic field, with an emphasis on determining field straightness, the most critical characteristic of the main solenoid.

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