A Dual 5T Superconducting Magnet System for the Brookhaven National Lab Electron Beam Ion Source

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***Abstract* – Cryomagnetics has delivered an upgraded magnet system to the Brookhaven National Laboratory's RHIC Electron Beam Ion Source (EBIS) project. This consists of two 2.25 meter long, 215 mm room temperature bore 5T Solenoids separated by 20 cm. The system features a zero boil off system design with optional shield cooler. An overview of the magnet design parameters, cryogenic design, and test results will be presented.**

***Index Terms*—superconducting magnet, electron beam ion source, zero boil off, RHIC**

I. INTRODUCTION

The primary ion injector for the Relativistic Heavy Ion Collider (RHIC) is the Electron Beam Ion Source (EBIS) [1]. RHIC accelerates beams of particles at nearly the speed of light and collides them together to recreate a state of matter thought to have existed immediately after the Big Bang some 13.8 billion years ago. The collisions reveal a glimpse of the basic constitutes of visible matter, quarks and gluons. The EBIS also produces ions for the NASA Space Radiation Facility (NSRL) to simulate cosmic rays found in space. The EBIS generates charged ions by trapping ions in an electrically charged drift tube structure inside a solenoid field. The voltages on the barrier drift tubes hold the ions, while the electron beam strips electrons off the trapped atoms. The electron beam is produced by the electron gun on one end to the collector at the opposite end. The superconducting solenoid focuses the electron beam to a compact size where it interacts with the trapped ions.

A straightforward method to increase the output intensity of an EBIS is by increasing the ionization trap length. In lieu of constructing an extended trap EBIS comprised of a single long solenoid with a uniform magnetic field, it has been deemed more appropriate to construct an extended trap EBIS by using two axially close coupled solenoids [2]. This scheme also allows the upstream solenoid to house a high efficiency gas injection cell that will facilitate injection of polarized Helium-3 and other gases. In the extended EBIS configuration the two solenoids are positioned on axis with 20 cm separation between end flanges resulting in a roughly 3600 kg force. The existing solenoid was sent to Cryomagnetics for rebuilding and a second identical solenoid was ordered. The solenoids required internal mechanical reinforcement to handle the added loads due to the magnetic interaction and no loss of helium during operation. The two solenoids have been delivered and have met all operating requirements. They are being operated in the EBIS Test area for development and testing of the new EBIS. This is seen in Figure 1 below.

Fig. 1. Two Solenoids in the EBIS Test Area at Brookhaven National Lab.

II. MAGNET DESIGN

One magnet had previously been fabricated and delivered to BNL but required a new cryostat due to the additional force now imposed by the second magnet. The old magnet was removed from the previous cryostat and set aside. A second solenoid was then manufactured identical to the first. Brookhaven National Lab (BNL) had previously specified the field profile and design parameters for the original solenoid.

Each magnet system consists of a 267 mm ID by 1940 mm long NbTi solenoid split into three sections, for quench protection, to produce the 5 Tesla field with the required homogeneity. Trim coils are used to maintain the field homogeneity requirements around the splits in the solenoids. The specifications for the magnet system are shown in Table I.

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TABLE I
MAGNET SYSTEM DESIGN SPECIFICATIONS

DESCRIPTION	Specification
Normal Operating Field	5.0 Tesla
Maximum Operating Field	5.5 Tesla
Field Homogeneity	±0.5% over ±750 mm
Field at ± 1000 mm	≥ 2.5 Tesla
Field Falloff Shape	Monotonic
Field Decay (persistent)	≤ 1.0 ppm/hr
Superconductor	Twisted Mulifilamentary NbTi/Cu
Coil Winding Tolerance	Cylindrical to 0.3 mm
Magnetic Field to Warm Bore Concentricity	≤ 1.0 mm
Quench Protection	Passive - adiabatic using copper matrix and diode protection
Cryogenic Cooling Method	Liquid Helium only with Zero Boil Off
Cryostat Design	Designed per ASME section VIII div 1
Room Temperature ID	215 mm
Maximum Length	2250 mm
Minimum Separation	200 mm

The magnetic design was accomplished using Cryomagnetics in house software which has been validated on magnets for over 30 years. This code calculates field profiles, peak fields, operating current and critical current ratios, strain levels, forces on coils, as well as the peak temperatures and voltages during a quench. The stored energy of each magnet at 5.0 Tesla is approximately 1.3 MJ while at 5.5 Tesla it is approximately 1.5 MJ. The inductance of each magnet is 350 Henries. The field profile for both magnets at 200 mm separation is shown in Figure 2.

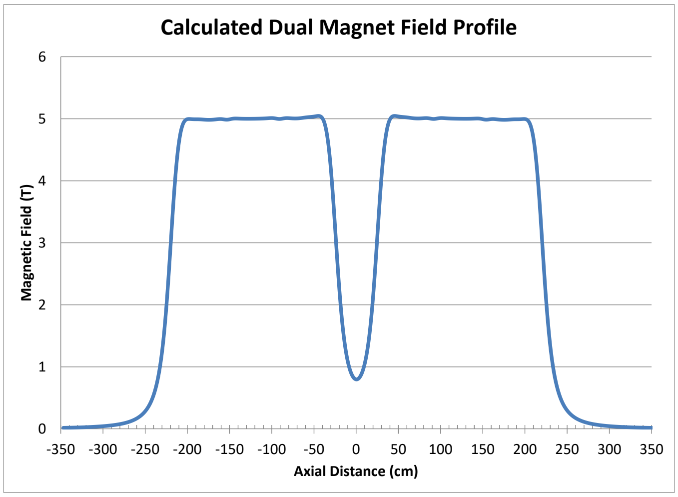

Fig. 2. Calculated Dual Magnet Field Profile.

The coil was wet wound with epoxy directly onto the approximately 2.0 meter long stainless steel bobbin which also served as the helium tank's bore tube and end flanges. Superconducting joints were made between coil sections and subdividing diodes were added for quench protection. A persistence switch was installed across the entire solenoid. An emergency quench heater was installed so that the magnet could be quickly quenched if any emergency situation arose which required a discharge of the magnet within a few seconds. The completed solenoid is shown in Figure 3.

Electrical resistance checks were carried out during the manufacturing to ensure no shorting of the turns occurred during the winding and finishing process. Once this was complete the magnet was delivered to the assembly area to be integrated into the cryostat.

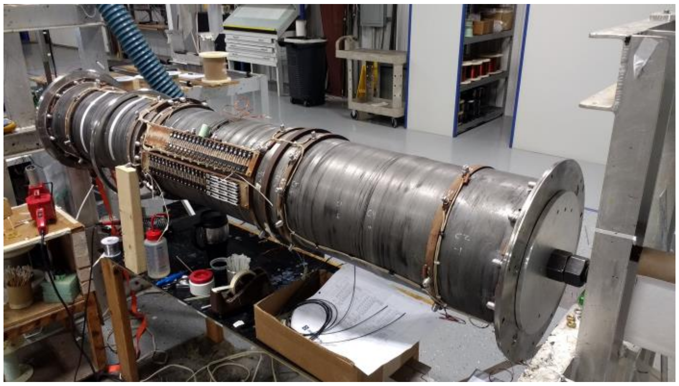

Fig. 3. Completed Solenoid.

III. CRYOSTAT DESIGN

The cryostat design is a recondensing, or zero boil off, liquid helium cooled magnet. A Cryomech PT415-RM cryocooler was used to cool the shields and the helium recondenser. Included in the design was an option for a second, single stage, cryocooler to be added. This was due to the fact that the original magnet would recondense for several months but later slowly lose recondensing margin. The root cause of this was never fully acertained and was not due to a helium leak; however, to avoid this happening in the new system and due to its expected higher refrigeration requirements, a stack for a second cryocooler was added to the design and would be installed if needed. A Sumitomo CH110 cryocooler was selected for this due to its high heat lift and low cost.

The helium vessel of the system was constructed from 304/304L stainless steel and had a volume of approximately 115 liters. Redundant helium level sensors were installed in the helium tank. The helium tank shell, bore tube, and end-plate thickness were designed according to ASME Section VIII division II pressure vessel code requirements.

The 80 K and 10 K shields were constructed of 1100 series aluminum with 6061-T6 aluminum reinforcements to carry the load. FEA was performed on the shields to ensure minimum deflection under the magnetic force as well as sufficient safety factors for the mechanical stresses in the axial and radial supports.

The outer vacuum vessel was also constructed from 304/304L stainless steel per the ASME code. The previous magnet system used only a single cryocooler but due to the issues The cryocoolers are installed in the vacuum space in separate stacks which can be disassembled if needed for cryocooler access. The Cryomech PT415-RM is connected to the 80 K shield at the first stage, 10 K shield via a clamp on the regenerator, and copper recondensing surface in the helium can at the second stage. The Sumitomo CH110 cryocooler is capable of 200 Watts at 77 K that is connected to the 80K shield only.

A third stack contained the quench relief port and magnet wiring such as helium level sensors, temperature sensors, persistent switch heaters, and voltage taps. Two 27.5 kPa Cryomagnetics' designed constant force quench relief valves were installed on this helium quench port stack as well as a 96.5 kPa ASME certified burst disk for backup.

Mechanical alignment of the magnetic axis to mechanical axis is accomplished via four adjustment mechanisms on each end. These mechanisms allow the cold mass to move relative to the outer vacuum vessel. Rigid connection points such as the cryocoolers have thermal strapping in the cooling path to allow for movement. The quench port has bellows for the same purpose.

A second ASME certified burst disk was installed on the outer vacuum can's vacuum space. Redundant temperature sensors were installed on the 1st and 2nd stages of the cryocooler, 80K shield, and 10K shield. Additional redundant temperature sensors were installed on the top and bottom of the magnet so that liquid nitrogen precooling and removal could be monitored. Table III shows the calculated heat loads of the system. The 10K shield was ignored and all heat from 80K was assumed to be incident upon the 4K surface.

TABLE III
CRYOSTAT HEAT LOADS

Description	Heat Load
80K Shield – 41.9 Watts Calculated	
Radiation	24.2 Watts
Axial Supports	1.9 Watts
Radial Supports	2.7 Watts
Current Leads (Full Current)	11.9 Watts
Quench Bellows	0.8 Watts
Gaseous Helium Conduction	0.4 Watts
4K – 1.25 Watts Calculated	
Radiation	0.53 Watts
Axial Supports	0.17 Watts
Radial Supports	0.06 Watts
Current Leads (conduction only)	0.15 Watts
Quench Bellows	0.10 Watts
Wiring (300K to 4 K)	0.20 Watts
Gaseous Helium Conduction	0.04 Watts

IV. TEST RESULTS

A. *Cryogenic Test Results*

The original magnet was installed in a new cryostat and cooled down in September 2017. A single Cryomech PT415-RM was used to cool the system on the first cool down. The system successfully recondensed and initially showed a recondensing power margin (heat applied to the cold head 2nd stage to maintain positive pressure in the cryostat) of approximately 0.10 Watts. It also showed a slight decrease in efficiency over the one month initial operating period along with a slow increase in shield temperatures. At this point the Sumitomo CH110 was ordered and the system warmed so that the cryocooler could be installed.

While waiting on the new cryocooler to arrive, the second, new magnet, system was completed. Once the second cryocooler arrived it was installed and the system was cooled down. This cool down is shown in Figure 4. Note that the magnet was precooled with liquid nitrogen immediately upon the start of the cool down.

Liquid nitrogen removal was at the 20 hour mark and took approximately one hour. The cryocoolers were started at 21 hours into the cool down process and run until the shields were near operating temperature as this lowers the amount of helium required for filling. The liquid helium fill occurred at 169 hours and required approximately 230 liters. At 197 hours into the cool down, the system had stabilized and was loss free. This time the recondensing power margin of the system was much higher at approximately 0.6 Watts with no signs of long term instability.

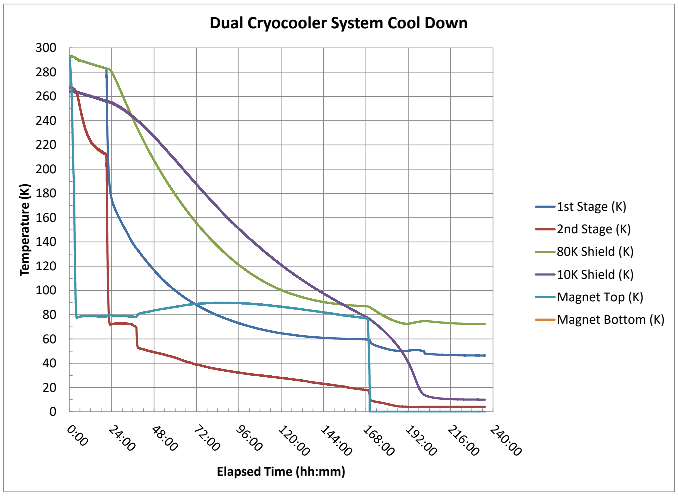

Fig. 4. Dual Cryocooler System Cool Down.

The original magnet was then retrofitted with the second cryocooler and cooled down. The magnet now operated with temperatures slightly better than the second magnet with a recondensing power margin greater than 0.8 watts. Again, no signs of long term degradation were seen in either system. A comparison of the single and dual cryocooler temperatures is shown in Table IV.

TABLE IV
SINGLE AND DUAL CRYOCOOLER SYSTEM COMPARISON

DESCRIPTION	Single Cryocooler System	Dual Cryocooler System
1st stage temperature	67.6 K	46.4 K
2nd stage temperature	4.19 K	4.11 K
80K Shield temperature	106.0 K	72.2 K
10K Shield	12.9 K	9.9 K
Recondensing pressure	5.2 kPa	3.4 kPa
Recondensing Power Margin	0.10 W	0.6 W

B. *Single Magnet Test Results*

The old magnet was the first system to be cooled down. It was charged to 5.0T and locked at field with no issues. The inductance of the magnet was measured as approximately 350 Henries based on the charge voltages. After stabilizing the drift was measured with a NMR meter and measured to be less than 0.03 ppm/hr. An on axis hall probe scan was used to verify the field uniformity. The field uniformity was measured as ±0.24% over the ±75 cm on axis region. The field profile typical of a single magnet is shown in Figure 4. The magnetic alignment versus mechanical alignment was measured by the use of a radial hall probe mounted in the bore at the point of maximum radial field on each end of the magnet. The magnet was aligned to within 1.0 mm of the mechanical axis at each end of the magnet with the use of adjustment mechanisms which were integrated into the cryostat.

Once the new magnet was cold and stable, the magnet was charged first to 5.0T then later to 5.5T (the new magnet required a 110% field test). No training quenches occurred. It's field profile and drift rates were also measured and found to be within specification. The drift rate of this magnet was 0.13 ppm/hr. This magnet was also aligned relative to the mechanical axis to within 1.0 mm at each end as before.

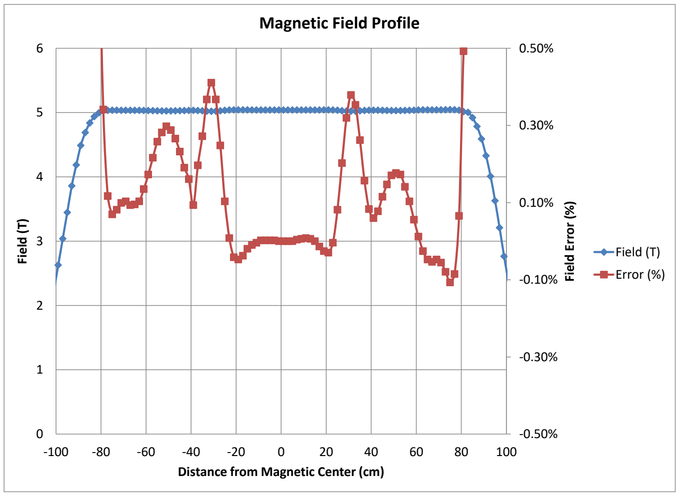

Fig. 4. Magnetic Field Profile.

C. *Dual Magnet Test Results*

Once each magnet was tested individually, both magnets were bolted together with 20 cm aluminum. This configuration is identical the one shown in Figure 1. Both magnets were charged together to 5.0T and had their persistent switches locked. The alignment at the open ends of the magnet was checked and found to still be within the 1.0 mm specification. An axial scan was also done between the magnets to verify field fall off and minimum field value.

A quench test was performed on the new magnet via the emergency quench heater. The new magnet quenched as expected and the old magnet did not quench. The peak pressure of the LHe chamber during the quench test was approximately 55.2 kPa well below the burst disk rating of 96.5 kPa.

The current in the old magnet was brought back up plus an additional one half percent to account for the induced current from the quench and persistent switch turned on. The new magnet was then charged back to 5.0T with no quenches and both were locked at field.

The old magnet was then forced-quenched like the new magnet. As before, the neighboring magnet did not quench. The peak pressure measured during the quench test in this magnet was approximately 62.0 kPa and again the burst disk did not rupture.

V. CONCLUSION

A dual 5T superconducting magnet system for the BNL electron beam ion source at RHIC has been manufactured, tested, and delivered.

The initial design used a single cryocooler, however, an additional shield cooler was added during the testing process to improve the recondensing abilities. The magnet system meets all the specifications and has been successfully charged, aligned, and quench tested.

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