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The Design and Fabrication of a 6 Tesla EBIT Solenoid

M. A. Green[a], S. M. Dardin[a], R. E. Marrs[b], E. Magee[b], S. K. Mukhergee[a]

a Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA
b Lawrence Livermore National Laboratory, Livermore CA 94551, USA

Abstract An electron-beam ion trap (EBIT) experiment allows one to strip virtually all of the electrons from a heavy element such as uranium in a device that is not much larger than a table top. Key to trapping the highly stripped ions is a superconducting magnet. The 6 T solenoid built for the Livermore EBIT experiment uses a modified Helmholtz coil design. The 6 tesla field region must be about 230 mm long and about 50 mm in diameter with a field uniformity of about one percent. Because the electron beam and the trapped ions are observed from the outside, gaps between the solenoid coils must be provided. The 6 T EBIT was fabricated from a Nb-Ti conductor with a copper to superconductor ratio of 1.8 and a critical current density of 3100 amperes per square mm at 4.2 K and 5 T. The conductor is a 55 filament conductor with a matrix diameter of 0.75 mm. The solenoid consists of four separate coils with holes for trapped ion observation between them. The solenoid will operate at a relative low current in persistent mode cooled by liquid helium in a 50 liter storage dewar. This report describes the design and fabrication of the 6 tesla EBIT solenoid for the Lawrence Livermore National Laboratory.

1. Introduction

Ions with energies of few electron volts are usually associated with the light elements such as hydrogen, helium or lithium. These atoms are part of a sequence of ions that have the same number of electrons but different nuclear charges. An ion near the end of such a sequence might be a uranium nucleus with one or two electrons. Atomic physics and other applications for highly charged ions are receiving increased attention[1]. Very highly charged ions are interesting objects, that play important roles in hot plasma, such as those in astrophysical x-ray sources, or controlled fusion devices. If the energy of these ions is low, they can interact with surfaces in surprising ways that may have applications in nano-technology.

Production of very highly charged ions is extremely difficult. One method for achieving such production is by directing a relativistic heavy ion beam from a large accelerator into a stationary foil target. This method is used at the Gesellschaft fur Schwerinenforschung (GSI) in Darmstadt Germany or at the Bevalac (before it was shut down in 1993) or the 88 inch cyclotron at the Lawrence Berkeley National Laboratory (LBNL), USA.

Another method of producing ions with very few electrons is to direct a modest energy electron beam into stationary ion target. The target of trapped ions is continuously kept stripped of electrons by the beam. This method is used in an electron beam ion trap (EBIT) such as the facility at the Lawrence Livermore National Laboratory (LLNL), USA. The EBIT approach is a much less expensive method for producing hydrogen like ions of heavy elements. The new LLNL apparatus for producing highly charged heavy nuclei ions is less than three meters long. A key to trapping the heavy ions long enough to strip off their electrons is a high field superconducting magnet. The superconducting magnet that is described in this report will be the central element for an improved EBIT experiment that produces 100 times more x-ray emission than the EBIT currently running at LLNL.

2. Solenoid Requirements

The superconducting magnet is a four coil solenoid that permits one to observe the plasma at two different levels in the device. The x-ray detectors should observe the plasma with as wide a viewing angle as possible. As a result, the detectors should be located as close to the plasma as possible and the observation ports should be as large as possible. Large viewing holes means that the field within the solenoid will not be very good. There is a compromise between viewing port size and the uniformity of the field in the solenoid. The solenoid is designed with a field uniformity of around plus or minus one percent over a region that is 20 mm in diameter and 290 mm in length. The nominal central induction for the solenoid within its good field region is 6 tesla. The inside cold bore diameter of the solenoid in the central region is 127 mm. At the ends of the solenoid the cold bore diameter is reduced to 101.6 mm. The nominal outside diameter for the solenoid helium vessel is 310 mm. This allows the x-ray detectors to be placed 160 mm from the central axis of the solenoid. The viewing angle from the detector into the central region of the plasma through any one of central eight ports is about 230 mrad. There are four more viewing ports that located axially about 95 mm from the eight ports located around the central region of the solenoid.

The inside bore of the solenoid is exposed directly to the plasma. In order for the EBIT to work efficiently, the vacuum within the cold bore must be very good (about 10^{-11} torr). Since vacuum in the magnet bore must be very good and the x-ray detectors are located close to the outside of the helium temperature vessel, a standard multilayer insulation system can not be used. The helium vessel for the magnet and the dewar above the magnet is vacuum insulated with a liquid nitrogen and a gas cooled shield. The expected helium usage for the superconducting magnet is expected to be about a half liter per hour.

3. The Superconducting Solenoid as Designed

The superconducting solenoid was wound using a round conductor made from a Nb-Ti alloy that is nominally 46.5 percent titanium. The design critical current density for the superconductor is 3100 A mm^{-2} at 4.2 K and 5 T. The bare 0.75 mm diameter conductor strand contains 54 filaments Nb-Ti in a pure copper matrix with a RRR of about 100. The copper to superconductor ratio for the strand is 1.8, and the twist pitch is about 12.7 mm. The nominal diameter of the formar insulated strand is 0.795 mm.

The superconducting solenoid consists of four coils that are level wound on a bobbin made from 6061-T4 aluminum. The four superconducting coils are hooked in series and they are inductively coupled to the aluminum bobbin. The inductive coupling to the bobbin contributes to the quench protection of the magnet.

The layers of round wire conductor were wound over a layer to layer separator of Nomex paper that was 0.125 mm thick. The conductor was wound under a tension of about 125 N. When this level of tension is applied to the conductor, the Nomex paper was supposed to be forced into the regions around the wire so that its average thickness was to be reduced to 0.075 mm. The coil ground plane insulation is 1.6 mm thick sheets of fiberglass epoxy between the coil and the aluminum bobbin. The four superconducting coils were potted in an epoxy resin that cured at a temperature of 130 C.

4. The solenoid as Built

The physical and electrical parameters of the 6 T EBIT solenoid as wound are given in Table 1. When the magnet was built, the current center for the four coils moved in the radial direction outward as compared to design for the following reasons: 1) The compressed thickness of the Nomex paper between the coil layers increased from 0.75 mm to about 0.90 mm. 2) The effective thickness of the ground plane insulation under each of the four coils is slightly greater than 1.6 mm because of extra Nomex paper. The current center radius of the two central coils (coils 2 and 3) averages about 0.77 mm larger than the design value while the average current center radius for the two end coils (coils 1 and 4) is about 0.49 mm greater than design. As a result, more coil current is needed to achieve 6 T.

Table 1 Nominal Parameters for the LLNL 6 Tesla EBIT Solenoid

Coil Number	1	2	3	4
Actual Inside Diameter at 292 K (mm)	127.31	160.66	160.61	127.36
Actual Outside Diameter at 292 K (mm)	214.21	269.85	270.08	214.26
Actual Coil Length at 292 K (mm)	66.71	53.00	53.04	66.68
Number of Layers	54	68	68	54
Design Turns per Layer	88	70	70	88
Actual Number of Turns	4752	4758	4758	4752
Current Center Radial Error (mm)	0.46	0.73	0.82	0.51
Current Center Axial Error (mm)	0.01	0.05	0.03	0.03

Bobbin Length at 292 K (mm)	472.44
Bobbin OD at 292 K (mm)	304.80
Bobbin ID Center at 292 K (mm)	127.00
Bobbin ID Ends at 292 K (mm)	101.60
Bobbin Mass (kg)	72.66
Total Magnet Mass (kg)	125.63
Solenoid Design Current (A)	123.12
Central Induction at design Current (T)	6.000
Peak Induction in Coil at Design Current (T)	~7.34
Good Field Length (mm)	299
Good Field Diameter (mm)	20
Field Uniformity dB/Bo (%)	1.42
Coil Self Inductance (H)	24.05
Bobbin Self Inductance (μH)	0.05
Mutual Inductance (mH)	0.934
Coupling Coefficient	0.72
Stored Energy at Design Current (kJ)	182.3

There are coil to coil differences that affect field uniformity: 1) The conductor diameter in coils 1 and 2 is slightly smaller than in coils 3 and 4. 2) The two central coils (coils 2 and 3) have two fewer turns than were called for in the original design. As a result of the increased radius of coils 2 and 3 compared to coils 1 and 4 and the missing turns in coils 2 and 3, the calculated field uniformity increased from plus or minus 0.9 percent to about plus or minus 1.25 percent along the solenoid axis. Within a region 20 mm in diameter and 300 mm long, the calculated field uniformity is about plus or minus 1.4 percent. The field uniformity can be improved by adding about 200 ampere turns on either side of the eight detectors pointing to the center of the magnet. The correction coils can be room temperature coils wound with insulated copper wire on the outside of the cryostat. Figure 1 shows the measured magnetic induction at room temperature as compared to the calculated induction with the coil at 0.528 A.

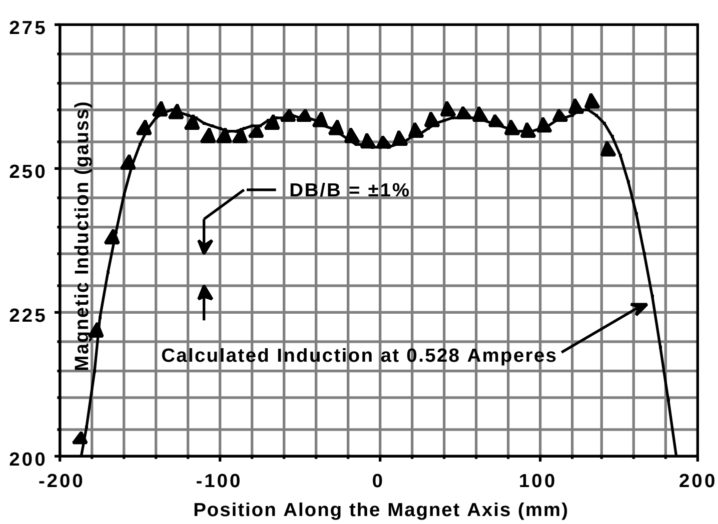

Figure 1 A comparison of Measured and Calculated Field Profiles

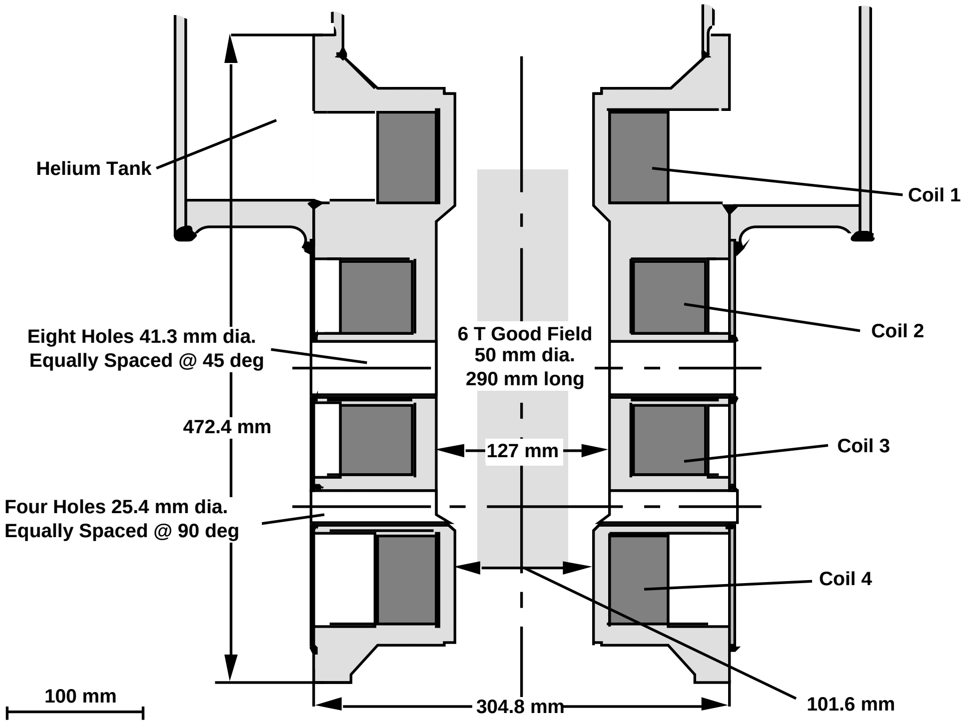

Figure 2 A cross-section of the 6 Tesla EBIT Solenoid

5. Cooling the EBIT Magnet

A cross-section of the EBIT solenoid is shown in Figure 2. Three of the coils are located below the bottom of the helium tank. The space on the outside of the coils between the coil surface and the helium vessel skin is filled with liquid helium. The helium filled spaces are connected by eight axial slots that are 12.7 mm deep by 25.4 mm wide. One of these slots contains the superconducting leads for the four coils. A second slot contains a feed pipe that carries liquid helium from the dewar feed tube to the bottom of the magnet (coil 4). The other six slots are used to circulate helium between the 50 liter helium tank and the space around the four coils. The bottom of the dewar between coils 1 and 2 serves as a platform for the superconducting splices between the four coils and the persistent switch. The bottom of the dewar liquid level gauge will be located just above top of coil one. With the use of a persistent switch, the current decay rate for the EBIT solenoid is expected to be less than 10^{-5} parts per hour. The design boil off rate for helium dewar is 0.4 liters per hour when the gas cooled electrical leads are retracted and the magnet is operated in persistent mode. It is expected that one can operate the magnet for five days without filling the dewar or recharging the magnet.

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{1] R. E. Marrs, P. Beiersdorfer, and D. Schneider, "The Electron Beam Ion Trap," Physics Today, p 27, October 1994

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