Overview of Hall D solenoid refurbishment and testing

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1 Overview

The solenoid magnet provides a 2.2 T magnetic field parallel to the beam direction at the center of the magnet. The inside diameter of the magnet is 185 cm and its overall length is 465 cm. In the configuration for Hall D, the inductance of the coil is 26.2 H, and the magnet will run at the nominal current of 1500 A resulting in a stored energy of 29.5 MJ. The iron and coil configuration is shown in Fig. 1 with the calculated magnetic field lines superimposed. The magnet was designed and built using standards that today would be considered very conservative. It is a cryostatically stable design and uses cryostats that were designed to be opened and serviced with hand tools. The magnet in its original configuration and use at SLAC are described in the technical note of Ref. [1]. Table 1 summarizes the important magnet parameters.

The solenoid is constructed of four separate superconducting toroidal coils and cryostats. A 306 ton iron flux return path, similarly split in four places surrounds and supports the coil assemblies. A common liquid helium reservoir is located atop the solenoid providing the gravity feed of the liquid to the coils. Full access to the interior is provided from both ends of the magnet for installation and maintenance of detectors.

The superconductor is a stabilized, composite, twisted multi–filament wire of niobium–titanium. The wire is made by soldering the superconductor composite between two copper strips to form a rectangular cross section 0.763 x 0.533 cm$^2$ [2]. The coil was wound directly on the cylindrical inner wall of the liquid helium vessel. As the coil was wound, a 0.025 inch-thick stainless steel support band and two 0.0075 inch-thick Mylar insulating strips were wound along with it for mechanical support and insulation. Cooling by the liquid helium is accomplished from the edges. Each of the four toroidal windings has its own predetermined number of turns, the configuration originally being selected for optimum central field homogeneity.

Each liquid helium vessel is surrounded by a liquid nitrogen cooled radiation shield and this assembly is centered in the vacuum tank by a circumferential series of tie bolts designed for minimum conductive heat flux to the helium cryostat. Radial centering and support are achieved by adjusting screws built into the four tie bolts.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central field</td>
<td>2.2 T</td>
</tr>
<tr>
<td>Operating current</td>
<td>1500 A</td>
</tr>
<tr>
<td>Total stored energy</td>
<td>29.5 MJ</td>
</tr>
<tr>
<td>Inductance</td>
<td>26.2 H</td>
</tr>
<tr>
<td>Inside diameter of coils</td>
<td>203 cm</td>
</tr>
<tr>
<td>Clear bore diameter</td>
<td>185 cm</td>
</tr>
<tr>
<td>Overall length (iron)</td>
<td>495 cm</td>
</tr>
<tr>
<td>Outside iron diameter</td>
<td>376 cm</td>
</tr>
<tr>
<td>Total iron weight</td>
<td>306 T</td>
</tr>
<tr>
<td>Total magnet weight</td>
<td>350 T</td>
</tr>
<tr>
<td>Max force on axial tie bolts due to magnetic forces</td>
<td>7500 lb</td>
</tr>
<tr>
<td>(coil 2 at 1100 A)</td>
<td>(25,000 lb rating)</td>
</tr>
<tr>
<td>Total Helium volume (including reservoir)</td>
<td>4,000 l</td>
</tr>
<tr>
<td>Helium heat load (refrigeration)</td>
<td>38 W</td>
</tr>
<tr>
<td>Helium system electrical lead flow (liquefaction)</td>
<td>0.2 g/s</td>
</tr>
<tr>
<td>Static nitrogen load</td>
<td>30 l/hr</td>
</tr>
<tr>
<td>Liquid helium storage dewar</td>
<td>4000 l</td>
</tr>
<tr>
<td>Liquid nitrogen storage dewar</td>
<td>10000 l</td>
</tr>
<tr>
<td>Cool-down time</td>
<td>3 weeks</td>
</tr>
<tr>
<td>Ratio of copper to superconductor in composite</td>
<td>20:1 (Grade A)</td>
</tr>
<tr>
<td></td>
<td>28:1 (Grade B)</td>
</tr>
<tr>
<td>Total conductor length</td>
<td>35.8 km</td>
</tr>
<tr>
<td>Total conductor weight</td>
<td>13.2 T</td>
</tr>
<tr>
<td>Turn on time (normal)</td>
<td>1.5 h</td>
</tr>
<tr>
<td>Turn off time (fast dump)</td>
<td>20 min</td>
</tr>
<tr>
<td>Dump resistor</td>
<td>0.072 Ω</td>
</tr>
<tr>
<td>Number of turns</td>
<td>4608</td>
</tr>
</tbody>
</table>

Table 1: Summary of characteristics of the solenoid in the Hall D configuration.
Selected tie bolts are instrumented with strain gauges to measure the forces on the assembly caused by magnetic fields.

The liquid helium volume is about 5000 liters and the heat load is estimated at 60 liters/hr equivalent. The volume of LHe for each coil is as follows: 1150 l (coil 1), 560 l (coil 2), 610 l (coil 3), and 460 l (coil 4). Refrigeration is provided by a CTI Cryogenics Model 2800 4.5 K helium refrigerator, which can deliver a linear mix of up to 200 W refrigeration or 2 g/s liquefaction. This conservative design, both of the refrigeration system and of a superconductor itself, has produced a stable, reliable and safe superconducting magnet.

2 Brief history

The superconducting solenoid was built in the early 1970’s for the LASS detector at SLAC. It operated at SLAC for experiment E-135 in 1981 and 1982 (see for example Ref. [3] and references therein). The experiment used all four coils, labeled as 1–4, a designation that we continue to use for Hall D even though we will use a configuration with a different order for the coils. The nominal central field for LASS was 2.24 T for a current of 1600 A\(^1\), although the magnet was originally designed to operate up to 1800 A.

\(^1\)Steve St. Lorant, original designer and magnet reviewer recalled that the magnet was not run above 1250 A, but the literature specifies operation at 1600A.
The solenoid was moved to LAMPF at Los Alamos National Laboratory (LANL) in 1985, where it was used for the MEGA experiment. The production data for MEGA was collected between 1993 and 1995 (see for example Ref. [4] and references therein). This experiment only used coils 1–3 and coil 4 was kept in storage until the present refurbishment effort for Hall D. The central field was 1.5 T operating at a current of 1178 A.

The solenoid was inspected in April 2000 by a team consisting of JLab staff and two of the original designers of the magnet, John Alcorn and Steve St. Lorant. The team concluded that the coils had been kept in excellent condition and decided to transfer the magnet to Jefferson Lab for use in the GlueX experiment in Hall D at Jefferson Lab. The magnet was transferred to the Indiana University Cyclotron Facility (IUCF) in October 2002 to refurbish the coils in preparation for use in GlueX. Upon completing work on coils 1, 2 and 4, these were transferred to JLab in summer of 2005, where the refurbishment effort continues. The yoke rings and iron end pieces were moved to JLab in October of 2006. The final closure of coil 3 is presently underway at IUCF.

3 Modifications and repairs

We briefly describe the changes and repairs that are being made to the magnet for its use in Hall D. These include changes to a) the configuration of coils and yoke, b) refurbishment, c) repairs of shorts to ground, d) new cryogenic system and controls, and e) compliance with new pressure safety guidelines.

3.1 Configuration of coils and iron yoke

There are several changes to the configuration of the coils and iron yoke which have been implemented to the magnet for use in Hall D. The major changes are the following:

1. enlarging of the upstream mirror plate to a diameter of 185 cm for ease of accessing detectors inside the bore,

2. switching the positions of coils 1 and 2, resulting in a coil configuration from upstream to downstream of (2,1,3,4). This change together with the addition of 3” iron baffles between coils 2 and 1, 1 and 3, and 4 and the downstream yoke reduces the axial forces on the coils.

3. adding iron at strategic locations to reduce saturation of the iron and reduce the fringe field of the magnet. The added iron includes cladding on the exterior surface of the yoke covering about 75% of the area, and increasing the length of the downstream iron ring by 6”.
3.2 Refurbishment

The refurbishment effort consisted of repairs and maintenance that did not require opening the helium vessel or work directly on the coils. It included finding and repairing the numerous leaks that have plagued the solenoid during previous operation. Coils 1, 3 and 4 had leaks in the nitrogen circuits and coil 2 had a leak in the Liquid Helium vessel. All of these were repaired at IUCF, with coil 3 requiring the replacement of its nitrogen shield. After repairs, all circuits were checked to have leak rates below $10^{-8}$ torr-liter/s.

The shield thermometry, which originally was based on thermocouples, was replaced with more accurate and modern PT-102 Platinum resistance thermometers, which are now the industry standard. We note that the carbon resistor thermometers inside the helium vessels, to check LHe levels, have been checked and retained. The coil support strain gauges were all replaced as many of the originals had failed over the years. Finally the multi-layer super insulation, which had deteriorated from previous maintenance and operations with oil diffusion pumps was replaced. During the course of this maintenance work, corrosion was discovered in some internal plumbing and all four 18-inch coil junction bellows. These have all been replaced.

3.3 Shorts to ground and repairs inside the helium vessels

Repairs inside the helium vessel were necessary to fix shorts to ground and reinforce the supports of sub-coils within coil 2. The first short to ground in the magnet developed in coil 4 at SLAC in 1973. This short was traced to a failure of the ground insulation between the titanium springs and the stainless axial straps and between the stainless straps and ground. Coil 4 was fixed by opening it and inserting G-10 strips between the coil and the stainless straps. After the repair all four coils passed hi-pot tests.

Shorts to ground were noted in 1986 in coil 3 ($\sim 0.1$ Ω) and in coil 1 ($\sim 25$ Ω), and were presumably present during the operation of the solenoid for the MEGA experiment. After arrival at IUCF all coils were re-measured. Coil 3 confirmed the same hard short to ground, and coil 1 had an observed short of 1.85 Ω to ground. Both shorts were found at the same locations as the ones measured at Los Alamos\textsuperscript{[5].\textsuperscript{2}} During repairs it was also determined that these shorts were due to a similar mechanism as that of the first short found in coil 4 and fixed at SLAC years earlier. There are two locations in each coil where such shorts to ground can develop, for a total of eight in all coils. Four locations have been shored up, corresponding to the downstream end in each coil. The short in coil 3 was fixed at IUCF and the short in coil 1 was fixed at JLab.

\textsuperscript{2}A logbook page from 1975 indicates that a 25 Ω short in coil 1 was observed at SLAC. The location seems to be different from the short found in coil 1 but this may simply be a case of confusion over different definitions of coil polarity.
One final operation was needed that requires opening one of the helium vessels. The force analysis for the new Hall D coil configuration found that sub-coils within coil 2 lacked adequate support. Therefore, additional buttressing is being added to this coil to solidify the structural support, which is an ongoing task at JLab. The helium vessel was opened, a repair strategy has been devised and the repair is waiting for supports to be fabricated. Upon exposing the coil, it was found that the steel strip had shorted to ground, but it has now been isolated. Therefore, there are no longer any shorts to ground in any of the four coils.

3.4 Cryogenic supply and control system

The cryogenic interface and control system for the magnet is completely new and based on proven designs currently in use on seven different SC magnets at JLab. The JLab cryogenic supply system delivers liquid nitrogen (LN2) at 77K and 3 psi, and supercritical He at 4.5K and 3 atm. Liquid He (LHe) is made in situ via expansion of the supercritical He through a Joule-Thompson valve.

The solenoid cryogenic system consists of a “cryo can,” containing a Joule-Thompson valve and small internal LN2 and LHe reservoirs, sitting on top of a “cryo box” containing large internal LN2 and LHe reservoirs. The external cryogen supply and return lines connect to the cryo can, which then feeds the cryo box and receives return gases from the box. LHe is made in the cryo can. The box distributes the cryogens to the four coils, receives the return gases from the coils and feeds them to the cryo can for return to the JLab cryogenic supply system.

The control system is based on Allen-Bradley PLC’s, chosen due to the extensive experience with this PLC line at JLab. This modern control system replaces the original manual system used for LASS and MEGA, allowing for PLC-based feedback control loops. This eliminates the need for very large cooling capacities and reservoirs which were necessary to accommodate short-term fluctuations in operating conditions when the system was under manual control. Most of the cryogenic system is common to all four coils. Specific to each coil are valves in the cryo box that control LN2 and LHe flow from the reservoirs to the individual coil cryostats, and temperature, strain and voltage sensors within each coil. We note that hard-wired interlock systems protect all relevant components from operating outside their allowed ranges, independent of PLC control.

The solenoid is powered by a new Danfysik System 8000 Type 854 10V DC power supply and energy dump system. The supply was purchased at the same time as an identical unit for Hall C, which has run successfully for a number of years and will continue to be used for 12 GeV operations. We are working with Hall C to develop a joint strategy on spare parts, maintenance and repair.
3.5 Compliance with pressure safety guidelines

The Pressure System of the Solenoid includes both Liquid Helium and Liquid Nitrogen Circuits made of ductile stainless steel and copper. They are considered Legacy Systems built pre 10CFR851 implementation at JLab and enjoy some relaxed emphasis on material and weld pedigree. The nitrogen shield and helium piping design is robust for any overpressure scenario. However, the toroidal shaped coil vessels are made with thin flat heads and non-standard weld joints that limit rating to 30 psia. Rare failure scenarios could raise pressures in the helium vessel during an event such that rupture is possible. We reduce the Probability of the most likely scenario—loss of insulating vacuum—by armoring thin walls and using engineered controls on the vacuum valve. We reduce the Consequence Level of a failure by redefining the pressure boundary to the robust outer wall of this double wall vessel system and assuring that the outer wall is very well vented. Reduction in both Probability and Consequence Level reduces the risk code (ESH&Q 3133) to Negligible. This low code shows we fulfilled the mandate of 10CFR851 by making the system equivalently safe to the ASME Consensus codes.

4 Turn-to-turn shorts

During the process of fixing the shorts to ground, the helium cryostats of coils 1, 2 and 3 were opened and their condition was examined. Several of the copper conductors were found to be shorted to the supporting stainless steel strip, although the location of the contacts could not be identified. In addition, metal chips have been found inside the cryostats and such fragments could bypass the Mylar insulation on both sides of the steel strip to create a short between coil windings. A visible short between windings was found upon opening coil 1. However, inspection of this area suggests that it did not occur at operating temperatures [6]. This particular short was accessible and has been repaired.

Nevertheless, there remains a potential for shorts between turns inside the coil windings and their consequences need to be evaluated, especially during a quench. The report of the Lehman Review in April 2010 [7] recommended to “fully assess the risk of additional shorts, [and a] quantitative analysis of the impact of shorts and resulting over-currents and high voltages should be extended to worst case situations, such as multiple-turn shorts and low-resistance shorts.” Two possible scenarios of shorts were considered:

1. The Mylar insulation between the copper cable and the stainless steel band is broken on both sides of the band. In this case, the short is through the stainless steel band, and the worst case occurs when the contacts are directly across the band, which creates a short with a resistance at 4 K of 3.1 $\mu\Omega$. A short of this type is our main case study.
2. A copper chip with a 100 mm$^2$ cross section by-passes the stainless steel band and two Mylar strips creating a short. At 4 K, this leads to a resistance as low as 10 nΩ.

Clearly a wide range of conditions must be considered, and we give the range investigated in Table 2. We believe this set covers the limits of possibilities that could occur within the magnet. The response of the system involves an interplay between the currents induced in the electrical circuits and the cooling provided by the helium bath. The current through the short heats the adjacent area, which changes the properties of the conductor. The cable around may lose superconductivity depending on the temperature and the current. The change of the cable resistivity affects the currents distribution between the shorted turn and the rest of the solenoid.

Two independent approaches were used to simulate the response of the system to a fast ramp down of the magnet. The first, which we summarize here, is a numerical simulation of a full model of the electrical circuits and heat propagation in the coils [8]. The second made the simplifying assumption of adiabatic equilibrium for the heat transfer, and was used as a check on the full simulation [9]. Both calculations are in good agreement.

We outline the algorithm of the full numerical simulation: The cable was split into 2 cm long sectors. It was demonstrated that a finer splitting would not improve the accuracy. At each time step the following processes were simulated:

1. Modifications of the material parameters in each spacial element accordingly to the local temperatures. The cable element may switch between resistive and superconductive states depending on the local temperature, the current and the magnetic field.
2. The current distribution in the coils accordingly to the updated resistances.

3. The heat generated by the electric currents.

4. The heat flow between the adjacent elements including the flow through the stainless strips to the adjacent turns.

5. The helium cooling of two sides of the cable.

6. Updating the temperatures of all the elements at the end of the step.

The size of the time step was optimized to provide calculation stability. The calculated maximum temperature, the induced currents, estimated resistance of the shorted turn and the power dissipated are plotted in Figures 2-3 for two different time scales.

The solutions often show oscillations of the current through the short and of other variables. They result from two processes with their own time scales - the current pumping into the shortened turn, and heating/cooling of the cable involved. For the maximum calculated power deposited, about 10% of helium may evaporate from the helium vessel.

Within the range of our input assumptions, we conclude that that the maximum temperatures in the magnet could possibly reach 60 K, but that the cryogenic system should be able to control a quench under these conditions. In summary, no dangerous overheating was observed over the very wide spectrum of parameters used in these calculations.

5 Single-coil testing

The purpose of testing magnet coils individually is to verify coil cool-down calculations, check coil operation, and to check that stresses observed when the coils are energized agree with Finite Element model calculations. Each coil will be tested separately with a reduced yoke, consisting of the iron ring for that coil and the iron end pieces. Judicious placement of the iron pieces relative to the coil will create stresses in the coil that mimic those expected in the full magnet. The calculated inductance for the single-coil and reduced yoke configuration is 6.2 H. The dump resistor is being correspondingly reduced for the test to 0.022 Ω to approximately match the same voltage drop per turn as in the full magnet. Testing will be performed at the operating temperature of 4.2 K and operating current of 1500 A. All strain gauges, pressure and temperature sensors will be carefully monitored for anomalous readings.

The entire solenoid safety system will be tested during the single-coil tests. Human and equipment safety systems for the test are currently under review by the JLab EHS&Q and 12GeV Safety groups, and they have approved our safety strategy during initial discussions. Most of the cryogenic system will also be tested. PLC programming for the test is complete and ready for commissioning.
solenoid, the small number of additional sensors and actuators in the cryo box have to be added and incorporated into the control algorithm, along with integration of all four coils. Additional benefits of the test include training of installation crews and operators, early construction of rigging fixtures and development of installation procedures, and early education about and experience with solenoid operation. Without the coil tests all this would have been done for the first time in the hall during commissioning of the complete solenoid magnet.

References


Figure 2: The results of calculations of the processes in a shortened turn during the fast ramp-down through the 0.07 Ω dump resistor, shown in a time interval of 0-50 s. The calculations were made for RRR=200, a 0.01 T residual magnetic field, for a turn with a 12 μH inductance and the κ-parameter of 0.45. Plot (a) presents the maximal temperature in the cable, plot (b) presents the current through the short, plot (c) presents the resistance of the shortened turn, and plot (d) presents the power absorbed by helium.
Figure 3: The results of calculations of the processes in a shortened turn during the fast ramp-down through the 0.07 Ω dump resistor, shown in a time interval of 50-600 s. The calculations were made for RRR=200, a 0.01 T residual magnetic field, for a turn with a 12 μH inductance and the κ-parameter of 0.45. Plot (a) presents the maximal temperature in the cable, plot (b) presents the current through the short, plot (c) presents the resistance of the shortened turn, and plot (d) presents the power absorbed by helium.