Commissioning and Testing the 1970's Era LASS Solenoid Magnet in JLab's Hall D

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***Abstract*—JLab refurbished and reconfigured the LASS 1.85-m bore Solenoid and installed it as the principal analysis magnet for nuclear physics in the newly constructed Hall D at Jefferson Laboratory. The magnet contains four superconducting coils within an iron yoke. The magnet was built in the early 1970s at Stanford Linear Accelerator Center and used a second time at Los Alamos National Laboratory. The coils were extensively refurbished and individually tested by JLab. A new Cryogenic Distribution Box provides cryogens and their control valving, current distribution bus, and instrumentation pass-through. A repurposed CTI 2800 refrigerator system and new transfer line complete the system. We describe the reconfiguration, the process and problems of recommissioning the magnet, and the results of testing the completed magnet.**

***Index Terms*—Conducting materials, DC power systems, magnetic field measurement, solenoids.**

I. Introduction

THE LASS Solenoid is the principle analysis magnet for the GlueX Experiment in Hall D at the Continuous Electron Beam Accelerator Facility (CEBAF) accelerator at Thomas Jefferson National Accelerator Facility (JLab) and is shown in Fig. 1. The Hall and recycled superconducting magnet were installed as part of the 12 GeV Upgrade [1]. The magnet was built at Stanford Linear Accelerator Center (SLAC) in 1971 [2] and reconstituted for the MEGA Experiment at Los Alamos in the 1990s. JLab refurbished, repaired and individually tested the coils and modified the yoke [3]. The magnet consists of four coils in series, contained within an iron yoke. See Table I for Parameters at SLAC and at JLab.

II. JLab Reconfiguration

A. Magnetics

JLab bored the upstream yoke pole from 0.41 m dia. bore to the clear bore of 1.85 m, drastically changing the theoretical axial forces on the upstream coils. The change imposed a 107 kN compressive load toward the downstream on each of the 24 support columns of Coil 1 at design field. The support columns are rated at 71 kN.

Fig. 1. Hall D Solenoid.

Our design changes brought this force to the 22 kN range by interchanging Coils 1 and 2 and adding three 76 mm thick iron irises with a 1.85 m bore called "baffles". Two were added in inter-coil locations and one added to the upstream pole tip of the downstream yoke as seen in Fig. 2.

Local electronics around the base of the magnet yoke could be used in a fringe field of up to 5 mT. We added two courses of 0.15 m iron cylinders, called cladding, to the outside of the original yoke to stay within this value. We did not add enough cladding to bring the field in the Hall to less than 0.5 mT to make the space safe for personnel with electronic medical devices. We opted to declare that personnel with electronic medical devices are not allowed in the Hall when the magnet is on.

The original SLAC configuration of the yoke had 0.15 m gaps at the downstream ends of the four coil yokes. This space housed experimental apparatus and the coil chimneys

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TABLE I
MAGNET PARAMETERS

Parameters	SLAC	JLab
Inside diameter of coils	2.03 m	*same*
Clear bore diameter	1.85 m	*same*
Overall length along iron	4.65 m	4.79 m
Number of turns	4608	*same*
Design Current	1800 A	1500 A
Running Current	1600 A	1350 A
Operating temperature (design)	4.2 K	4.5 K
Operating temperature (actual)	4.5 K	4.5 K
Maximum central field at design current	2.55 T	2.29 T
Maximum central field at running current	2.28 T	2.08 T
Inductance at design current	22 H	26.1 H
Inductance at running current	25 H	26.4 H
Energy at design current	36 MJ	29.4 MJ
Energy at running current	32 MJ	24.1 MJ
Total conductor length	35.84 km	*same*
Total conductor weight	13150 kg	*same*
Substrate material	Copper	*same*
Copper-to-filament ratio (Conductor A)	20:1	*same*
Copper-to-filament ratio (Conductor B)	28:1	*same*
Number of separate coils	4	*same*
Longitudinal coil arrangement	1-2-3-4	2-1-3-4
Turns per coil 1 using Conductor B	1428	*same*
Turns per coil 2 using Conductor B	928	*same*
Turns per coil 3 using Conductor B	776	*same*
Turns per coil 4 using Conductor A	1476	*same*
Total helium volume (including reservoir)	3500 L	3200 L
Protection circuit limiting voltage	500 V	90 V
Protection circuit resistor	0.28 Ω	0.06 Ω
Inside iron diameter	294.6 cm	*same*
Outside iron diameter	375.9 cm	*same*

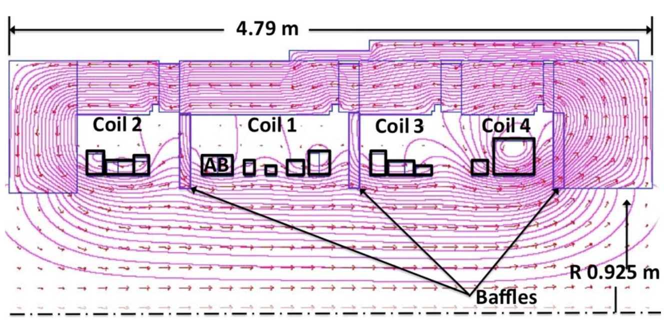

Fig. 2. Half solenoid cross section at 45° to the vertical with subcoils, the relative changes in the magnet flux density field profiles in the magnet, and yoke are shown for Hall D magnet configuration.

and vacuum vent pipes to the right side. We filled most of this gap with filler rings. The rings are subject to a 0.30 m wide interruption at the top for the vertical coil chimneys and a 0.15 m wide slot on the right side for the original vacuum vent pipes. We added balancing interruptions to the filler rings on the bottom and on the left side to eliminate unbalanced radial forces. The GlueX Experiment requires that the solenoid have a gradient in the field, peaking near the downstream end. Fortunately Coil 4 was built with double current density to give a boost to the local field. We added an additional 0.15 m of iron to the downstream yoke pole to reduce the fringe field outside the downstream end.

B. Insulation Vacuum Changes

Because of the history of leaks, we installed vacuum breaks between the four coil's insulating vacuums and the vacuum volume in the Distribution Box so one leak would not degrade the entire insulating system. We also changed the pump out location from the side vacuum vent pipes to the chimneys just above the connection bellows. The good pump out path to the internal vacuum insulation volume of the coils greatly reduces pump-out times.

A single roots type pump and a flex hose evacuates the vacuum volumes sequentially into the range of turbo pumps. We use one turbo pump on a common manifold with isolation valves at each coil to continue the pump down to insulating vacuum levels of $\leq 10^{-6}$ Torr. From this level of vacuum, leak free volumes become self-pumping when liquid helium is in the coils. The difference between the original 3 m high × 3 m long × 1 m wide SLAC vacuum apparatus and our 0.1 m dia. Turbo Pump on the common manifold is dramatic.

In the event of a rupture of the internal helium or nitrogen vessels or tubing, the vacuum vessels needed additional venting capacity. We added multiple flat plate, spring-loaded, O-ring sealed relief plates with no additional machining on the vessels as we incorporated the plates into existing access covers. The gas exhausts into regions where personnel are not exposed to oxygen deficiency hazard.

Individual vacuum gauging for each volume is resident in the chimney area where a Pirani gauge for crude vacuum and a cold cathode gauge for high vacuum are placed on a manifold with valves at the vacuum volume end and at the pump out end. Faulty gauge heads may be changed out without compromising the main vacuum volumes.

C. Cryogenics

The Helium Refrigerator is located in a separate building. The Jefferson Lab Cryo Group designed and manufactured the transfer line system from the refrigerator to the Hall and the Distribution Box that supplies cryogens to the Solenoid [4]. The system includes a U-Tube/bayonet severable interface between the two systems to allow separate debugging and commissioning. The Distribution Box also contains all control valves and all helium circuit instrument feedthroughs, houses the Vapor Cooled Leads and the current distribution bus which connects the individual coils in series. At final assembly, preplaced pull tapes allowed threading the bus conductor harnesses into the vessel, through G-10 conduits and into their final positions. The bus harnesses consist of two lengths of SSC superconductor braid combined with two lengths of #2 stranded copper wire. Pull tapes were also preinstalled to aid threading instrument wires to instrument feedthroughs.

D. Instrumentation and Control

Our instrumentation and control system uses a Programmable Logic Controller (PLC) for expert control, EPICs for operator control and a National Instruments PXI to provide fast data acquisition and analysis. Our Safety System consists of 15 hard wire or PLC elements that trip the Power Supply to a Slow Dump. Energy is dissipated through the power supply's internal circuitry. Twenty hard wire or PLC based elements, including the hard wire Quench Detector (QD), are interlocks that trip a Fast Dump. The QD compares the voltage of Coils 2 & 1 against Coils 3 & 4. A fast dump interlock trip opens a Dump Switch that severs contact between the Power Supply and coils. Magnet Current then flows through the current loop formed by a 0.06 Ω Dump Resistor and three diodes in parallel, draining the stored energy with a time constant of 7.2 minutes.

The PLC contains a Sequence Of Events (SOE) monitor feature that reveals the interlock that tripped first. Unfortunately, the SOE never worked for us during all earlier commissioning cycles because of coding and memory glitches. It is running now.

A redundant, independent monitor of current, based on a shunt, is able to open the power supply contactor above a set current. This redundant element compensates for failure modes of the Power Supply's Zero-Flux Current Transducer based current control where current limits could be bypassed.

We placed 20-turn pickup coils on the inner, upstream and downstream edges of all four coils. The PXI System, at the start of every ramp, looks for lags in pickup coil voltage signals with respect to current as a sign of turn-to-turn shorts.

E. Installation

The last coil tested individually was Coil 2 and it revealed an intermittent, ohm level short to ground. After warming up the coil, we burned the short out using capacitive discharge technique. This short was not seen in any later operation.

In order to avoid unnecessary conductor shifts, coils were left in their stand-up, final configuration while moving them about a quarter mile from a testing building to Hall D. The Solenoid's yokes and coils were mounted on two piers cast onto the Hall D floor.

III. 1st Commissioning Cycle—April/May 2013

A. Successful Ramp to 1500 A

In April of 2013, the Solenoid was filled with liquid helium. We checked out all systems and interlocks per a checklist. Immediately on turning on the Power Supply, the hard wire QD tripped. The Power Supply had not been ordered with a tune to the very large inductance of this Solenoid. Transient current pulses at power supply turn-on and start of ramp generate enough unbalanced signal to trip the QD. We solved this temporarily by adding a "momentary" switch that jumpered out the hard wire quench detector during transient periods while a person "manned" the switch.

After a nuisance trip at 1360 A, a 6 Ω short to ground appeared in the first pancake of subcoil 3B, nearly the center of the coil sets. This short is consistent with a solder ball bridging the 2 mm gap between conductor and the bare surface of the coil's support bulkhead. We can run with this one short. A second short creates transformer type loops and can lead to burn out of a coil. Detecting a second short is vital. The Power Supply's Ground Fault Detector (GFD) is "blind" to a ground fault at or near its lead's landing point on the coil. This feature allows us to mask our first ground fault but using an indirect method. We landed the GFD lead between two resistors of about 2000 Ω each. The ratio of these resistance values matches the ratio of inductances on either side of the existing ground fault. The other ends of the leads on the resistors were landed on corresponding plus and minus bus bars in the power supply. During ramping, the GFD Lead sees zero volts with respect to ground because the ratio of resistive voltages generated by the resistors matches the ratio of inductive voltages on either side of the ground fault. This virtual mask of the ground fault was successful; the GFD did not trip during subsequent ramps.

We ramped to 1500 A, stayed at that current for 20 minutes and then ramped down.

B. Quench

The next day, we ramped at a slightly slower rate. At 1460 A, the magnet quenched, dumping its energy to the dump resistor and internally to the coils. The system vented all helium through a relief valve and rupture disk. Our Fast Data Acquisition System caught the voltage tap voltages. Testing was stopped until a review allowed a go-ahead.

C. Observations on the Quench Data

Only Subcoil 1AB quenched in Coil 1 for the first 22 s while the adjacent turns of Coil 1, in the main helium chamber, remained superconducting. Helium Bath Pressure was higher at the time of quench—1.35 Atm $= 4.56$ K, rather than the 1.29 Atm $= 4.49$ K when current was 1500 A.

After 15 s, a second quench engulfed the whole of Coil 4, even though its leads are thermally isolated from Coil 1. The compressing helium had, by that time, raised the helium bath pressure to 1.44 Atm $= 4.63$ K.

Calculations show that the quench was not due to a short and that local heating did not create a low liquid level in the antechamber surrounding Subcoil 1AB. Problems with conductor damage, leads and splices are also not considered likely because of successful earlier running at 1500 A.

Our analysis shows that the conductor filament size (145 μm) is too large to inhibit flux jumps per theory [5] that was developed contemporary with our conductor's production. During ramping before the quench, voltage tap data showed small, positive voltage spikes on voltage taps of subcoils while adjacent subcoils had inverse (negative) voltage spikes. We interpreted these indications as conductor movements or flux jumps. Unfortunately, Coil 1AB's voltage tap signal was too noisy to discern a similar voltage spike at the time of quench. But no reverse voltage spikes were seen in the non-noisy data from nearby subcoils. We conclude that motion and flux jumps are unlikely candidates for the cause of the quench.

Temperature however may be a factor [6], [7]. A sample of this first generation conductor, of unknown reel number, was tested at the University of Twente to measure short sample current vs. temperature at several magnetic fields. The slope from the data is -1000 A/K compared to -414 A/K for specification

TABLE II
EVALUATIONS OF THE CAUSE OF THE QUENCH

Fault	Evaluation
Short Developed	No
Problems at splices	Very unlikely
Conductor damaged	Very unlikely
Gas bubble exposed conductor	Unlikely
Conductor motion	Unlikely
Flux Jump	Unlikely

conductor [8], indicating heightened temperature sensitivity. Our path forward is determined by subsequent reviews [9]. The evaluations are summarized in Table II. We concluded that the clear cause of the quench would never be known. We also prefer to *not quench* again. The GlueX Collaboration has also concluded that there is no compelling physics reason to run the solenoid at the design current of 1500 A at this time. Consequently, for the foreseeable future, we will run well away from quench, at our "Running" transport current of no more than 1350 A.

IV. 2ND COMMISSIONING CYCLE—JULY/AUGUST 2013

A. Successful Limited Ramp

We installed circuitry to tune the power supply for our ∼26 H inductor and installed a programmed ramp feature in the firmware that minimizes spikes on current change. We also installed a Temperature/Current Margin Monitoring System. The PLC issues warning when the bath temperature is high enough to encroach on a 135 A margin from possible quench and the PLC trips a slow dump when a 110 A margin is breached.

The Cryo Group filled the solenoid with liquid helium—but with difficulty. The CTI 2800 Refrigerator started to plug with carbon dust abraded from the carbon beds at the very heart of its heat exchangers. The refrigerator capacity decreased drastically and blow-downs to vent the carbon accumulations were only partially successful. During blow downs, no liquid helium supply was available to the Solenoid. The Cryogenic Group augmented the refrigerator during these cycles in operation using 1000 L Dewars of LHe obtained from other sources on site.

The programmed ramp and tuning additions to the power supply worked without any problems. No voltage spikes were seen. Vexingly, fast dumps at around 1000 A plagued us. Unfortunately our attempts at fixing our SOE System failed again and we were blind to the cause of the trips. After several shifts of failed ramps, we found the cause of the trips. The Vapor Cooled Lead (VCL) helium flow controllers/meters indicated "no flow" for a fraction of a second and initiated the fast dump via their hard wire interlock. We jumpered the controllers out of the interlock system and set the helium flow to that required for maximum current by adjusting and locking the controller's isolating valves. The control system has several other methods of safeguarding the Solenoid from VCL failures, so we remained protected. The cause of this anomalous flow reading remains unexplained.

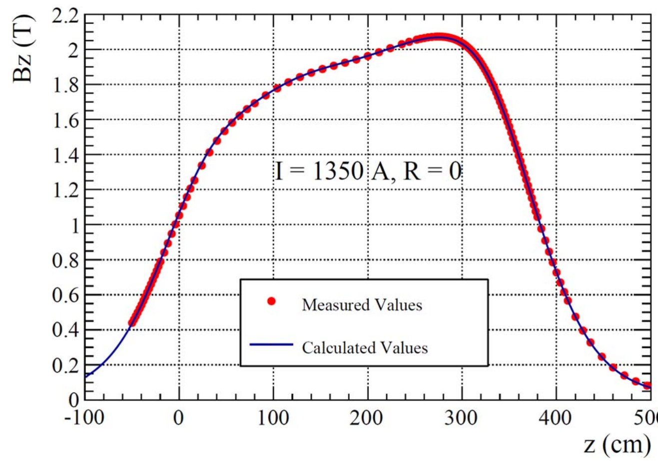

Fig. 3. Calculated and measured magnet flux density plot along the magnet bore at 1350 A.

The solenoid easily ramped to 1360 A, as the top current of a small hysteresis cycle, and was brought back to 1350 A.

B. Field Mapping

We measured the Solenoid at its central bore at 1350 A over about 3 hours. Fig. 3 shows the comparison of calculation using POISSON to the measurement data. The discrepancy is typically less than 1 part in 1000 with the data systematically lower by a few parts in 10 000. We then ramped down to 1300 A for mapping at characteristic positions throughout the bore over 18 hours. Point-to-point variations from calculated field in the central area were found to be about 1 part in 1000, while in the high-gradient area they are about 1 part in 100.

The mapping system was based on a plastic slug containing a multi-axis Hall Probe that was pushed in, by hand, to predetermined axial positions in a precision aluminum tube. The tube was positioned in the bore to a similar tolerance. A laser based distance meter of similar resolution and an accurate electronic level read out the exact position of the slug and its orientation. The aluminum tube was placed to additional, representative positions within the bore to sub mm accuracies by simple fixturing. This limited mapping is able to generate the field map necessary for Physics.

V. 3RD COMMISSIONING CYCLE—JULY/AUGUST 2014

The Cryo Group completely refurbished the refrigerator, ridding it of any carbon beds and finding that it has the capacity to cool down the Solenoid and fill it with liquid. To save time, they did augment the latest fill with two 1000 L Dewars. The Helium Bath's pressure is now 1.23 Atm = 4.45 K, 0.05 K lower than during the Solenoid's 1500 A cycle. Subsequently, the Solenoid ran flawlessly at 1200 A for 4 days in anticipation of the Fall Physics Checkout Running Period.

VI. Conclusion

The Solenoid is robust and proven to withstand a quench and fast ramp downs without damage. It runs reliably at up to 1350 A despite a higher resistance, intermittent ground fault. The lower current is now acceptable to the Physics Researchers. Recent tests show I_c is a strong function of Bath Temperature for this 1st generation conductor. The newly refurbished refrigerator yields a lower bath pressure resulting in an improved temperature margin over previous runs.

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