Conceptual Design of the JLab Hall D Replacement Solenoid

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***Abstract*—The 12 GeV upgrade at Jefferson Lab includes plans for a new solenoid that will replace the existing solenoid made with the Large Aperture Superconducting Solenoid (LASS) coils from Stanford Linear Accelerator Center (SLAC). The conceptual design for the replacement solenoid presented here includes the magnetic design, winding arrangement, conductor selection, quench detection, and protection and cooling scheme. The magnetic design implements three separate coils to provide a 3.8 T field parallel to the beam direction and addresses the fringe field requirements of the facility while integrating into the existing iron yoke. The conductor consists of Superconducting Super Collider (SSC) cable (Nb-Ti) soldered into a copper channel stabilizer. The conductor is layer wound the hard way onto individual internal mandrels. The quench protection system implements a dump resistor and switch. Results from a 3-D quench code are provided for quench initiating at different locations. The magnet is conduction cooled by natural circulation of two-phase helium through cooling tubes mounted at the Outside Diameter (OD) of the cold mass.**

***Index Terms*—Quench detection, quench protection, siphon effect, SSC cable.**

I. Introduction

A CONCEPTUAL DESIGN for a replacement solenoid for use in Hall D of Jefferson Laboratory (JLAB) is presented. An existing magnet, known as the LASS magnet [1], has been obtained and will be used for initial commissioning of the Hall D facility. The existing magnet consists of 4 individual solenoids; each is housed in a separate cryostat, and integrated into a warm iron yoke. Because of the age of the LASS coils, the intent is to integrate the existing iron yoke into a new magnet design that meets the field requirements and spatial constraints [2]. The conceptual design of the new magnet system is presented. The structural considerations are part of this study and are discussed in detail separately [3].

A self-consistent magnet design is presented and the overall design is shown in Fig. 1. The windings use the SSC cable soldered into a copper channel with sufficient cross section to provide conductor stability and acceptable temperature rise in the event of a magnet quench. The winding design is shown to meet the field requirements with a temperature margin that is in excess of 1.5 K at the peak field point of approximately 3.8 T on the conductor. The windings are conduction cooled via a cold mass cooling assembly that operates in a natural convection mode. The high operating current afforded by the SSC cable is matched to HTS current leads which are cooled with a cryocooler.

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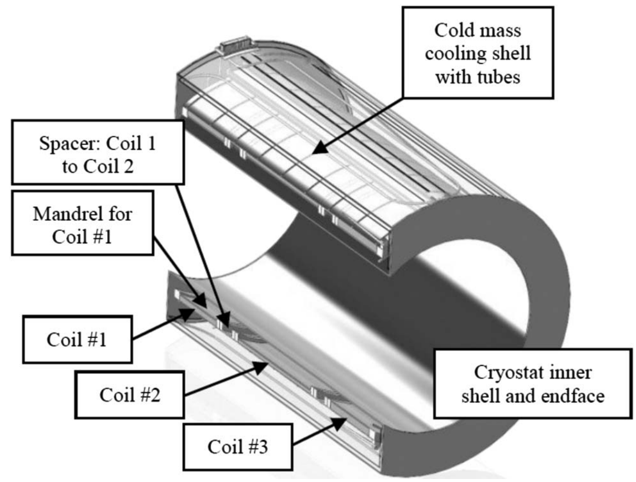

Fig. 1. Section view of the solenoid. Outer shell of both cryostat and radiation shield are transparent to view cooling shell.

TABLE I
SOLENOID PARAMETERS

Cryostat Length	3.65 m	Coil 1 turns per layer	106
Cryostat ID	2 m	Coil 2 turns per layer	208
Cryostat OD	2.9 m	Coil 3 turns per layer	110
Peak Field	3.8 T	Coil 1 number of layers	3
Temp Margin	1.5 K	Coil 2 number of layers	2
Operating Temp	4.5 K	Coil 3 number of layers	4
Hot Spot Temp	96 K	Stored Energy	32.2 MJ
Operating Current	5656 A	Inductance	2 H

II. Design Description

The solenoid design consists of the conductor selection, winding scheme and magnet design. Refer to Table I for a summary of solenoid parameters.

A. Conductor Selection

Three conductors were evaluated for the magnet design: SSC cable in copper channel, SSC cable in aluminum co-extrusion and cable in conduit conductor using new strand. Because the

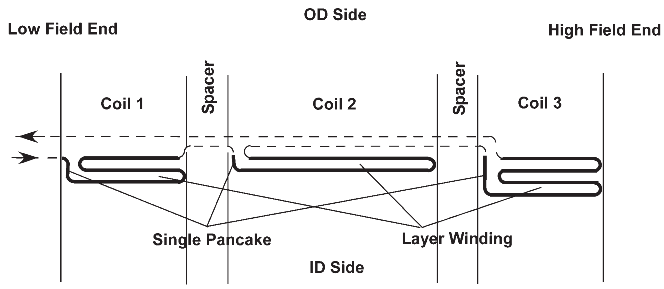

Fig. 2. Schematic of winding scheme showing each coil winding initiated with a single pancake and continuing with layer winding.

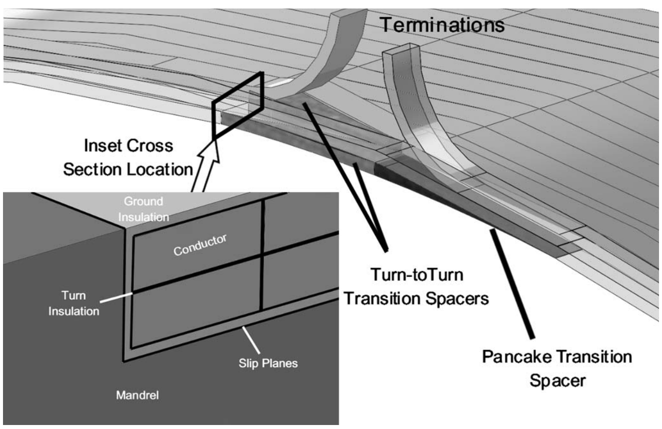

Fig. 3. Coil 2 pancake winding and layer winding along mandrel shown (mandrel is hidden). Pancake winding is transparent to display the spacers used for the pancake and turn-to-turn transitions. Inset indicates stack-up of slip plane, insulation and conductor on mandrel (mandrel is visible).

SSC cable already exists and is available at JLAB, and for other cost advantage reasons, the SSC cable in copper channel design was recommended.

SSC cable uses Nb-Ti superconductor and is described in detail in [2]. The design uses a target current sharing temperature of around 6 K. This is based on setting a nominal temperature margin in the conductor at about 1.5 K above the 4.5 K nominal operating temperature of the superconductor.

B. Winding Scheme

The magnet consists of 3 coils wound the hard way on individual mandrels connected by axial structural spacers. Hard way winding has an advantage in conduction cooled designs in that the heat removal, which is via radial conduction, goes through fewer layers of insulation. The winding is comprised of a single pancake and the rest of the coil, which is layer wound. The winding starts within each coil at the ID using a single pancake, which is wound outwards; the rest of each coil is layer wound as shown in Fig. 2. A layer of insulation installed after completing the single pancake separates it from the layer-wound part of the coil. With this winding scheme the ends of the conductor are always at the OD, and, given conductors of sufficient length, only 2 joints—between Coils 1 and 2 and between Coils 2 and 3—are required.

Fig. 3 zooms to the end of Coil 2 to demonstrate the stack-up of materials from the mandrel as well as the spacers needed for winding transitions. Slip planes between the mandrel and the winding will be arranged by covering the mandrel at its OD and the sides facing the winding with a layer of Tedlar or Mylar film. Ground insulation is installed on top of the slip planes facing the coil winding. Turn insulation will be applied as part of the winding process. Turn to turn transitions will be arranged using custom made G10 spacers and remaining small gaps will be filled with fiber glass cloth. The azimuthal position of the termination of the layer-wound part of the coil has to be arranged at certain distance from the termination of the single pancake. The termination point is the location where the outer side of the conductor crosses the OD of the winding. After finishing the winding the tails of the conductor will be bagged to prevent their contact with the epoxy during vacuum pressure impregnation (VPI). They are secured to avoid unwinding before finishing VPI and heat treatment. Ground insulation will be installed at the OD of the winding. The coil will be vacuum bagged or placed in a mold, VPI'd with epoxy and cured. After removing the bags and cleaning, the coil is ready for assembling the cold mass.

C. Magnet Design

The magnet design, and particularly the design of the cold mass, is strongly defined by the choice of the winding scheme. The conductor is designed to operate at a nominal current of 5656 A, where the current density in the superconductor is nominally 1315 A/mm^2. Conservative scaling [4] shows that the critical current density, Jc (4.5 K, 3.77 T), for this conductor is 2865 A/mm^2, so the fraction of critical current at the nominal operating current density is 0.46. The current sharing temperature using the same scaling is 6.19 K, implying a temperature margin of 1.64 K at the peak field point under the assumed operating temperature of 4.55 K. With an alternative fit [5] to $Jc(T, B)$, which is based on the average strand performance, the critical current density at (4.55 K, 3.77 T) is 3517 A/mm^2 and the fraction of critical on this basis is only 0.37. The current sharing temperature based on average strand data is 6.51 K, giving a temperature margin of almost 2 K.

With a stored energy of 32.2 MJ, the system inductance is 2.01 H. The combined copper cross section in the channel and the cable is 81.8 mm, so J_{Cu} on quench is 69.2 A/mm^2. A 70 mΩ dump resistor will provide a dump voltage of about 400 V across the magnet terminals and result in a hot spot temperature of about 96 K based on RRR 75 copper, while allowing for a 0.5 second quench detection/protection delay before activating the dump circuit.

III. Quench Protection and Detection

Since the some of the quench detection design parameters are driven by the quench protection system design, quench protection is discussed first. The quench code used here is written by the lead author and has been continually improved over more than a decade while being applied to many magnet systems, including the MECO production solenoids [6] and the MICE coupling coil [7].

A. Quench Protection

The JLAB solenoid conductor has been conservatively designed with sufficient copper stabilizer to keep the hot spot temperature in the winding during quench at values below 100 K with a simple protection scheme. The protection design requires that a dump resistor be inserted into the coil circuit following detection of a threshold resistive voltage, Vth. The dump activation circuit requires Vth to be continuously present for longer than a specified time, Td.

With the simple protection approach, the power supply charges the coil while some current also trickles through the dump resistor. The coil design has an inductance of about 2 H, so if the magnet were to be charged to the full current of 5656 A in an hour, the charging voltage would be about 3 V. If the dump voltage is limited to about 400 V, the dump resistor, Rd, is about 70 mΩ, so an "extra" current of about 43 A flows through the dump resistor, dissipating about 130 W. The coil current would be metered downstream of the dump resistor. Once the coil is charged in the superconducting state, the power supply voltage needs to only make up for the small voltage drop in the leads to the magnet. On detection of a quench, the switch is opened, the coil current decays through the dump resistor with a characteristic time of: $L/(Rd + Rcoil(t))$, where L is inductance, $Rcoil$ is the coil resistance and t is time. Since the coil resistance grows from $t = 0$ until approximately $t = 40$ s, the discharge time "constant" decreases in magnitude as the transient progresses. The dump resistor is on the room temperature side of the cryostat. The dump resistor should be placed as close to the magnet terminals as possible to minimize the chances for an open circuit in the leads between the magnet and the dump resistor. The benefit of having an external dump resistor is that when the magnet dumps, much of the stored energy is dissipated outside the cryostat and this will minimize the time for re-cooling the magnet to 4 K. Probably the main disadvantage of the design is that the quench protection is active and requires positive (and reliable) detection of the quench and opening of the protection switch.

For increased reliability and greater assurance that dump will be activated when quench is detected, an additional, redundant dump switch is added to the circuit. The added switch might be mechanical, for example, whereas the other switch could be solid state. Both switches would be triggered to open at the same time. Each must be designed to withstand the full dump voltage, 400 V in this case.

For this conceptual design, 3D quench code analyses were performed on the 4-layer coil at the high field end of the magnet, Coil 3. A similar analysis for quench initiated from the minimum field point showed a lower hot spot temperature. In either case the magnet is well protected from quench. The quench analysis was run with a voltage threshold (Vth) of 0.5 V, and a time delay (Td) of 0.5 s. Because of the low hot spot temperature in both cases, larger values of Vth and Td could be chosen in final design to create additional margin against generating false quench protection trips.

B. Quench Detection

Quench detection is typically done with voltage taps which are electrically connected to the coils at specific locations. Usually, the tap has a resistor placed close to the connection to the coil so that if the voltage tap lead is shorted, it is less likely to carry excessive current that could lead to coil damage. Also, voltage taps are often installed in a redundant fashion at each location so that if one fails, another is available for use in the quench detection circuitry. The voltage tap leads are routed in twisted pairs to minimize inductive pickup, and the differential signals are subtracted, often in a bridge, and the output amplified in the quench detection electronics. By careful calibration and appropriate signal scaling to offset differences of inductance across different tap locations, pairs of tap signals from different sections of each winding are compared so resistive voltages above Vth can be detected. If the voltage remains above the threshold for more than Td, quench protection will be initiated and the dump switch will be opened.

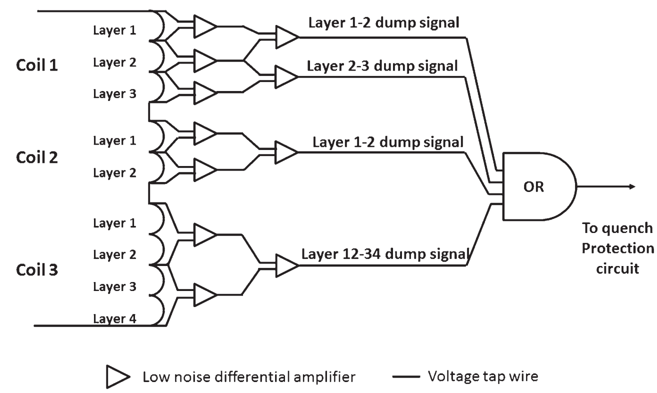

Fig. 4. Schematic of possible arrangement for voltage taps and signal processing. Wire twisting, isolation resistors, and tap redundancy are not shown.

A possible arrangement for the voltage taps and signal processing is shown schematically in Fig. 4. Processing for coils 2 and 3 is straight forward, because each of these coils has an even number of layers. While the grouped layer inductances will not be equal, they will be close (due to the similar geometry and characteristics of the layers), and differences can be compensated electronically. Nonlinearities of the inductances as a function of the current, due to the influence of the iron, can be compensated electronically following calibration. Coil 1 has three layers, so here each layer voltage is evaluated individually, but then the individual layer to layer signals are processed in combination. Quench threshold voltages and delay times required for safe coil discharge by the quench protection system are reasonable ($Vth = 0.5$ V, $Td = 0.5$ s), so the demands on the quench detection system are not high.

The pancake coils can either be included between the taps of one of the layers (probably the first) or their voltage tap signals could be input separately as yet another input to the comparison circuitry. The details would be finalized during the final design stage.

IV. Cooling Scheme

The solenoid is cooled by a two-phase helium flow circulating by natural convection (siphon effect) in cooling tubes at a saturation temperature of about 4.3 K. The goal of the cooling scheme is to provide a reliable circulation of helium around the cold mass with a maximum 10% vapor composition (by mass) at the cryostat exhaust flow [8]–[10].

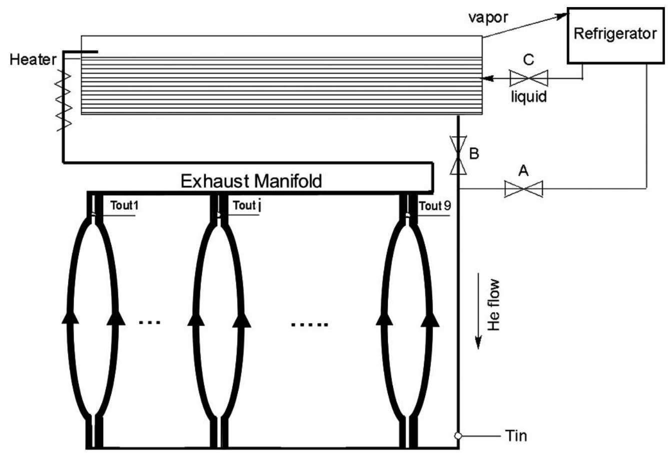

Fig. 5. Principal scheme of the magnet siphon cooling circuit. Pairs of arcs shown represent three of nine pairs of tubes carrying parallel He flow around cold mass OD. A, B, and C are valves and locations of temperature measurements are shown.

The principle scheme of the solenoid thermal siphon cooling is shown in Fig. 5. The cooling scheme consists of 18 half circular aluminum D-shape tubes and a split cylindrical aluminum clamshell. Nine tubes are welded to each half of the clamshell and the clamshell is compressed to the solenoid cold mass OD as seen in Fig. 1. Two inlet 0.5 inch OD manifolds run along the bottom of the solenoid. Two outlet 1.0 inch manifolds run along the top of the solenoid. The top manifolds with two-phase flows have slopes (about 1 degree) for better bubble removal. All inlet and outlet cooling pipes are assembled in a chimney and connected with a service cryostat located above the solenoid.

The heater at the exhaust manifold in the cooling scheme shown in Fig. 5 serves three purposes. First, during the siphon-cooling test, the heater simulates the heat load of the heat dissipation during full current operation. Second, the heater can help to initiate the helium flow circulation at the end of a cool-down, when the solenoid is cold and the siphon replaces the forced flow. Third, if it is necessary, it can serve to decrease temperature of the coil during normal operation by providing higher helium circulation in the cooling tubes.

During initial cooling with cold helium gas valve A is open, valve C is slightly open, and valve B is closed (valves labeled in Fig. 5). When the magnet temperature drops close to the liquid helium temperature the valve C is fully open to fill the supply cryostat with liquid helium. When the magnet temperature drops to 4.5 K–4.8 K the forced cooling mode should be switched to the thermal siphon cooling, for which the valve B is opened and the valve A is closed. The heater can be temporally switched on to initiate siphon circulation. Helium vapor is sent to the refrigerator return line in every mode of operation.

The magnet thermal siphon cooling system requires the minimum size refrigeration system because the full heat of helium vaporization is used to remove the heat from the coils. The cooling passages are designed without vapor pockets and with proper vents for bubbles. The natural convection system automatically directs higher flow rate to the tubes with the greatest heat load. The required maximum 10% vapor content must be satisfied in all channels and final sizing will be determined during the final design stage of the project.

The cold mass is surrounded by an aluminum radiation shield, which is cooled by a forced flow of boiling liquid nitrogen running in tracers at an average pressure of about 2.0 bar, which corresponds to an average saturation temperature of about 84 K. The nitrogen tracers are located at both the inner and outer parts of the radiation shield. The radiation shield is covered with MLI blankets to reduce heat flux from the room temperature walls of the solenoid vacuum vessel to the shield.

All cold surfaces are covered with Al foil to reduce radiation heat loads [11]. For our thermal analysis we use a radiation heat flux to the 4.3 K cold mass of 0.02 W/m^2. Application of the adhesive Al tape to surfaces which are cold during operation does not spoil the insulating vacuum because the adhesive is frozen and it does not outgas in the vacuum space. The surfaces, as-received or with regular machining and covered with Al tape provide very low radiation heat loads. The adhesive foil is in a good thermal contact with cold surfaces, which is important for better performance in the surrounding vacuum.

V. Conclusion

A self-consistent magnet design is presented here that includes the conductor selection, winding scheme, magnet design, as well as the quench detection and protection and cooling scheme. This conceptual design will be used by JLAB as a reference design in soliciting bids for the Hall D solenoid final design and fabrication effort.

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