Overview of Torus Magnet Coil Production at Fermilab for the Jefferson Lab 12 GeV Hall B Upgrade

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Abstract— Fermi National Accelerator Laboratory (Fermilab) fabricated the torus magnet coils for the 12 GeV Hall B upgrade at Jefferson Laboratory (JLab). The production consisted of 6 large superconducting coils for the magnet and 2 spare coils. The toroidal field coils are approximately 2 m x 4 m x 5 cm thick. Each of these coils consists of two layers, each of which has 117 turns of copper-stabilized superconducting cable which will be conduction cooled by helium gas. Due to the size of the coils and their unique geometry, Fermilab designed and fabricated specialized tooling and, together with JLab, developed unique manufacturing techniques for each stage of the coil construction. This paper describes the tooling and manufacturing techniques required to produce the six production coils and two spare coils needed by the project. [1]

***Index Terms*—Superconducting Magnets, Detector Magnets, CLAS12 Torus, Conduction-Cooling**

I. Introduction

THE 12 GeV upgrade to the CEBAF Accelerator [1] includes upgrades to the accelerator and experimental halls. Hall B is in the process of being upgraded with new detectors and superconducting magnets [2]. One of the superconducting magnets is a large torus approximately 8 m in diameter, consisting of 6 coils, Fig 1. Fermilab (FNAL) was contracted to provide eight coil cold masses to Jefferson Lab, six for the magnet with two spares. Because of the large geometry of the coils, FNAL had to develop new tooling and procedures for fabrication [3], [4]. The tooling and procedures are described in this paper.

II. Magnet and Coil Design

The magnet consists of 6 torus coils arranged in a single electrical circuit, and utilizes a single supercritical helium cooling circuit [5]. Each of the magnet coils is housed in a separate cryostat and supported at the central cold hub, as well as the outside perimeter creating a hexagon as seen in Fig. 1. The cryostat contains MLI, instrumentation, and the aluminum coil cold mass. Coil cold masses consist of a highly polished aluminum case with lid containing the coil assembly and a number of Cernox™ temperature sensors. Coils are built based on a design by Jefferson Laboratory and utilize conduction cooling via a rectangular copper cooling tube on the coil ID soldered to a copper heat shield that encompasses the coil windings. Each coil layer consists of 117 turns of SSC dipole cable soldered into a stabilizing copper channel. The cable is wrapped in 50% overlap 75 µm E-glass. Between coil layers, a 0.38 mm layer of G10 prevents layer to layer shorts. Ground insulation on the faces of the coil consists of a minimum of 4 layers of 175 µm E-Glass cloth. Inside perimeter insulation consisted of 0.8 mm G10 directly adjacent to the cooling tube wrapped in 2 layers of 175 µm glass tape. A cross section of a completed coil cold mass can be seen in Fig. 2.

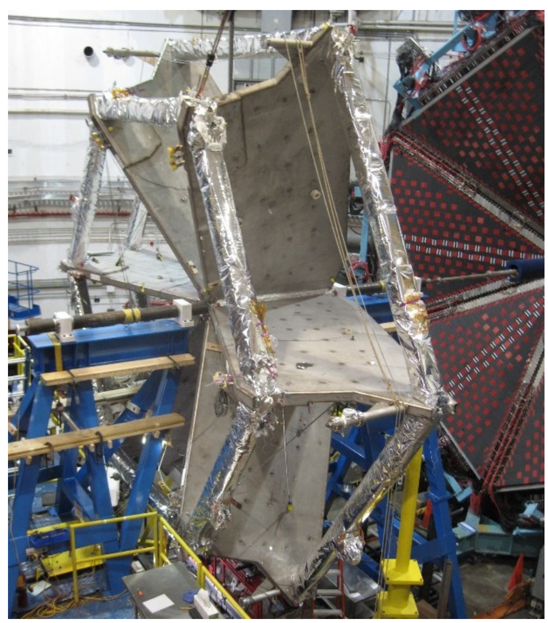

Fig. 1. Six Torus coils installed in Hall B.

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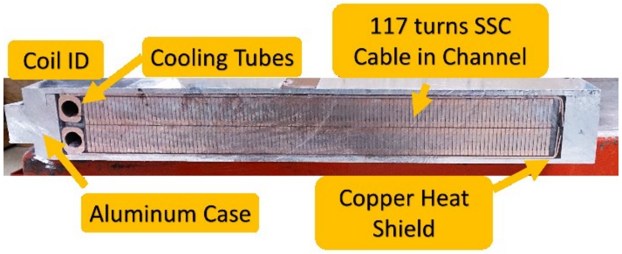

Fig. 2. Cross section of potted coil cold mass displaying coil design.

III. Coil Winding

Winding CLAS12 coils at Fermilab turned out to be a significant undertaking. Each coil contained around 1000kg of superconducting cable in addition to having a fairly large size and high required tension. Existing winding systems were unable to support the significant weight of the cable and coil, or the high torques required for winding. As cable spools for the project had a maximum radius of 2 m and required winding tension of 445 N a much larger winding station had to be designed. Both the new winding table and tensioner are of the hub drive type. The winding table also doubled as the feed spool holder during the insulation process in which the stabilized cable was transferred off of the spools supplied by the vendor and cleaned, followed by a run through the insulating machine in which 20 mm wide by 75 µm thick E-glass tape was applied at 50% overlap. Cable was then split between spools for the first and second layers of the coil.

Coils are then wound by first winding the 2 turns of cooling tube around the winding mandrel, followed by winding the coil. The coil is wound as a double pancake by winding 117 turns of the first layer with the second layer cable supported above the coil, then winding the second layer. After each coil layer was wound, Shims were installed around the inner winding radius to compensate for dog-bone of the turns and the coil was clamped to set its size before transfer to the impregnation mold. Winding of a second layer coil is shown below in Fig. 3.

Fig. 3. Winding of layer 2 coil.

To ensure coils are free of electrical problems, after winding each layer a series of electrical measurements are made. The primary test to indicate problems at this stage of fabrication is an AC turn to turn short test, capable of detecting shorts up to about 1 Ω between adjacent turns. A sharp inflection point in plotted phase and magnitude indicates a short, Fig. 4.

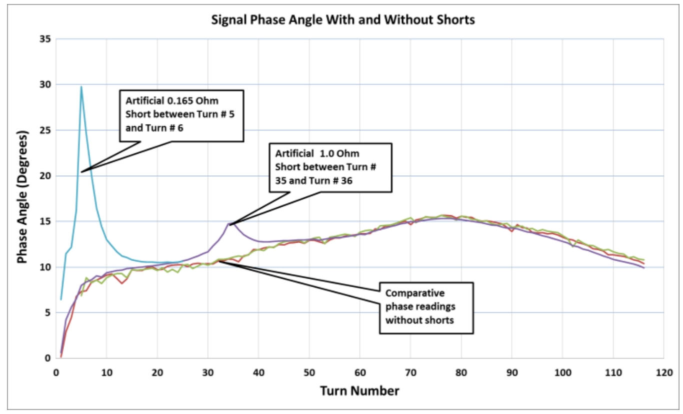

Fig. 4. Turn to Turn short detection output.

As the AC measurement is less sensitive in the area of the layer jump, an additional DC resistance turn to turn test was also performed in the 4 turns in either layer surrounding the layer jump from the 5th production coil on.

With both layers complete, leads are stabilized further by soldering an additional copper bar to the superconductor side of the cable and formed such that they will fit in the potting mold.

IV. Coil Impregnation

After coil winding was successfully completed, they underwent a 1st impregnation step in which all of the coil insulation as well as ground insulation is impregnated with CTD-101k epoxy. Once impregnated, it is possible to handle the coils to install the copper heat shield and transfer as a single large object into the coil case. Initial attempts to impregnate coils with the additional copper heat shield proved unsuccessful as the copper proved too much a barrier to epoxy flow to be practical for this coil geometry.

The final impregnation plan utilized a layer of polypropylene mesh too allow a uniform epoxy flow over the surface of the coil as well as a route for trapped and evolved gases to escape to one of the 3 main vacuum pump out ports. Between the mesh and fiberglass ground insulation layers, a layer of perforated FEP film served as a permeable release film to provide clean, easy release properties without causing adhesion problems as with nylon peel-ply. On earlier coils, nylon peel-ply had been used, but it was found to outgas significantly and caused poor adhesion of the epoxy to the ground insulation.

As the large geometry of the torus coils prevented them from being potted in Fermilab's long vacuum impregnation oven, a different approach had to be used. A large mold was constructed of a top and bottom plate with an inner ring and an outer ring. Coils were inserted into the mold by an injection plate on the winding table that lifted the coil into the mold. A partial cross section of the mold and winding table can be seen below in Fig. 5.

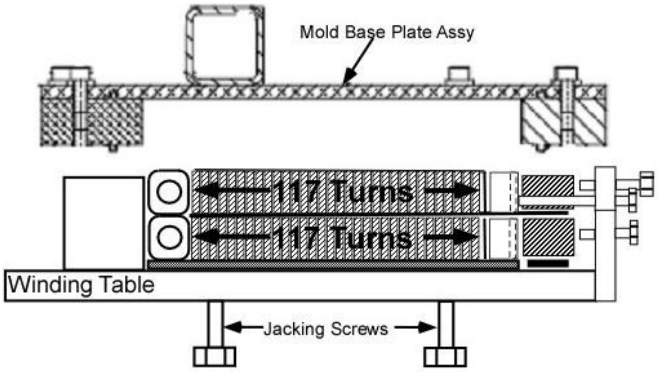

Fig. 5. Mold and coil insertion.

As this configuration had a very large sealing area, a form in place gasket type system was utilized to seal the mold. The first section of the mold was sealed by filling a milled channel on both the inner and outer mold walls with Momentive RTV21. As the RTV has a limited pot life once catalyzed, it was critical to complete mold sealing within 1 hour while the RTV was still liquid. Food service ketchup bottles allowed quick and controlled application of RTV. The rings were dropped into place and the RTV was allowed to cure overnight. After sealing the upper half of the mold, the mold was rotated such that the cavity faced down and the coil was raised off the winding table into the mold. The mold and coil were then rolled over, the exposed side of the coil prepared with ground insulation, FEP, and polypropylene mesh. To finish the mold sealing process, a strip of low density foam was adhered to the mold to form a channel ~10 mm wide around the perimeter of the mold as seen in Figure 6. The channel was then filled with RTV similar to the first half mold sealing and the top plate of the mold was then installed.

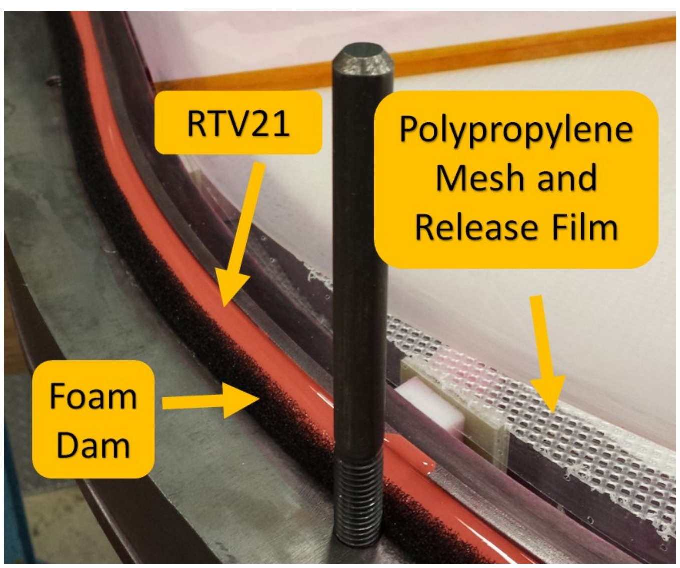

Fig.6 Components in mold sealing.

After the RTV had set overnight, the mold was helium leak checked before transfer to the potting box. Criteria for passing was no detectable leak and verified with rate of rise (RoR) test over 10 minutes where the mold is isolated from the vacuum pump and pressure rise is recorded.

Impregnation takes place in a large wooden box that exists solely to surround the coil mold in insulation. Traditional R19 fiberglass building insulation was used and succeeded to keep steady-state heating power less than 2000 W. Power was provided by a large DC power supply capable of 1250 A at 120 V run through the coil to act as a large resistive heater with resistance of 830 mΩ to 1260 mΩ based on temperature and cable geometry. Temperature control feedback was based on the temperature coefficient of resistance of the magnet. An additional 8 thermocouples mounted across the coil provided validation of the coil temperature. A view of the impregnation setup is presented in Figure 7.

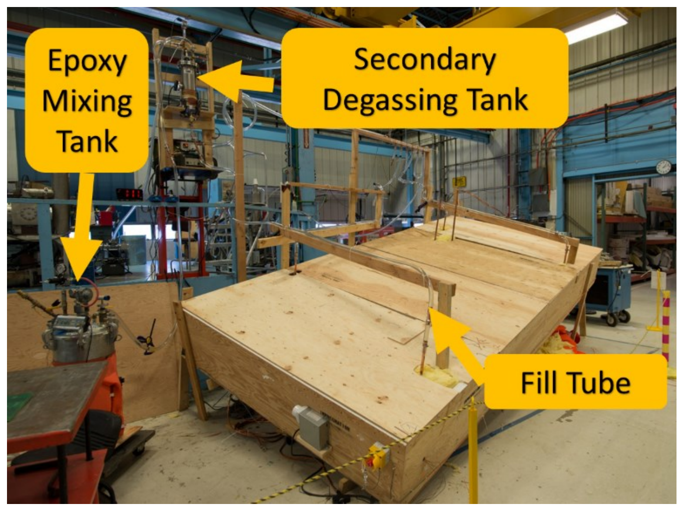

Fig. 7. Coil impregnation setup.

Coils were then out-gassed under vacuum for a minimum of 24 hours at 60° C before cooling to the potting temperature of 50° C. While out-gassing, vacuum pressure was continually logged and a Rate of Rise test was completed every morning and evening while servicing the cold traps. Typical RoR values started at 90 mTorr/min and reduced to <15 mTorr/min.

When the coil temperature stabilized at 50° C, epoxy mixing began. 48 liters of CTD-101K were mixed for the 1st coil impregnation, with approximately 32 liters to fill the coil, and 4 gallons as overhead to keep as top-off resin if required as well as to pot cable samples. Epoxy was initially mixed in a large batch in a 80 liter heated mixing tank at 50° C and evacuated to 800 mTorr for 1 hour. After initial mixing, it was introduced in small batches into a secondary out-gassing tank where it was outgassed for an additional 30 minutes with agitation at 55° C. From the secondary tank, small batches of ~0.8 L were added to the coil by gravity feed every 7 minutes until full. When full, a number of vacuum to atmosphere cycles were completed to fully saturate the coil. The coil was then allowed to soak for 24 hours at 58° C before the cure cycle began. The cure cycle took place over 3 days with a gel stage, cure, and post-cure as seen in Figure 8.

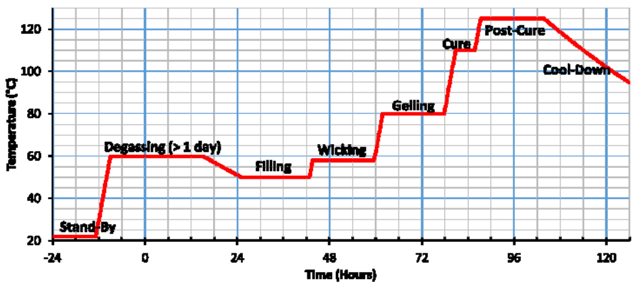

Fig. 8. Coil Outgas, Fill, and Cure cycle.

When cool enough to handle, the mold was removed from the box, followed by removal of the top and bottom mold plates as well as the outside mold ring. After impregnation, the inside mold ring ended up being shrink fit in the coil and had to be extracted. A method was developed to heat the coil in the same fashion as during potting with a small DC power supply supplying 60 amps of current to the coil with the coil elevated off of the table until it expanded enough for the ring to slide out. Coils are then prepared for soldering by removing mold flash and dressing the coil surface. Occasionally small cosmetic bumps were left from the mesh and FEP, which were removed by light sanding. A view of an impregnated coil in the process of demolding can be seen in Fig 9.

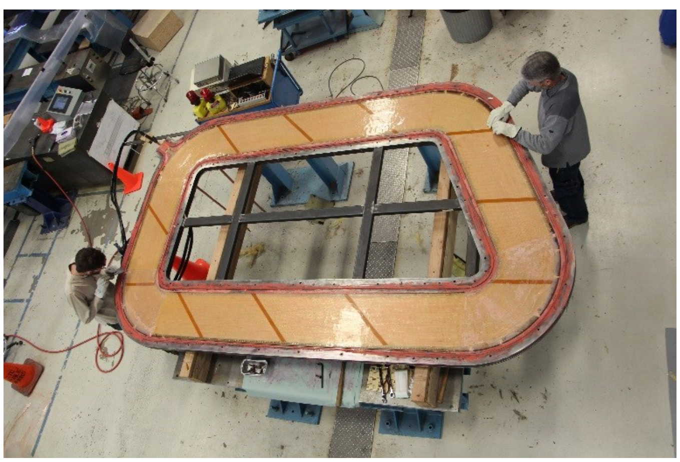

Fig. 9. Coil 006 after removing the mold lid.

V. Heat Shield Soldering

Cooling to the torus coils is provided by conduction cooling from a supercritical helium cooling tube around the inside perimeter of the coil [3], [5]. Two layers of OFE Copper sheet distribute cooling to the coil through a solder connection located at the cooling tube. The copper is folded down around the OD of the coil to ensure complete coverage of the coil with a minimum of one layer of copper.

Copper soldering was performed with a special clamping tool to hold the copper in place while heating the joint to soldering temperature. A custom PID controller with timer was developed to quickly heat the copper shield to soldering temperature and minimize overshoot to prevent damage to the superconductor and epoxy below. The system worked extremely well such that two technicians were able to successfully solder one side of the coil which contained 7 m of cooling tube in approximately 6 hours. This was a significant improvement over the approximately 20 hours to solder with the previous tooling and with more consistent results.

VI. Coil Cold mass (CCM) Potting and shipping

After heat shield installation, the coil was inserted into an aluminum coil case by placing the aluminum case onto the coil using a crane. The coil and case were then flipped over to allow the coil to be shimmed into position as required by survey to meet JLab requirements. All voids in the case were then filled using fiberglass as tightly as practical. In the corners where an epoxy inlet or vacuum port was located, a piece of sandblasted stainless mesh was used to keep the filler glass from impeding resin flow as potting of the 1st model coil highlighted this necessity.

The case lid was sealed in place by wet-sanding all contacting aluminum surfaces under a bead of Scotch-Weld DP-190 epoxy adding additional epoxy, and screwing the lid into place. The potting process was the same as 1st impregnation with the same equipment. Sealing the case was another task with a tight timeframe to complete as the DP-190 has a working time of 90 minutes. Beads of epoxy were applied to both the case and case lit and sanded using Scotch-Briteµ\™ and an orbital palm sander. Additional epoxy was then applied to the case, the lid placed, then fastened using 230 screws.

Impregnation proceeded following the same procedure as the first impregnation but with reduced epoxy batch size to scale the fill rate to the required volume. After curing was complete, the case was cleaned and polished, and the cooling tubes formed into their final position Fig. 10. A final series of electrical measurements and visual inspection were made to confirm coil properties before being packed and shipped to JLab.

Figure 10. Completed coil cold mass ready to ship.

VII. Summary

In total, Fermilab delivered 8 complete cold mass assemblies to JLab. Three practice coils had been fabricated beginning in early 2014, with production coil fabrication lasting from August 2014 through June 2015. This very important phase of the project was successfully completed, with magnet commissioning at JLab expected in mid-2016.

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