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 Lab (JLab). The production consisted of six large superconducting coils for the magnet and two spare coils. The toroidal field coils are approximately 2 m × 4 m × 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 supercritical helium. 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 the two spare coils needed by the project.**

***Index Terms*—CLAS12 Torus, conduction cooling, detector magnets, superconducting magnets.**

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]. 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 [4], [5]. Each of the magnet coil cold masses is housed in a vacuum vessel shell and supported at a central cold hub, as well as by cold columns at the outside perimeter creating a hexagonal torus as seen in Fig. 1. Additionally, the cryostat system contains a 40 K aluminum shield, multi-layer insulation, and instrumentation. The vacuum vessel is completed in the field by welding individual enclosures over each cold column and welding to the coil vacuum shells. 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 Superconducting Super Collider dipole cable soldered into a stabilizing copper channel [6], [7]. The cable is wrapped in 45% 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.

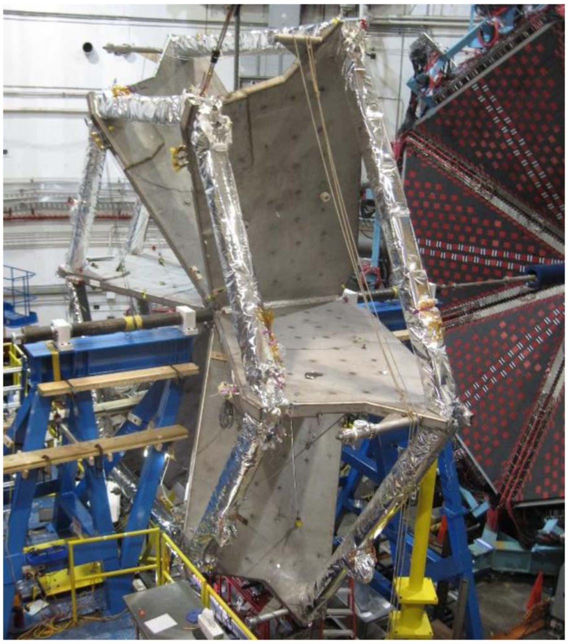

Fig. 1. Six torus coils installed in Hall B.

Manuscript received October 20, 2015; accepted February 9, 2016. Date of publication February 29, 2016; date of current version May 6, 2016. Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

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Digital Object Identifier 10.1109/TASC.2016.2533264

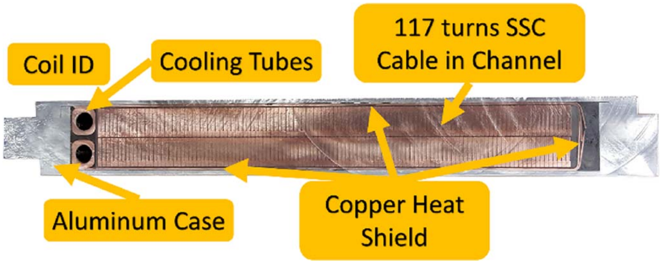

Fig. 2. Cross section of potted coil cold mass displaying coil design.

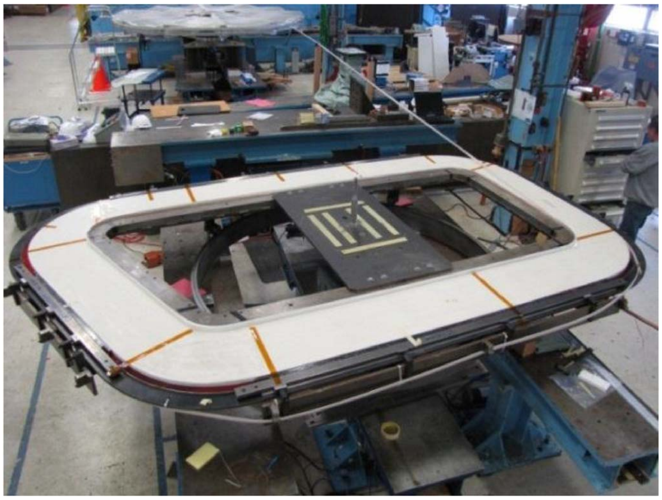

Fig. 3. Winding of layer 2 coil.

III. COIL WINDING

Winding Torus Coils at Fermilab turned out to be a significant undertaking. Each coil contained around 1000 kg of superconducting cable in addition to having a fairly large size and high 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.

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.

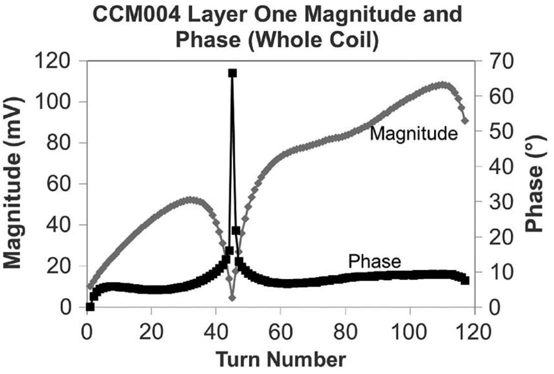

Fig. 4. Turn-to-turn short detection output for CCM004. Spike indicated short at turn 45.

In production coil 4 a short was found at the layer jump after impregnation which was indicated by coil inductance measurements, and subsequently repaired. 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 half of the ground layer insulation was impregnated with CTD-101k epoxy [8]. Once impregnated, it is possible to handle the coils to install an additional 360 μm of ground layer insulation, and 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.

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 from below by an elevator 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.

The 1st impregnation of practice coils was plagued with voids until a layer of polypropylene mesh was incorporated to allow a uniform epoxy flow over the surface of the coil as well as act 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 fluorinated ethylene propylene (FEP) film served as a permeable release film to provide clean, easy release properties without

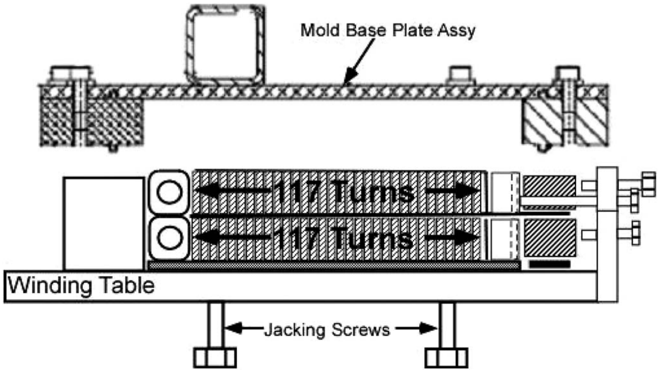

Fig. 5. Mold and coil insertion.

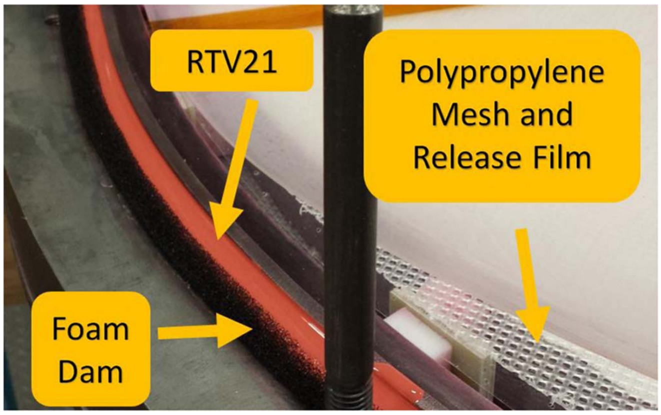

Fig. 6. Components in mold sealing.

causing adhesion problems. On earlier coils, nylon peel-ply was used, but it was found to outgas significantly and caused poor adhesion of the epoxy to the ground insulation.

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 [9]. 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 rings to the mold base plate, 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 and 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 $\sim$10 mm wide around the perimeter of the mold as seen in Fig. 6. The channel was then filled with RTV similar to the mold base plate sealing and the top plate of the mold was then installed.

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.

Fig. 7. Coil impregnation setup.

Impregnation took place in a large wooden box that exists solely to surround the coil mold in thermal 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 Fig. 7.

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 L of CTD-101K were mixed for the 1st coil impregnation, with approximately 32 liters to fill the coil, and 15 L 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 an 80 L heated mixing tank at 50 °C and evacuated to 800 mTorr for 1 h. After initial mixing, it was introduced in small batches into a secondary out-gassing tank where it was outgassed for an additional 30 min with agitation at 55 °C. From the secondary tank, small batches of $\sim$0.8 L were added to the coil by gravity feed every 7 min 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 h 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 Fig. 8.

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 shrunk 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 A of current to the coil with the coil elevated off of

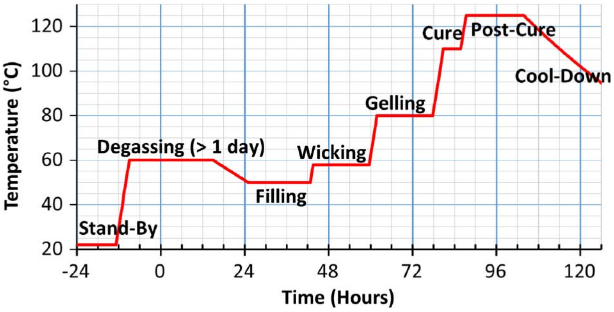

Fig. 8. Coil outgas, fill, and cure cycle.

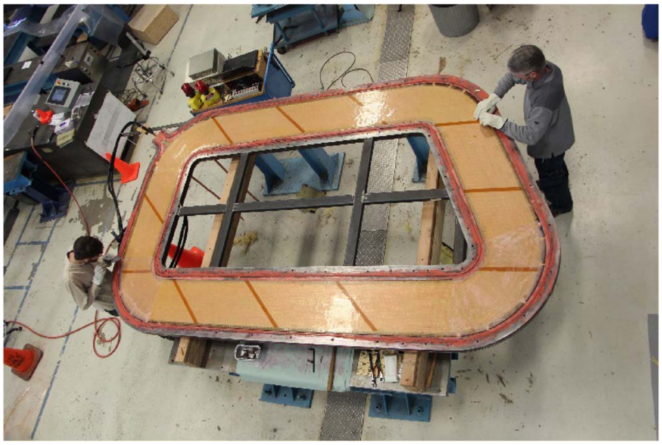

Fig. 9. Coil 006 after removing the mold lid.

the table until it expanded enough for the ring to slide out. Coils are then prepared for adding the heat shield and soldering it to the cooling tube 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.

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 form the heat shield and 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 step-function 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 hrs. This was a significant improvement over the approximately 20 hours to solder with the previous tooling and with more consistent results.

Fig. 10. Completed coil cold mass ready to ship.

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 based on post-impregnation metrology. 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. Potting of the 1st practice coil highlighted this necessity.

The aluminum case was sealed using Scotch-Weld™ DP-190 epoxy between mating surfaces of the case and case lid [10]. To ensure a strong bond between the mating surfaces, both surfaces were prepped by applying a small amount of DP-190 and while still wet, sanding with an orbital palm sander to break the oxide layer. An additional, larger bead of DP-190 was then applied, to provide the actual seal. The lid was then placed and fastened with 230 screws. The entire sanding and sealing operation was completed within the 90 minute working time of the DP-190.

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 as seen in Fig. 10. A final series of electrical measurements and visual inspection were made to confirm coil properties before being packed and shipped to JLab.

VII. SUMMARY

In total, Fermilab delivered 8 complete cold mass assemblies to JLab. Three practice coils were fabricated beginning in early 2014, with production coil fabrication lasting from August 2014 through June 2015. Up to three coils were in process at a time during fabrication with completion in 5–8 weeks. This very important phase of the project was successfully completed, with magnet commissioning at JLab expected in mid-2016.

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