Design and Manufacture of the Conduction Cooled Torus Coils for The Jefferson Lab 12 GeV Upgrade

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***Abstract*— The design of the 12 GeV Torus required the construction of six superconducting coils with a unique geometry required for the experimental needs of Jefferson Labs Hall B. Each of these coils consists of 234 turns of copper stabilized superconducting cable conduction cooled by 4.6 K helium gas. The finished coils are each roughly 2 X 4 X 0.05 meters and supported in an aluminum coil case. Because of its geometry new tooling and manufacturing methods had to be developed for each stage of construction. The tooling was designed and developed while producing a practice coil at Fermi National Laboratory. This paper describes the tooling and manufacturing techniques required to produce the six production coils and two spare coils required by the project. Project status and future plans are also presented.**

***Index Terms*—SSC cable, fabrication, coil, torus, Superconducting magnet, epoxy potting.**

I. Introduction

The 12GeV upgrade of the CEBAF accelerator includes upgrades to the accelerator and the experimental halls. The changes for the experimental Hall B include upgrades to the physics detectors and two new superconducting magnets [1-6]. One of those is a solenoid magnet that is currently being designed and fabricated by industry. The second is a large Torus magnet, Fig. 1. The overall magnet is being designed and will be assembled at Jefferson Laboratory (JLab). The coils for that magnet are currently being fabricated at Fermi National Accelerator Laboratory (FNAL) by the Magnet Systems Department. The unique geometry of these coils required the development of new tooling and procedures to fabricate the coils. The tooling and procedures to fabricate those coils will be described in this paper.

II. Torus Magnet and Coil Description

The CLAS12 Torus magnet consists of six coils housed in an aluminum case that is approximately 2 x 4 x 0.05 m, Fig. 2. Each of the six coils for the torus consists of 234 turns of SSC 36 strand outer superconducting cable [7] soldered into a copper stabilizer, total length per coil of ~2000 m. The six coils produce a peak magnetic field of 3.58 T when powered at 3770 A. The magnet will have an overall inductance of 2.0 H, stored energy of 14.2 MJ and will be roughly 8 m in diameter when fully assembled. A cross sectional view of the coil is given in Fig. 3. Each coil is conductively cooled by supercritical helium gas supplied at 4.6K from cooling tubes located on the coil inner diameter (ID). Two layers of 0.635 mm copper are soldered to the cooling tubes and surround the coil. The copper sheets provide the principal conduction media for cooling the coil. The coil is vacuum impregnated separately and is then positioned and potted a second time in its aluminum case.

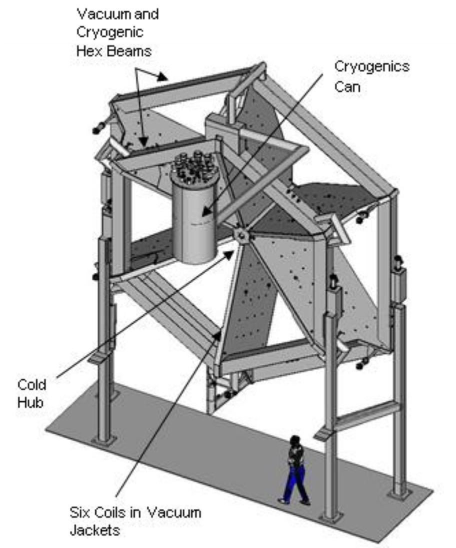

Fig. 1. The CLAS12 Torus Magnet

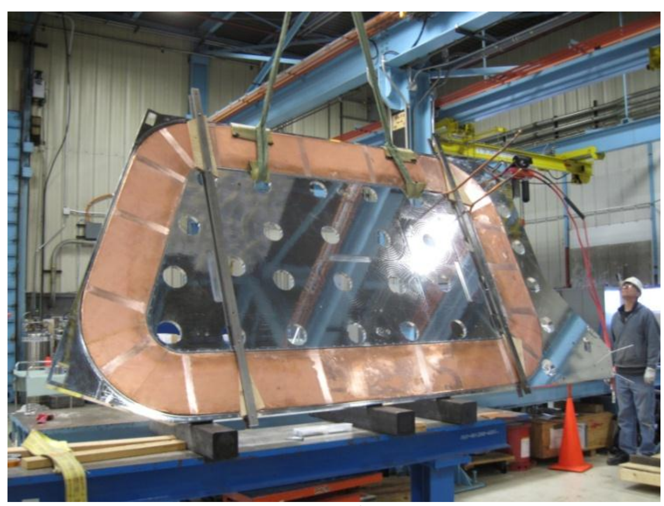

Fig. 2. Practice coil inside the coil case before the coil lid is installed. Cooling tubes and leads can be seen at the upper right corner.

The six coils in their coil cases are then shipped to JLab

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where each coil is wrapped in multi-layer insulation (MLI) and surrounded by an aluminum thermal shield also insulated with MLI. This cold mass is then supported in a stainless steel vacuum jacket that is welded around the coil. The final assembly of the six vacuum jacketed coils will take place in Hall B.

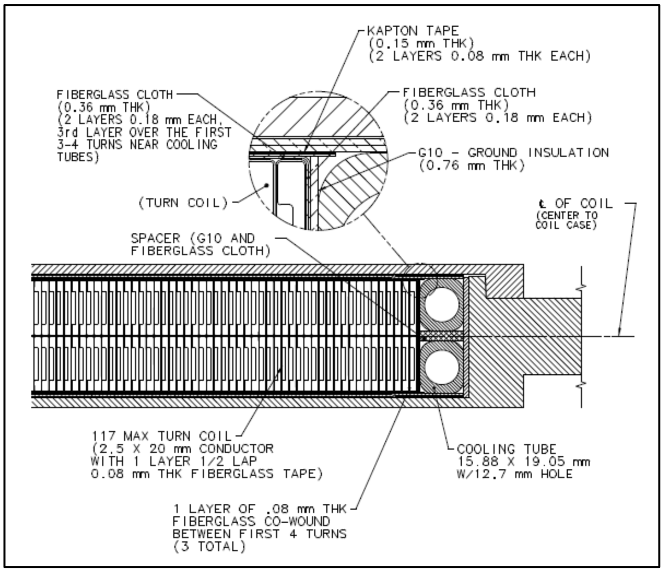

Fig. 3. Construction detail for the Torus coils, showing conduction cooling mechanism and coil winding details. The coil cross section inside of the aluminum case is 353 x 45 mm.

III. Conductor, Cleaning, and Insulating

The SSC cable is soldered into a copper stabilizer by industry. After soldering the surface solder layer is removed from the copper to improve epoxy bonding and then shipped to FNAL. At FNAL the conductor is cleaned once again with Scotch-Brite® pads clamped around the conductor, vacuumed, and wiped with alcohol as it is removed from the vendor supplied conductor spool and wound onto a specially prepared spool at FNAL, Fig. 4. These specially prepared spools have tighter tolerances than the vendor spools and an extra ring that supports the conductor so as to not damage the conductor or insulation during spooling operations. These spools are also electrically insulated so that the conductor can be hipot tested during insulation application.

After the first pass cleaning the conductor receives the same cleaning a second time while it is insulated with 19.1 mm wide, 0.08 mm thick E-glass tape in a half lap fashion, Fig. 5. The insulation machine, tensioning machine, winding table and the control systems for each were all specially made for the Torus project.

IV. Coil Winding

The coil is wound onto a specially designed winding table. The table provides a mandrel that was machined to provide the coil inner geometry and is also designed to mate to the potting mold during coil insertion. The winding table is also designed to push the coil into the potting mold after winding. Winding first starts with the cooling tube which is wound twice around the table and shimmed to height with G10 strips between the two passes. The ends of the cooling tube are routed through the bottom of the table. After winding the cooling tubes are pressure and helium leak checked. The cooling tubes are wrapped with 0.76 mm G10 and two layers of 0.18 mm glass cloth to form the ground layer insulation between the tubes and coil.

Fig. 4. The conductor being cleaned from right to left. The aluminum spool with conductor from the soldering company is positioned on the winding table at right. The cleaning station, shown above, is located between the two wooden spools. The tensioner with the FNAL aluminum spool is on the left.

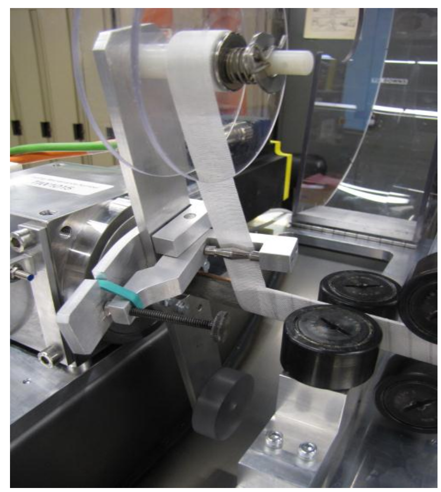

Fig. 5. Conductor being insulated with the newly designed machine.

Next, the spool with the insulated conductor is positioned on the winding table and half of the conductor wound onto a second spool on the tensioning table. The winding table spool is then removed and a support post installed between the table and spool. Then the layer to layer transition is formed using a specially designed tool that bends the conductor the hard way, positioned onto the winding table, and shimmed on both sides with G10 strips. The first layer of 117 turns is then wound in a continuous fashion. Finally, 3.2 mm of G10 and three layers of 0.76 mm glass cloth are added for ground insulation on the outer perimeter. Then the coil is clamped to shape with clamping bars on each of the coils 'straights'. The coil undergoes electrical testing, which includes a specifically designed turn to turn short test measurement capable of detecting both 'hard' and 'soft' (of about 1 ohm) shorts between adjacent turns, Fig. 6. The instrument utilizes an AC signal (19.8 kHz, 30 V) injected into the complete coil. Successive readouts are measured for each turn pair through an insulation transformer followed by a lock-in amplifier which yields the profile of the magnitude and the phase. A smooth trajectory of both Magnitude and Phase, function of the turn number, is expected. If a short is present it reveals itself through a sharp change in said profile.

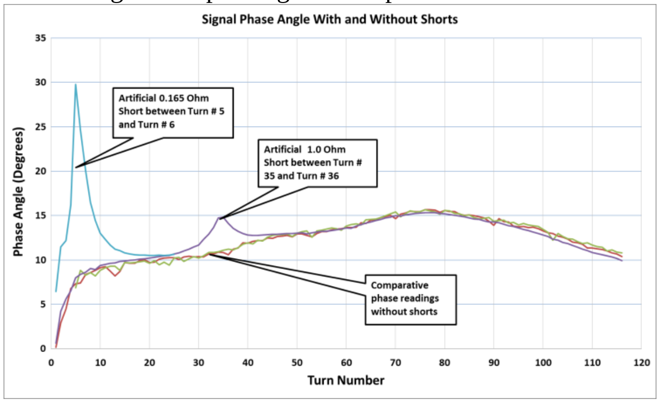

Fig. 6. Turn vs relative phase measurements. Different size shorts are introduced at different locations to test the procedure.

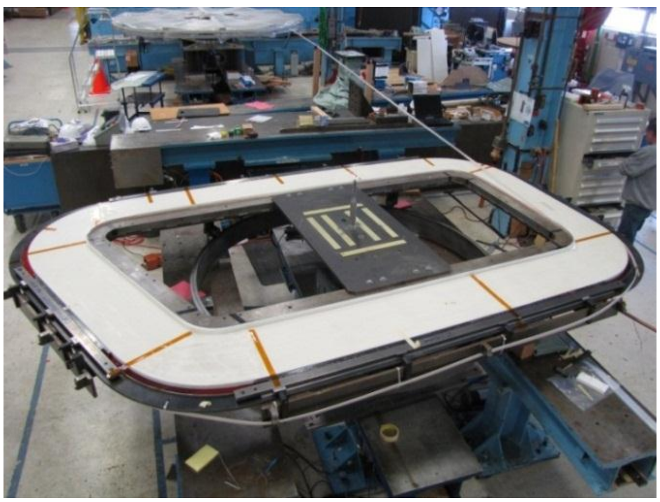

Fig. 7. First pancake wound and clamped on the winding table. Pancake insulation installed. Second layer spool can be seen at top.

After the first layer is wound a 0.3 mm G10 interlayer insulation is installed, Fig.7. The G10 has holes drilled through it and is spiral wrapped with 0.08 mm glass tape to help promote epoxy flow between the two pancakes during impregnation. The 2nd layer of conductor is then wound in the opposite direction on top of the G10 with the same procedures used for the first layer. After this two layers of 0.18 mm glass cloth are installed on top of the coil as part of the ground insulation. A layer of peel ply and polypropylene mesh is then added on top of the ground insulation. This will be explained later in the paper. The coil is then ready for insertion into the potting mold.

The potting mold consists of five parts and is made from mild steel to closely match the thermal expansion of the copper stabilizer. There is an inner and outer mold wall that are both precision machined to match the designed shape of the coil, and an upper and lower mold plate. The fifth part is a small plate that fits around the cooling tubes to aid in sealing the mold for potting. Prior to the coil insertion the mold is coated with mold release and the inner and outer mold walls assembled onto one of the mold plates. The assembly is sealed with a RTV silicone adhesive. This assembly is then positioned over the winding table using precision pins. The pins insure that the inner perimeter of the winding table aligns with the inner perimeter of the potting mold. The coil and clamping bars are pushed up into the mold using the aluminum push plate and twenty eight jacking screws designed into the winding table, Fig. 8. Once inserted, the coil is clamped between the push plate and mold and then flipped. The push plate is removed and the ground layer insulation, peel ply and polypropylene mesh are then installed over the exposed pancake and the mold sealed for potting.

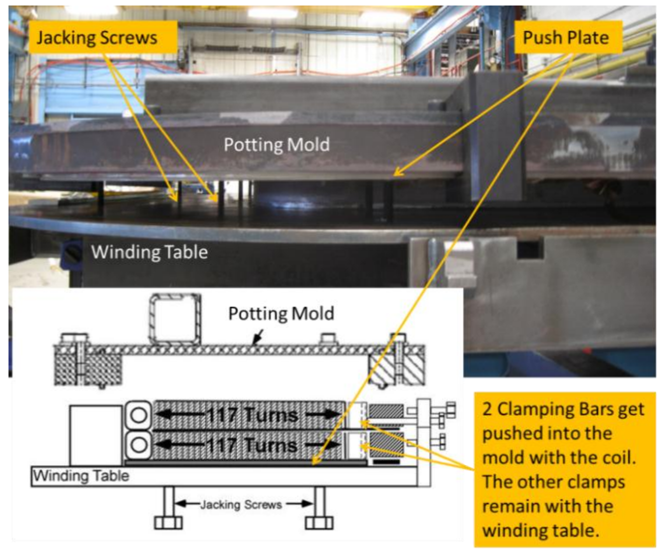

Fig. 8. Schematic of the coil before pushing into the potting mold and a picture with the coil after being pushed completely into the potting mold.

V. Coil Potting

The coil in the potting mold is too large to be potted using FNAL's existing facilities so a different method had to be used for potting. The mold is first mounted at an angle inside an insulated box constructed just for this purpose, Fig. 9. The coil leads are connected to a PID controlled power supply and the conductor used as both a heater and as a temperature probe for the coil and potting mold. The potting mold is evacuated and outgassed at 90 C. CTD101K [8] epoxy is used to pot the Torus coils. The epoxy is mixed and degassed and then batch fed into a low point fill line coming out of the top of the mold. Three vent lines, one in each of the other three corners are used to monitor the epoxy as it fills the mold. After the mold is full, atmospheric pressure is restored and the epoxy is taken through its recommended cure cycle.

A practice coil was constructed using prototype conductor to develop and practice all of the procedures described so far. After potting, this coil was cooled to liquid nitrogen temperature at JLab and then sectioned to test the quality of the potting. A dry spot was discovered in the coil near the top of the mold, Fig. 10. Unfortunately, the first production coil was also potted using nearly the same procedures before this coil was sectioned. Upon investigation this coil also had voids.

Fig. 9. The potting mold being positioned into the insulated box. The fill tube can be seen in front mold corner.

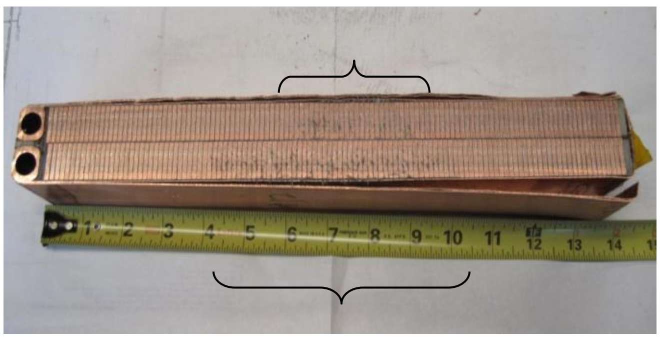

Fig. 10. A section of the failed practice coil. Void area is inside the brackets in both pancakes.

Because of this, the design of the coil and the potting procedures were thoroughly reviewed and changes to both were implemented [9]. Changes in procedures include steps to improve the outgassing of the epoxy, lowering the epoxy temperature during filling to improve pot life, a slower fill rate and a prolonged soak period to allow more time for the epoxy to flow and wick into the coil. Changes in design were done to improve the epoxy flow inside the coil. These include changes to the inter pancake insulation, and delaying the soldering of the copper foil until after the first coil potting. Not installing the copper foil before potting gave room in the mold to include a layer of peel ply and polypropylene mesh. The mesh gives room for the epoxy to flow over the coil. The layer of peel ply allows easy removal of the mesh after potting. The new procedures and design have been tested multiple times on a 70 cm coil model. Both the new procedures and design changes will be tested on a second practice coil in the near future.

VI. Copper Foil Soldering

After potting two sheets of 0.635 mm of annealed OFE copper are soldered to the cooling tubes on each side of the coil and then folded over the outside of the coil. Two layers of .006" Kapton are installed on the inner layer of copper for ground insulation and an additional layer of glass is installed between the Kapton and coil to aid in epoxy flow between the two during the second coil potting. Once the copper is installed on both sides of the coil it is inserted inside of the aluminum coil case. A nominal 2 mm and 3 mm gap is left on the inner and outer diameter respectively to allow for positioning the coil in the case. Shims are used to position and hold the coil for potting. The remaining gaps are filled with glass cloth. The coil case cover is then sealed for the second potting using RTV, Fig 11.

Fig. 11. Finished coil with copper foil installed into the aluminum coil case. Cooling tubes can be seen coming out of the case with leads at lower right.

VII. Second Coil Potting

The coil is then epoxy impregnated a second time in the aluminum case using the same basic procedures as developed for the first potting. The difference in thermal expansion between aluminum and copper insures an adequate preload on the coils after cool down. This is the one step of production that has not yet been prototyped. After potting, the coils receive their final round of quality control tests and are then shipped to JLab for installation into their vacuum vessel and ultimate assembly in Hall B.

VIII. Status And Plans

In the near future, the second practice coil will be potted at FNAL, visually inspected, and sectioned to test the quality of the modified 1st coil potting procedure. After that FNAL will go back into full production of the Jlab Torus coils. During full production FNAL will be working on three coils simultaneously. An online traveler system developed at FNAL is used to track the production of the coils and insure all quality checks are done and recorded. The first production coil should be delivered to JLab this fall with the last coil finished in early 2015.

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REFERENCES

[1] C. H. Rode, "Jefferson lab 12 GeV CEBAF upgrade," *Trans. of Cryogenic Eng. Conference, CEC: Advances in Cryogenic Engineering*, vol. 1218, 2010, pp. 26-33.

[2] R. J. Fair, G. L. Young, "Superconducting magnets for the 12 GeV upgrade at Jefferson Laboratory", *IEEE Trans. Appl. Supercond., submitted for publication*, ASC2014.

[3] L. Quettier *et al.,* "Status of Hall B superconducting magnets for the CLAS12 detector at JLAB" *IEEE Trans. Appl. Supercond.*, vol. 22 (3), June 2012.

[4] O. Pastor *et al.*, "Eddy Current and Quench Analysis on Thermal Shield in Torus Magnet for 12GeV Upgrade", *IEEE Trans. Appl. Supercond., submitted for publication*, ASC2014.

[5] R. Legg *et al.*, "Liquid nitrogen tests of a Torus coil for the Jefferson lab 12 GeV accelerator upgrade", *IEEE Trans. Appl. Supercond., submitted for publication,* ASC2014.

[6] R. Rajput-Ghoshal, R.J. Fair, P. K. Ghoshal, J. Hogan, D. Kashy, "An investigation into the electromagnetic interactions between a superconducting Torus and solenoid for the Jefferson Lab 12 GeV upgrade", *IEEE Trans. Appl. Supercond., submitted for publication,* ASC2014.

[7] R. M. Scanlan, J. M. Royet, "Recent Improvements in superconducting cable for accelerator dipole magnets", Particle Accelerator Conference, 1991. Accelerator Science and Technology, Conference record of the 1991 IEEE, pp. 2155-2157, Vol. 4.

[8] Composite Technology Development, Inc., Lafayette, CO.

[9] Jefferson Lab internal report, "Hall B Torus CCM VPI – Findings and Recommendations", April 2014.