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Superconducting Solenoid Magnet R&D for Muon Conversion Experiments

N. Andreev, V. S. Kashikhin, V.V. Kashikhin, M. Lamm, A. Makarov

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Introduction

The United States and Japan have a common goal of developing magnet technologies for future muon conversion experiments [1, 2]. In cooperation with the High Energy Accelerator Research Organization in Japan, we are building small aluminum stabilized NbTi test solenoids in order to test coil fabrication techniques as well as to study conductor properties. During the past year, the first coil was made using conductor developed for the Riken Superconducting Ring Cyclotron [3]. In order to test these coils near the expected excitation current and magnetic field on conductor, an "SC Cable Test Solenoid" has been designed. The main idea of this Cable Test Solenoid is to place a Test Coil (in this case, the Riken coil) between two Main Coils (wound of well known NbTi Rutherford cable), which generates the required field of ~5T. All 3 coils are connected in series. The cross section of the Main Coil is designed to fit into the Fermilab Vertical Magnet Test Facility (VMTF) Dewar and shall have sufficient margin to operate well above the critical current of the Test Coil. Note that the Test Coil can be changed to test different cables (for example, a future solenoid in this collaboration).

Splice studies were also performed in order to develop an effective way to create electrical joints between aluminum stabilized conductor and NbTi Rutherford cable. These joints will be needed in order to make the series electrical connection between the Test Coil and the Main Coils, and may be needed in a future full scale magnet.

The solenoid design aspects, electrical joint test results and the status of Test Coil fabrication are presented.

1. Solenoid Conceptual Design

Fermilab designed the SC Cable Test Solenoid to test SC solenoid coils made of NbTi cables, in magnetic fields of ~5 T. The solenoid contains three sections (two Main

Coils, and one Test Coil), assembled together, and electrically connected in series. The Test Coil is installed between the two Main Coils. The Main Coils are furnished with carbon steel (AISI 1010) flanges on the top and bottom of solenoid, attached permanently to the Main Coils, providing homogeneous field distribution in the coils, and reducing the difference in peak fields in Main and Test Coils. All three coils are tighten together with six stainless steel bolts 3/4”-10, located inside the solenoid aperture. These bolts give an additional coil pre-stress in the vertical direction during assembly. It should be noted that magnetic forces work in a desirable direction providing additional coil compression. Aluminum rings installed on the coils O.D. create additional pre-stress during the solenoid cool down to LHe temperature. The Main Coils are wound from two NbTi SSC cables in parallel. The cables are insulated from each other along the whole length but soldered together on the ends. The first conductor proposed for Test Coil is the aluminum stabilized Riken cable, supplied by Japan. The whole magnet system assembly is designed to fit in the 640 mm diameter of FNAL VMTF cryostat.

1.1. Magnetic design

The magnetic circuit of the system consists of one Test Coil and two Main superconducting coils. The coils ampere-turns are chosen to generate a 5 T field in the Test Coil. The Main Coils allow for a substantial decrease in the conductor volume in the Tested Coil but reproduce the large Lorentz forces and field, as in longer solenoids. Magnetic field simulation results are shown in Fig. 1.1 - Fig. 1.3.

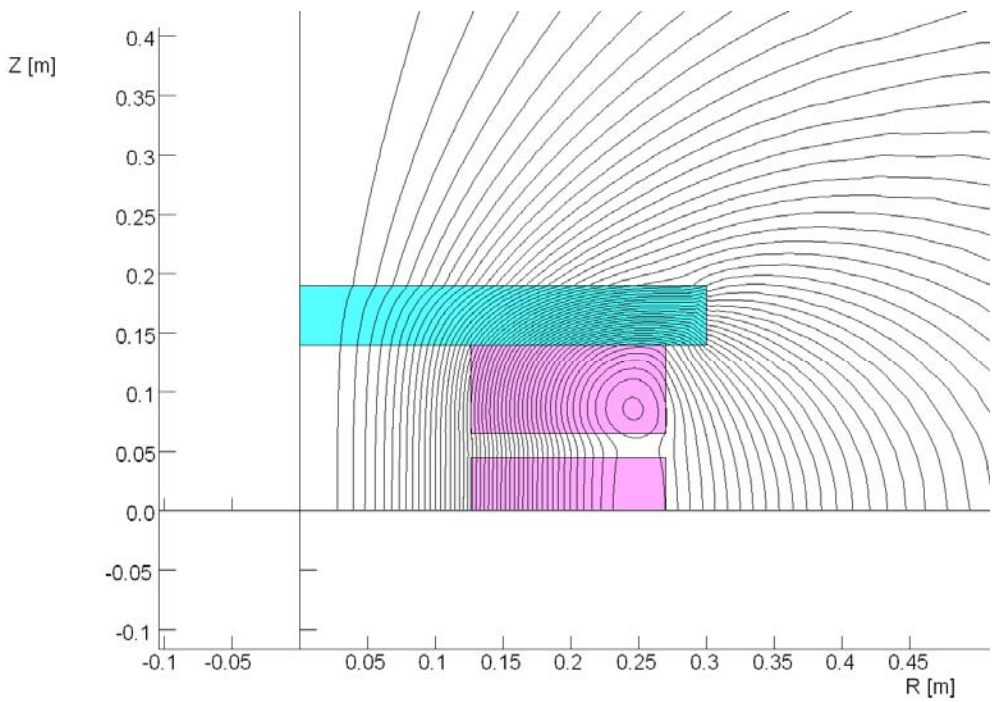

Fig. 1.1. Magnet system geometry and flux lines.

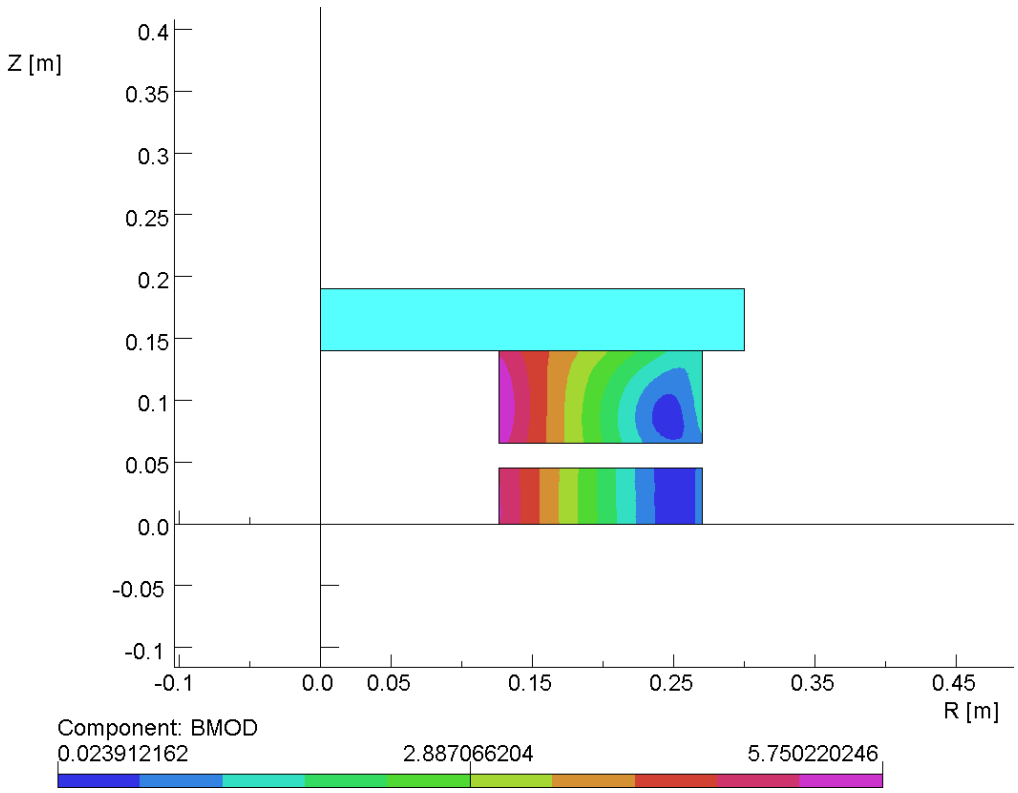

Fig. 1.2. Field distribution inside coils.

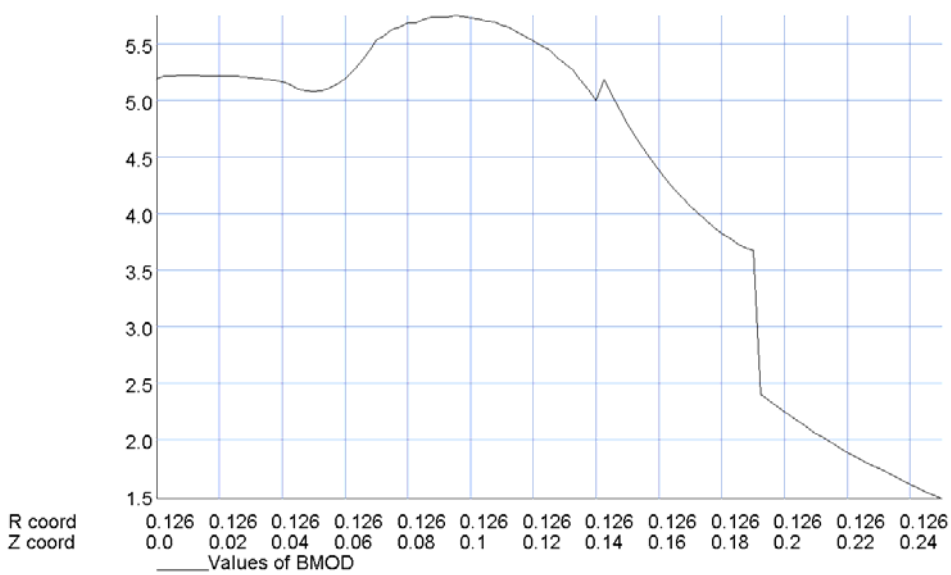

Fig. 1.3. Flux density along Z-axis at inner coil radius 0.126 m (5.2 T in the Test Coil, and 5.75 T in the Main Coils).

The double SSC cable cross section is much larger than the NbTi portion of Riken cable, and thus will provide a larger quench margin for the Main Coils, as shown in Fig. 1.4.

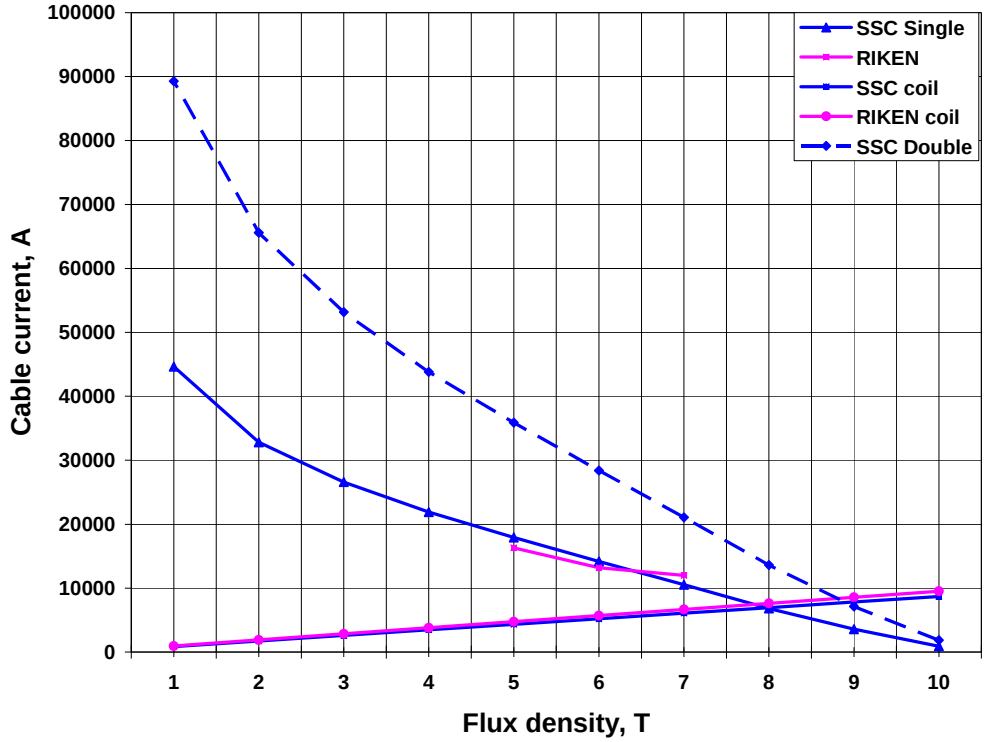

Fig. 1.4. SSC (blue) and RIKEN (magenta) cable short sample current limits, and coils load lines.

Fig. 1.4 shows that Main Coils have about 1 Tesla field margin relative to the Test Coil. So, if the mechanical stability both coil systems will be the same the Test Coil will quench earlier than the Main Coils.

1.2. Mechanical design

Coils are to be wound on stainless steel bobbins. Using the double SSC cable for the Main Coils winding, the cable are wound "hard way" to eliminate circulating currents caused by the flux difference. The "hard way" winding was also used for the Test Coil. Special attention was paid to the sufficiency of insulation in the conductor transition areas. The Test Coil is also equipped with two stainless steel heaters, installed between the bobbin and coil inner surface. All coils are independently vacuum impregnated with epoxy. For more accurate temperature monitoring a 5-10 mm thick G10 spacer will be placed between Main Coils and Test Coil to thermally insulate the Test Coil.

Lorentz forces generate hoop stress in the coils which are intercepted by the coils and outer bandage rings. Estimated force values shown in the Table 1.1.

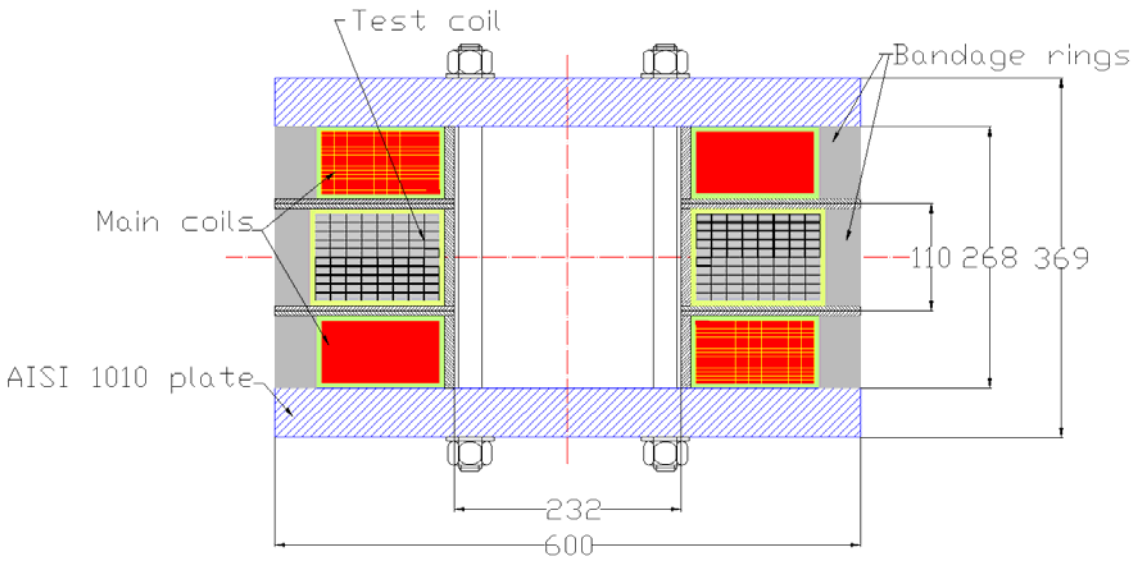

Fig. 1.5. Magnet system cross-section.

The Main Coil and Test Coil cross sections are shown in Fig. 1.6 and Fig. 1.7.

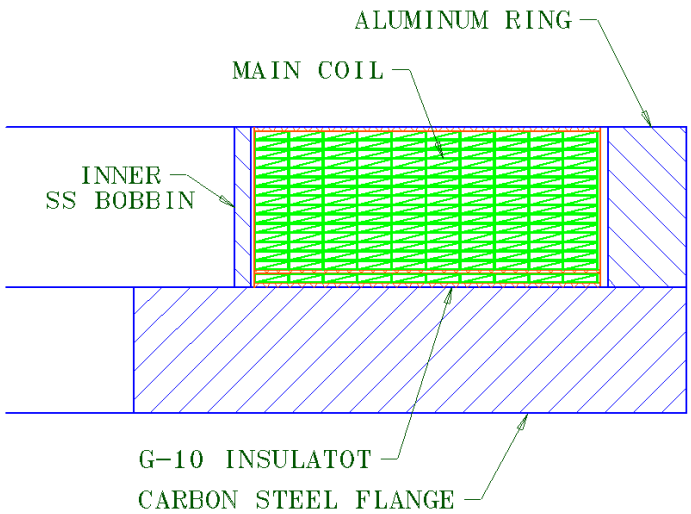

Fig. 1.6. Main Coil cross section. Coil contains 16 layers per 10 turns (160 turns per coil), 200 m of SSC cable required per coil.

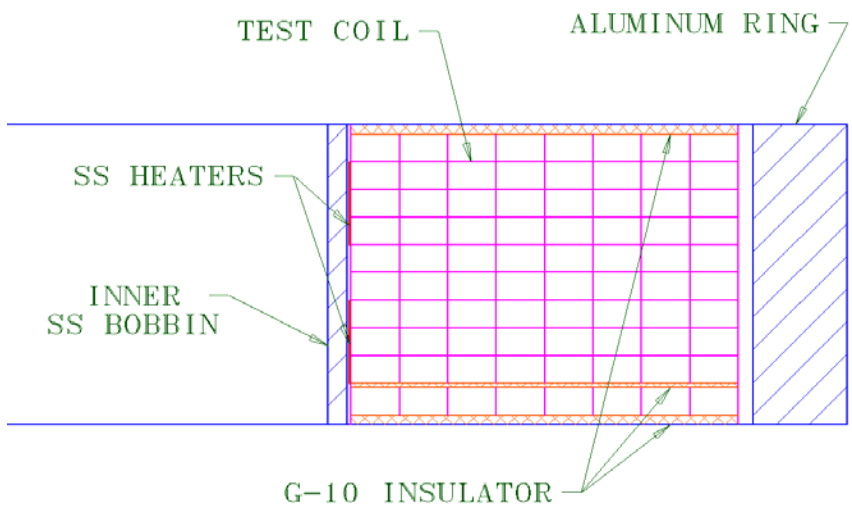

Fig. 1.7. Test Coil cross-section. Coil contains 10 layers per 8 turns (80 turns), 110 m of RIKEN cable required.

1.3. Design parameters

The magnet system parameters are presented in Table 1.1. There is some freedom in the parameters choice for a final design related to the test cable maximum length, insulation and transition turn thickness, etc.

Table 1.1

Parameter	Unit	Value
Nominal current	kA	5.0
Peak short sample limit current (RIKEN)	kA	~7.4
Nominal field in the test coil at 5 kA current	T	5.2
Inductance	H	0.04
Outer diameter	mm	600
Height	mm	369
Inner bore diameter	mm	232
Number of 3/4”-10 bolts		6
Lorentz forces:		
Test coil Fz	kN	-23
Test coil Fr	kN	1030
Main Coil Fz	kN	-522
Main Coil Fr	kN	1613
RIKEN bare conductor dimensions	mm x mm	8 x 15
SSC (double) bare conductor dimensions	mm x mm	2.9 x 12.3
Total RIKEN conductor length	m	110
Total SSC (single) cable length	m	400

2. Spice Studies for Aluminum Stabilized Conductor

Testing of the proposed Riken superconductor magnet will require the connection of this aluminum stabilized conductor to "bare" Rutherford cables. In a muon conversion experiment there will likely be a similar transition. Connection of these cables through soldering is problematic due to the aluminum stabilizer. Thus the aluminum stabilizer must be removed in order to make a copper to copper soldering joint and thus achieve the required splice resistance on the order of 1 $n\Omega$. This section summarizes studies at Fermilab to achieve this low resistance connection.

Figure 2.1 shows a cross section of the Riken conductor. Attempts to mechanically remove the aluminum stabilizer by filing, milling and sand blasting proved to be very difficult and judged to be impractical on an actual magnet lead. Thus the focus turned to chemically removing the stabilizer. In particular, HCL and NaOH solutions were employed under different conditions in order to prepare a copper surface that would adhere to the solder.

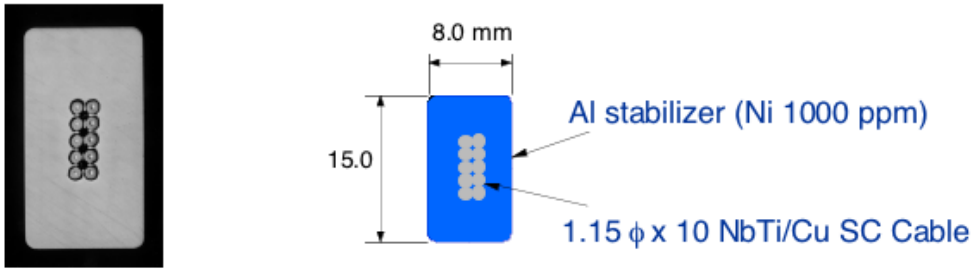

Fig. 2.1. Cross Section of RIKEN conductor.

Figure 2.2 shows the results of etching samples in room temperature baths of HCL and NaOH. For these samples, one side of the cable was preliminarily machined to speed up the process. As shown, both methods were effective in removing at least some of the aluminum. The HCL samples looked much better with approximately 10 mm of aluminum removed. The NaOH process was greatly improved by pre-heating the solution to 55º C. However, both room temperature and heated processes proved to be unsatisfactory because we were unable to tin the exposed copper/ NbTi strands.

Fig. 2.2. a) Results of etching samples in HCL and NaOH for approximately 8 hours at room temperature. One side of the aluminum was mechanically removed to speed up the chemical process. B) Etched sample in heated NaOH solution

Finally, samples were first etched in heated NaOH. This was followed by submersing the sample into the HCL solution. The result is shown in Figure 2.3. The resultant Copper/NbTi cable was easily tinned using either of two standard solder and flux. The tinned cables were easily soldered together for a solid joint.

Figure 2.3 a) Treatment with NaOH and HCL (see text) b) Successful solder joint

We have developed a reliable way to remove the aluminum stabilizer completely from the splice area, tin the NbTi portion of Riken cable, and solder it to the SSC NbTi pre-tinned Rutherford cable. However, it looks very attractive to have the aluminum stabilizer covering entire splice area. The R&D will be continued in this direction.

The results of this R&D will be used on our Cable Test Solenoid for the connection between Main Coils and Test Coil.

3. Fabrication of the Test Solenoid

In January 2010, the fabrication of the Test Solenoid was started.

3.1. Coil winding

As it was mentioned above, there are 3 coils to be wound for the Test Solenoid: one Test Coil from the Riken aluminum stabilized conductor, and two Main Coils from the double SSC cable. The following is a series of photos illustrating the Test Coils fabrication process.

In order to have both magnet leads coming out from the solenoid outer layer, the following technique was employed. The total length of coil conductor (80-turns worth) was split in two portions: the 72-turns worth portion of conductor was suspended above the winding table while the 8-turns portion was set on the remote tensioner. The "split" point is the conductor transition area from the coil first layer to the second layer.

Figure 3.1.1: Winding table at beginning of coil winding.

The first 8-turns layer of conductor was wound as a "pancake type" section (a flat coil with the turn radius increasing with each turn).

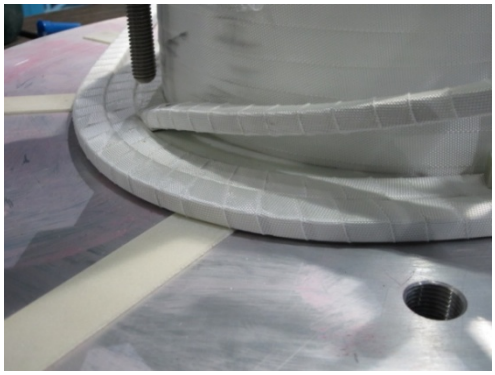

Figure 3.1.2: "Pancake type" section winding. First 3 turns have been wound.

Once the first coil layer was wound, the lead was secured on the winding table, and the 72-turns worth conductor portion, suspended before above the winding table, was moved and secured on the tensioner, and wound as a “solenoidal type” coil (each turn in the layer has the same radius while the layer radius increasing with each layer). After 9 turns of first layer wound, the cable has a transition to the second layer (also 9 turns). This process was continued until all 72 turns wound.

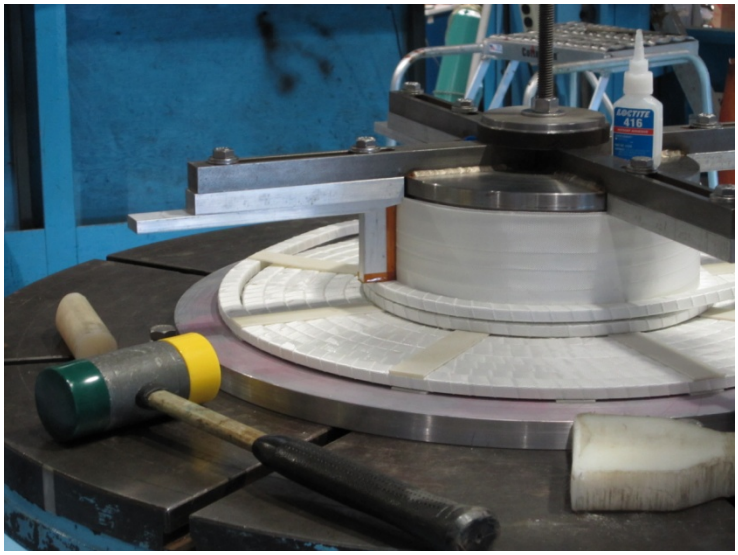

Figure 3.1.3: Solenoidal type coil winding. First 2 turns of first layer have been wound.

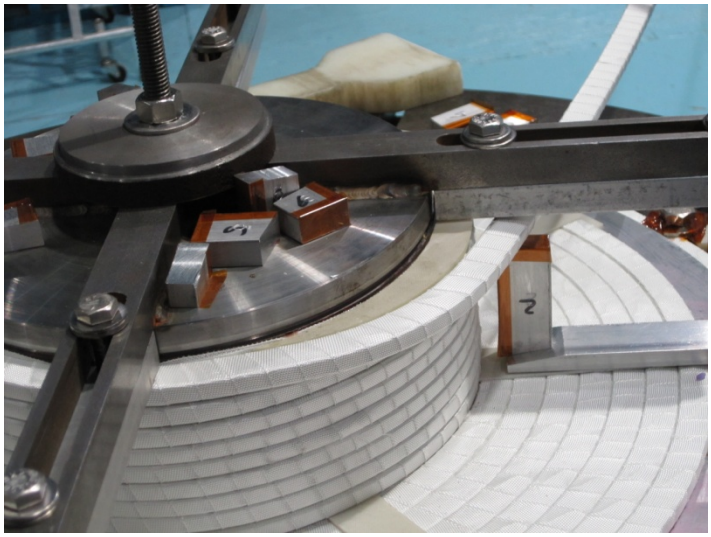

Figure 3.1.4: Solenoidal type coil winding. First layer has been wound. Preparing for the transition to the second layer.

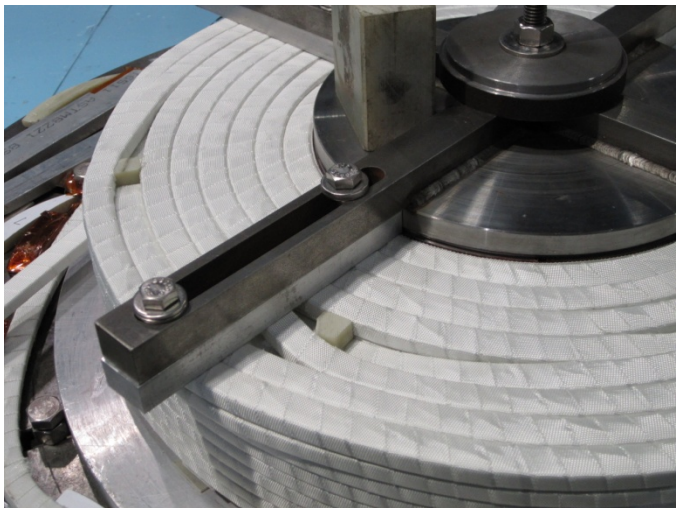

Figure 3.1.5: Final layer winding completed.

3.2. Coil potting

Once the coil is wound, it has to be potted with epoxy. A special potting tooling shall be used for this process. Two removable aluminum tooling flanges installed on the top and bottom of coil, the inner bobbin, and the outer aluminum ring create the mold for the coil potting. The inner bobbin and outer aluminum ring will stay with the coil after the potting, while the top and bottom flanges will be removed and used for the other coils potting. Two G-10 insulators, installed in outer ring slots create a reliable insulation for the coil leads. All mold parts were vacuum sealed with a suitable RTV. Connectors for the epoxy supply and return lines were installed on top and bottom flanges.

Below are some photos demonstrating the Test Coil potting preparation.

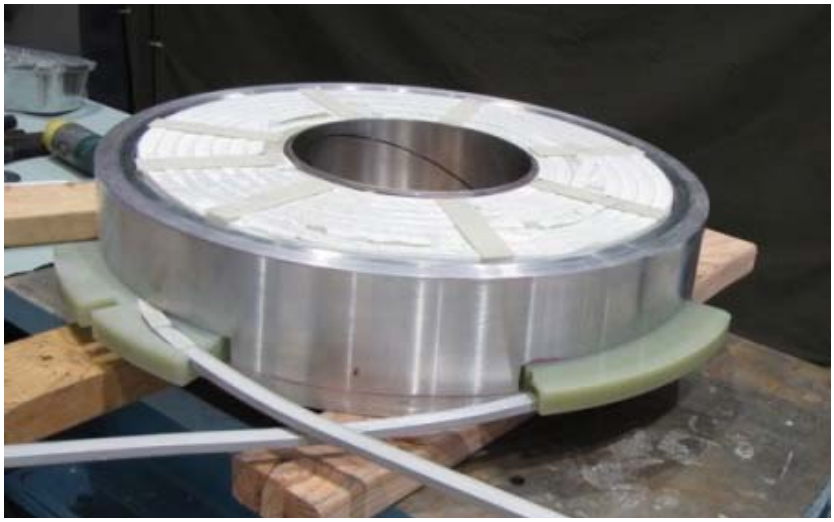

Figure.3.2.1: Test Coil with the outer aluminum ring and G-10 lead insulators, installed on the bottom aluminum flange.

Figure.3.2.2: Test Coil with completely assembled mold parts, sealed with RTV.

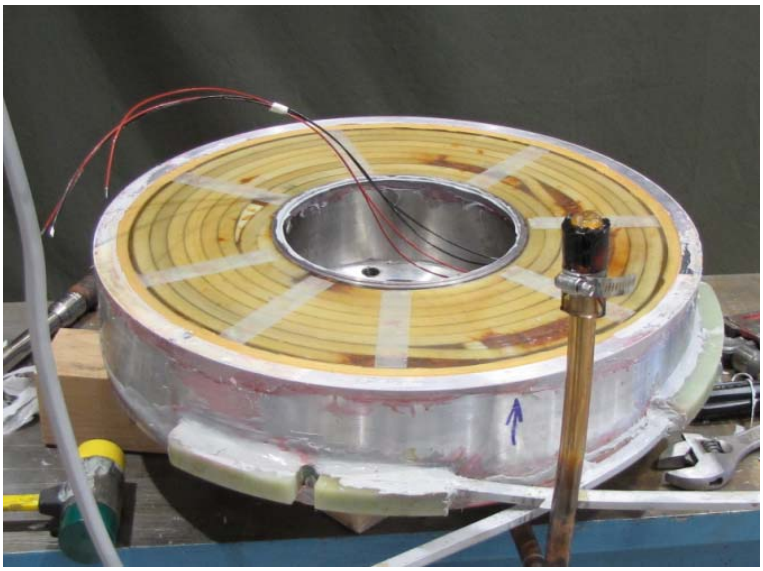

Figure.3.2.3: Test Coil in the mold after epoxy curing. The top flange has been removed.

We used the vacuum coil impregnation with the CTD-101K epoxy (a common epoxy used for the cryogenic magnets with a very low viscosity). It is well known that unfilled epoxy tends to crack, if it fills the voids greater than 1.5 mm. To minimize this cracking probability, different filler materials can be added to epoxy prior to potting. The potting was done in two steps: impregnation with the thin epoxy, and then – impregnation with the Cab-O-Sil filled epoxy. The first step assumes a good saturation of coil with epoxy. The second step allows replacing of thin epoxy in big voids with Cab-O-Sil filled epoxy. After the coil vacuum impregnation is completed, it was cured at 250°F for 12 hours. Then the top and bottom flanges shall be removed, and the coil electrically tested.

We expect the solenoid fabrication to be completed by the end of March 2010, and solenoid tested at VMTF by the middle of May 2010.

4. Considerations for use in the future

The proposed magnet system will allow testing various superconducting coils using existing FNAL VMTF test stand with only a modest amount of tested cable length. The peak field could be increased by adding of good tested coils to the auxiliary coils or by replacing NbTi coils with Nb3Sn. In this case 10 T field level will be achievable.

The magnet system should be quench-protected with an energy extraction circuit with less than 1 kV peak voltage. During tests the stress of outer aluminum bandage rings should be carefully monitored to be less than 200 MPa.

References

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2. Mu2e Collaboration, "Proposal to Search for $\mu^- N \rightarrow e^- N$ with a Single Event Sensitivity Below 10^{-16}", Fermilab Proposal E-973, 10 Oct 2008, Mu2e-doc-388-v1, http://mu23-docdb.fnal.gov
3. T. Kawaguchi *et al.* "Design of the Sector Magnets for the RIKEN Superconducting Ring Cyclotron", Proceedings for PAC 07, Vancouver, B.C. Canada, pp. 3419