Design and Fabrication of the Mu2e Cable Test Solenoid

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***Abstract*— The Mu2e experiment assumes use of superconductor solenoids, which requires extended R&D on different superconductor cable performances, working in strong field in the critical current range. To test these cables, the Mu2e Cable Test Solenoid was designed and fabricated at Fermilab. The solenoid contains three coils (two Main coils, and one Test coil), connected in serial. The Main coils are wound of the well known SSC NbTi cable. They are permanently attached to the solenoid top and bottom carbon steel flanges. The Test coil is replaceable, and meant to be installed between two Main coils. This coil can be wound of any superconductor cable which needs to be tested (the first Test coil was wound of RIKEN heavy aluminum stabilized NbTi cable). The cable's cross section ratio in the Main Coils and the Test coil ensures operating of Main coils in the current ranges far away from the critical value for their cable, while the Test coil always works near its critical current range. The solenoid design and some cable splicing issues are presented.**

***Index Terms*— Accelerator magnets, Cables, Solenoids**

I. INTRODUCTION

The necessity of building strong SC solenoids and required R&D for the Mu2e experiment was discussed elsewhere [1]-[3]. The Mu2e Cable Test Solenoid was designed and fabricated at Fermilab to test different types of NbTi cables in the magnetic field ~5 T at the currents, close to critical values for the tested cables. The cross section of solenoid is shown in Fig.1

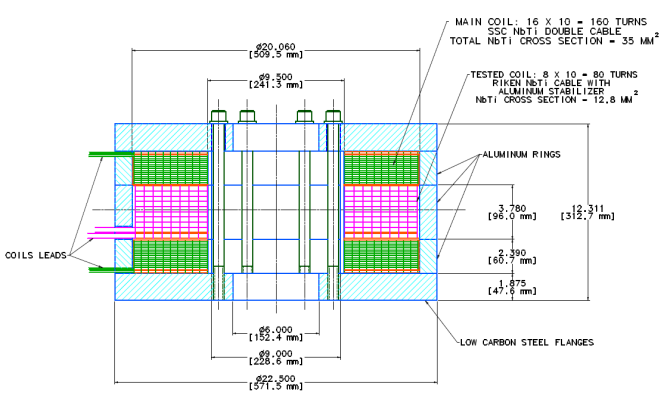

Fig. 1. Mu2e Cable Test Solenoid cross section

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The solenoid contains three vertical sections: two Main Coils and one Test Coil, installed between Main Coils. They are electrically connected in series. Main Coils are furnished with low carbon steel flanges on the top and bottom of solenoid, attached permanently to the Main Coils, to provide homogeneous field distribution in the coils, and reduce the difference in peak fields in the Main and Test Coils. All three sections tighten together with six stainless steel threaded tie rods 3/4"-10, located inside the solenoid aperture. These rods give an additional coil pre-stress in 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 coil's O.D. create additional pre-stress during the solenoid cool down to LHe temperature.

The Mu2e Cable Test Solenoid main parameters are presented in Table I.

TABLE I SOLENOID MAIN PARAMETERS

Parameters	Value
Nominal current	5×10^3 A
Peak short sample limit current (Riken cable)	~7.4×10^3 A
Nominal field in the test coil at 5×10^3 A	5.2 T
Inductance	4×10^{-2} H
Solenoid outer diameter	572 mm
Solenoid height	313 mm
Lorentz forces:	
Test coil Fz	2.3×10^4 N
Test coil Fr	1.03×10^6 N
Main coil Fz	5.22×10^5 N
Main coil Fr	1.613×10^6 N
Riken bare conductor cross section	8.06 mm x 15.09 mm
SSC (double) cable cross section	2.9 mm x 12.3 mm
Riken cable length	100 m
SSC (single) cable length	800 m

It was decided to wind the Main Coils from two NbTi SSC cables in parallel. This cable was available at Fermilab in the sufficient quantity. The cable originally was tapered, so two cables were flipped to avoid the key-stoning accumulation effect. The first conductor proposed for the Test Coil was the aluminum stabilized Riken cable, supplied by KEK, Japan. This Riken cable cross section is shown in Fig. 2.

Since the Riken Cable has a heavy aluminum stabilizer around NbTi strands, we also were working on developing a technique for reliable splicing of this cable with the SSC NbTi Rutherford cable, used for the Main Coils. This activity included the R&D on the procedure of aluminum stabilizer removal from the splice area, the NbTi cable strands pre-tinning process, and two cables soldering.

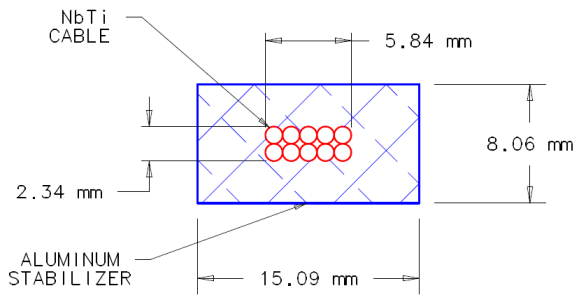

Fig. 2. Riken cable cross section

The whole magnet system assembly should fit into the 640 mm diameter of FNAL VMTF cryostat.

II. Coil Winding

Each coil was wound on the insulated with kapton and fiberglass tape stainless steel bobbin. Using the double SSC cable for the Main Coils winding, the cable shall be wound "hard way" to eliminate circulating currents caused by the flux difference in each cable. The "hard way" winding was also used for the Test Coil in attempt of using the same winding fixture and winding technique. Special attention should be paid to the sufficiency of insulation in the conductor transition areas. The Test Coil is also equipped with two stainless steel strip heaters, installed between the bobbin and coil inner surface.

Fig. 3. Test Coil winding setup

In order to get both coil leads coming from the coil's outer radius, each coil was wound as a combination of "pancake" and "solenoidal" types of coil. As it is shown in the Fig. 3, the cable part for the "pancake" type of coil is secured at the tensioner, and the cable part for the "solenoidal" type of coil is hung above the winding table. Once the "pancake" part is wound, the cable for the "solenoidal" part will be moved to the tentioner.

The Test Coil winding in process is shown in Fig. 4. The "pancake" type part of the coil is wound already (the lower flat layer), and the "solenoidal" part of the coil winding is in process.

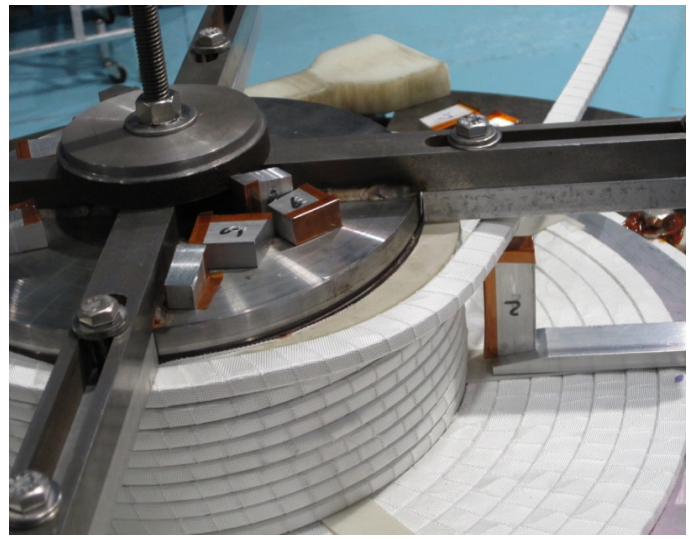

Fig. 4. Test Coil winding in process

Special G-10 spacers installed in the coil transition areas prevent the cable insulation from being damaged. Once a coil is wound, an aluminum outer ring, a removable aluminum mold flange (two flanges for the Test Coil), and special G-10 leads insulators were installed to ensure reliable insulation of coil leads from the outer ring. After this each coil was vacuum impregnated with CTD-101K epoxy separately.

The Test Coil with outer ring and leads insulators installed is shown in Fig. 5. G-10 insulating strips on the coil create the additional insulation between coils and provide better epoxy flow across the coil.

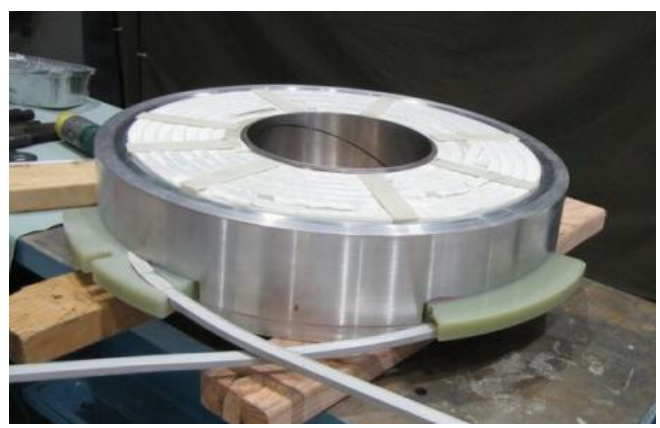

Fig. 5. Test Coil with outer ring and leads insulators installed

All three coils were assembled together using stainless steel threaded tie rods (shown in Fig. 6). The coil leads were spliced (tin soldered together) using special copper channels, to have all 3 coils connected in series. Besides, these copper channels serve as stabilizer in the cables splice area.

The coils and heaters were hipot tested against each other and against ground with 1 kV.

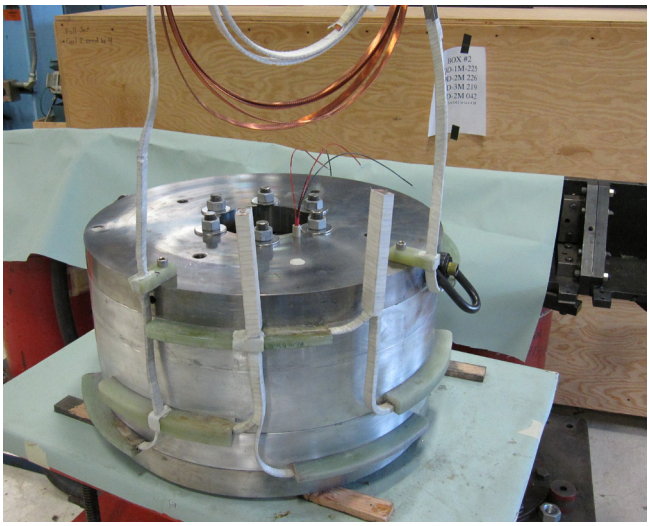

Fig. 6. Mu2e Cable Test Solenoid final assembly

III. Cable splicing

As it was mentioned above, there is a difficulty of soldering aluminum stabilized Riken cable to the SSC cable. Both NbTi cables shall be tinned in the splice area all way through prior to soldering to each other. The aluminum stabilizer must be removed from the Riken cable while the copper layer around the NbTi strands shall be intact. At Fermilab we performed a R&D on etching off the aluminum from the Riken cable using different solutions and etching temperature regimes. The best results for the etching were obtained using the hot 50% NaOH solution. It looks practical to remove most of aluminum from the cable mechanically prior to etching to expedite the etching process. Some Riken cable samples with the etched off aluminum stabilizer on the end are shown in Fig. 7.

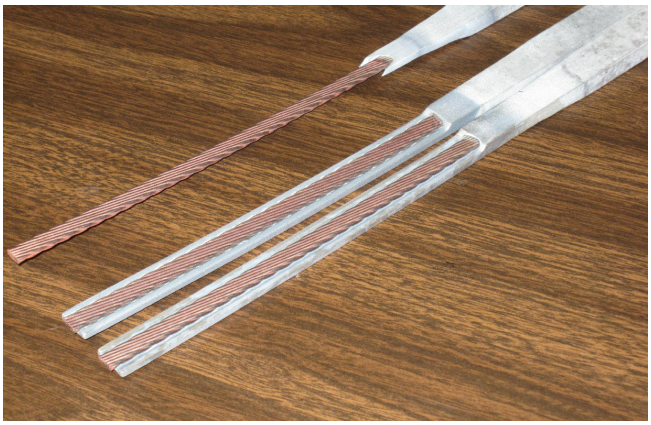

Fig. 7. Riken cable samples with etched off aluminum stabilizer

The upper sample demonstrates the non-machined cable etched for 8 hours. The two lower samples were pre-machined on one side, and then etched for one hour. The machining of aluminum on one cable side only was done in attempt to keep the aluminum stabilizer all over the splice area, but unfortunately, aluminum was etched off all around the NbTi strands, leaving a gap of 1-1.5 mm between NbTi and aluminum, making the existing aluminum stabilizer useless in the splice area. For the real Test Solenoid we removed aluminum stabilizer completely all around the NbTi in the splice area, clamped both NbTi leads with pre-tinned copper channels overlapping the aluminum stabilizer, and filled all the gaps between cables and channels with a tin solder.

Another problem found after the etching off the aluminum stabilizer with NaOH was the poor solder ability of exposed NbTi strands – the solder did not stick well to the strands surface, no matter what type of flux we used. Eventually this problem was successfully solved by the additional treating of the NbTi cable with 50% HCL solution at room temperature for a half of hour. After this treatment the cable ends were brushed with a liquid flux, immersed into a tin pot for a few minutes, and immediately wiped off with a cloth. This method allows tinning of NbTi cable all way through, which benefits to the further cable splicing.

IV. Conclusion

The Mu2e Cable Test Solenoid was designed and fabricated at Fermilab to test different types of NbTi cables in the magnetic field ~5 T at the currents, close to the critical values for the tested cables. The cable hard way coil winding technique for a combination of “pancake” and “solenoidal” types of coil was developed. The problems related to the splicing (soldering) of heavy aluminum stabilized Riken cable with non-stabilized NbTi SSC cable were successfully solved, as well as the cables splice area stabilizing problems.

References

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