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Superconducting Solenoid and Conductor R&D for Muon Conversion Experiments for CY2010

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Abstract

This report summarizes the work done at Fermilab during CY2010 on the development of superconducting solenoids for future muon conversion experiments. This work is part of the US-Japan agreement.

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 and study conductor properties. This report covers the second year of this collaboration. During the first year, the first coil (MODEL 1) was made using conductor developed for the RIKEN Superconducting Ring Cyclotron [4]. In order to test these coils near the expected excitation current and magnetic field on conductor, an "SC Cable Test Solenoid" was designed and built. The main idea of this Cable Test Solenoid is to place a Test Coil (such as the RIKEN coil) between two Main Coils (wound of well known NbTi Rutherford cable), which generates the required field of ~5T.

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.

In last year's report [3], the design of this coil test facility was described, along with the start of the coil fabrication. Also presented were the results of spice studies aimed at developing effective electrical joints between aluminum stabilized conductor and bare NbTi Rutherford cable.

In this report, we discuss the second-year accomplishments. In this year (CY2010) MODEL 1 was finished, and assembled with the two Main Coils into a single test unit. It was then tested in the Fermilab test facility (VMTF), up to field of ~5T. The results of this test are presented. Additionally, a concept design for "MODEL 2" was developed, using aluminum stabilized conductor produced by Hitachi cable. Here the emphasis will be placed on fabrication techniques as well as conductor performance. Finally, "cable stack" tests were performed on ATLAS cable, in order to understand the mechanical properties of the aluminum stabilized conductor. These results are applicable to the mechanical design of the COMET and Mu2e full scale solenoids.

1. MODEL 1 Design and Fabrication

RIKEN superconductor, supplied to Fermilab from Japan, has high mechanical strength, good thermal and electrical stability. As described in last year's report, this test set-up includes two main coils made from hard bent fiber glass / Kapton insulated Rutherford-Type double layer NbTi SSC cable wound around two separate but identical mandrels sandwiching the RIKEN cable test coil wound around its own mandrel. The goal of this set-up is for the two main superconducting coils to generate a large fraction of the magnetic field in the space of the test coil placed between them thereby augmenting the magnetic field distribution in the whole experimental test set-up. The main coils substantially decrease the conductor volume in the test coil by reproducing the large Lorentz forces and field as in longer solenoids.

The primary features for this RIKEN coil test magnet assembly is listed in Table 1.1 below and the cross section of the global mechanical assembly is shown in Figure 1.1.

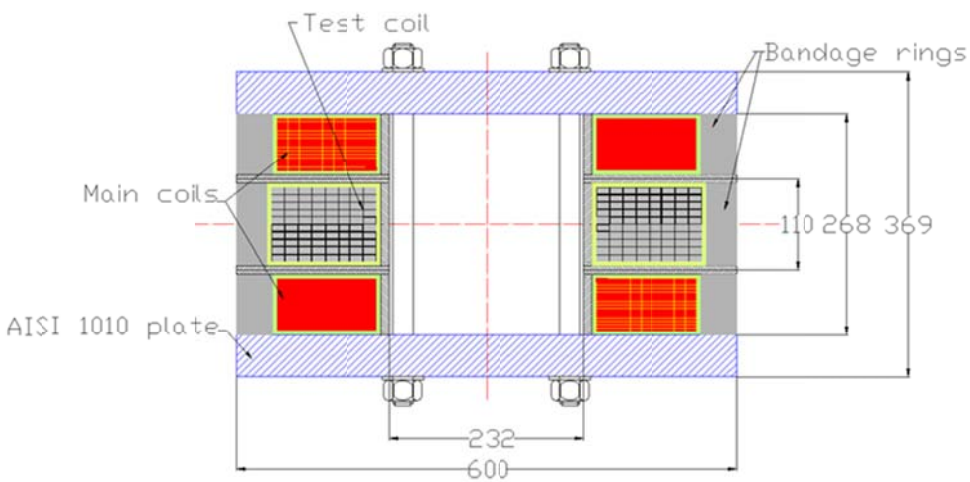

Fig. 1.1 Al stabilized NbTi coil test magnet cross section.

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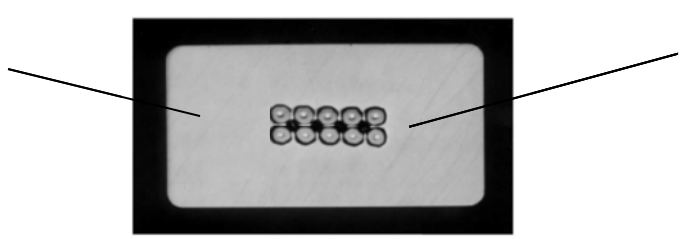


or

Fig. 1.2 Cross section of Al stabilized NbTi superconductor cable [4].

Table 1.1: Primary features of RIKEN coil Test Magnet

Cable strand type (Main Coils)	2 parallel NbTi Rutherford Type SSC cable
Cable strand type (Test Coil)	Aluminum stabilized NbTi cable
Cable Insulation (Main Coils)	Fiberglass with 40% overlap, Kapton with gaps
Cable Insulation (Test Coil)	Fiberglass with 40% overlap
Bore Diameter	232 mm
Impregnation epoxy type (Main Coils)	CTD101K
Impregnation epoxy type (Test Coil)	CTD101K
Vacuum epoxy impregnation temp (Main Coils)	60^0C
Vacuum epoxy impregnation temp (Test Coil)	60^0C
Impregnation cycle (Main Coils)	10 hours
Impregnation cycle (Test Coil)	10 hours
Spacers / laminates for interfaces	G10 strips
Coil Fabrication Start Date (Test Coil)	02/25/2010
Cold Mass Completion Date (Test Coil)	03/24/2010
Coil Fabrication Start Date (Main Coils)	03/30/2010
Cold Mass Completion Date (Main Coils)	05/15/2010
Overall Cold Mass Completion Date	06/08/2010

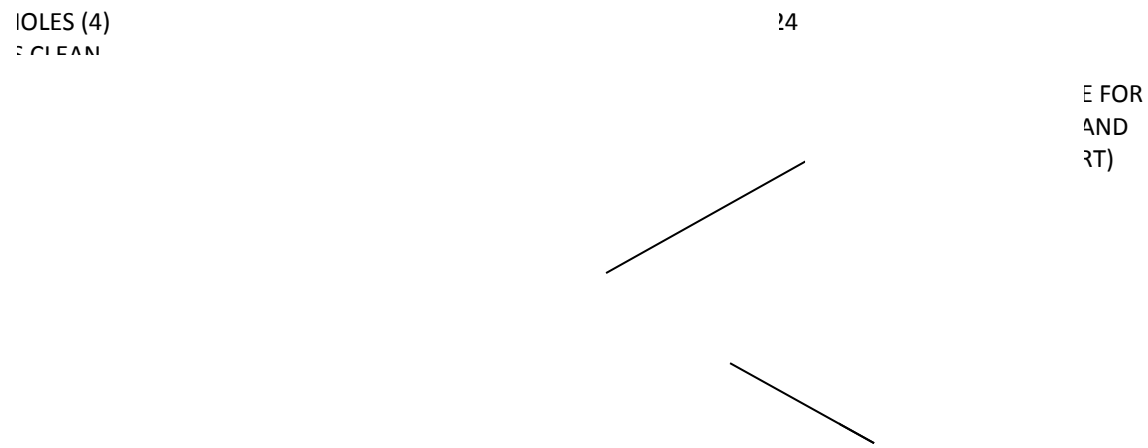


Fig. 1.3 Schematic of magnet showing splice connections current leads and top support plate.

NbTi superconductor cable array embedded in the center of this aluminum alloy. An extrusion process was used to facilitate the bonding between the aluminum alloy and the superconductor [4]. Figure 1.2 shows the cable crosssection.

The coil winding and vacuum impregnation is described in last year's report [3]. The detail of the final assembly, including the coupling of the RIKEN coil and 2 main coils, is shown in Figure 1.3. A picture of the final assembly is shown in Figure 1.4.

Fig. 1.4 Final structural assembly showing the splices between the main and RIKEN coils. The current leads are also shown.

2. MODEL 1 Test Results

2.1 Test Overview

The Magnet Description document which captures the important attributes, instrumentation and test plan for the magnet, is posted at http://tiweb.fnal.gov/website/controller/1759. For test records, magnet is designated the name: "Mu2e_SOL_01". . The top SSC cable coil in Mu2e_SOL_01 is named "Top", the bottom SSC coil is "Bottom" and the RIKEN conductor coil is designated as the "Test Coil". The magnet was mounted to the 30 kA Top Plate assembly for VMTF and final preparations for testing were completed the last week of September 2010. Figure 2.1 shows the magnet connected to the assembly, with a warm-bore tube installed and centered in the magnet aperture.

As there were no internal voltage taps, only three voltage tap segments were instrumented via taps at the coil-to-coil splices and leads. With three coils, the "half coil" segments for quench protection were made up of the Top+Test coil for one half, and Bottom coil for the second half. Two Cernox sensors were mounted on the cold mass outer skin to monitor top and bottom edge temperatures of the solenoid during the test.

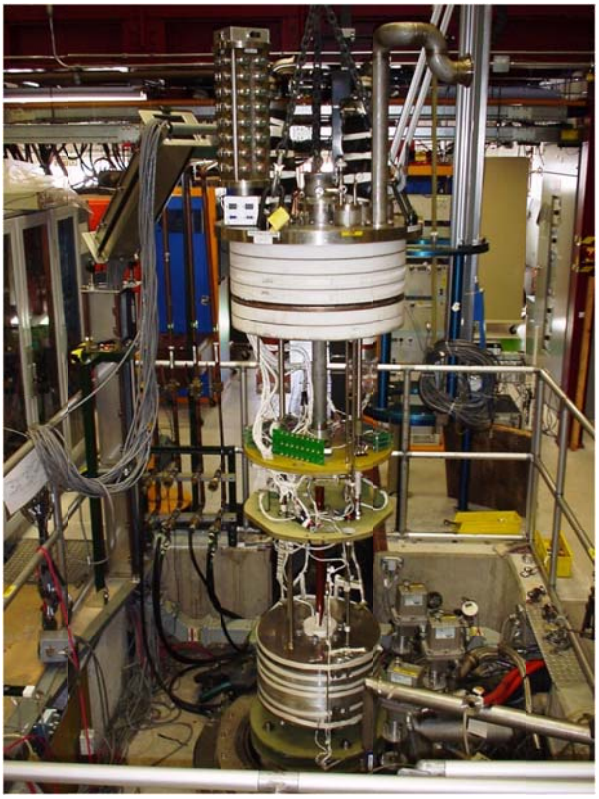


Fig. 2.1 Mu2e_SOL_01 mounted to the 30 kA Top Plate Assembly with warm-bore tube inserted at VMTF.

The magnet was tested in one cold test cycle. The cool down to 4.5 K occurred on September 29th. The magnet passed cold hi-pot of 1000 V with leakage current 0.24 μA. Quench training at 4.5 K began on October 1st. Training and ramp rate studies continued until October 15th at which time the MTF cryogenic plant was shut down for maintenance.

2.2 Cold Magnetic Field Measurements

A 3-axis Senis Hall probe (S/N 26-05) with 10 T range was used to capture the axial magnetic field strength profile with the magnet powered at 3000 A. This allows comparison to the magnetic field model prediction for the field on axis, to validate the model (which is used to predict the peak field on the coils, and quench current). The prediction was made using Opera2D, constructed using the as-built geometry (defined by drawing #460692). The BH property of the steel flanges (AISI 1018) was assumed to be "average mild" steel, which has a permeability of about 600 below saturation. The Hall

probe was mounted on a long G-10 shaft within in a probe support that centered it, with B_z aligned with the magnet axis. A scale on the shaft allowed manual positioning with <1 mm accuracy. Angular orientation of the probe was not well controlled, so the B_x and B_y values have not been studied. Figure 2.2 shows a comparison of measured and predicted B_z versus Z-Z_0, where the center point Z_0 is obtained from the measured B_z symmetry. As shown, the measured and predicted fields are in good agreement.

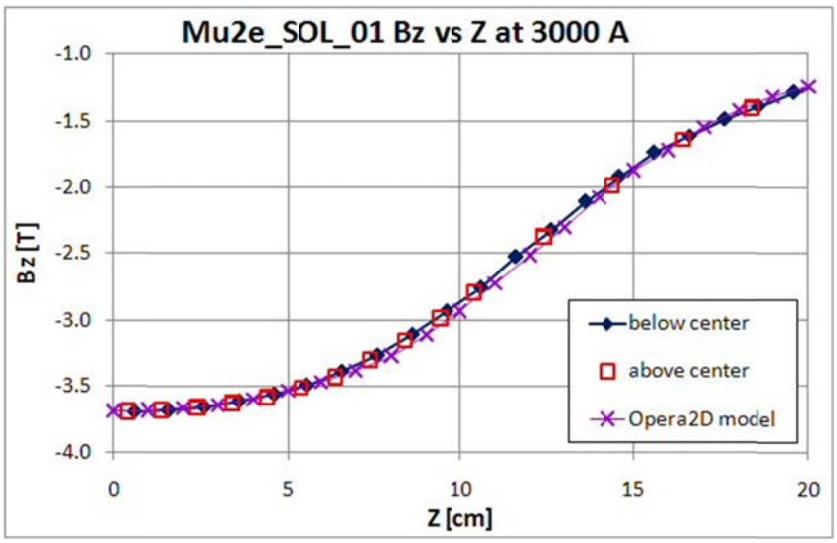


Fig. 2.2 Measured and predicted axial field strength (B_z) versus position along the solenoid axis (Z).

2.3 Quench Performance

The quench training history is shown in Fig. 2.3 and 2.4. Quench current started quite low and training was very slow, but steady. Ramp rate dependence was found to be very strong. This is believed to be a result of a strong Eddy Current coupling to the aluminum support structure. Therefore, most of the quench studies were made at low ramp rate (using higher ramp rates at low current, to get to the quench region in a reasonable time); 1 A/s was the lowest achievable ramp rate. Lowering the temperature from 4.5 K to 3.0 K did not improve performance (not shown). The peak current was 3960 A which corresponds to a peak field of approximately 4.8 T in the center of the RIKEN coil.

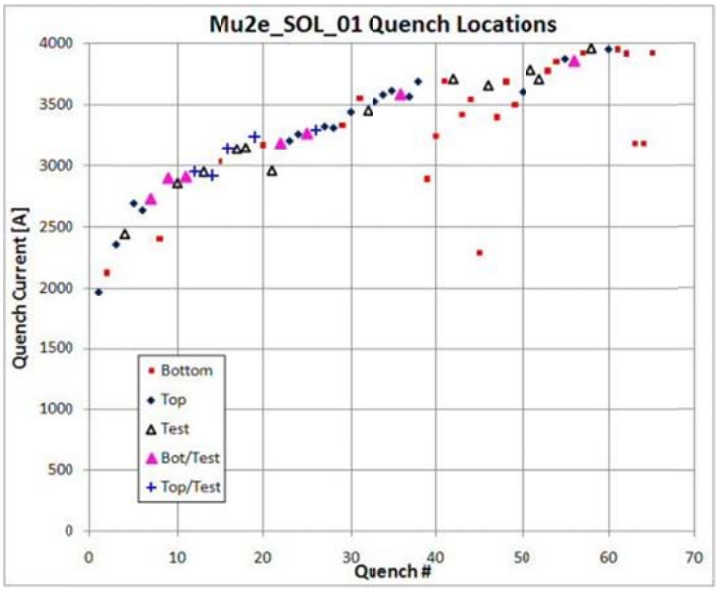


Fig. 2.3 Ramp rate dependence of Mu2e_SOL_01 quench current, with quench locations shown.

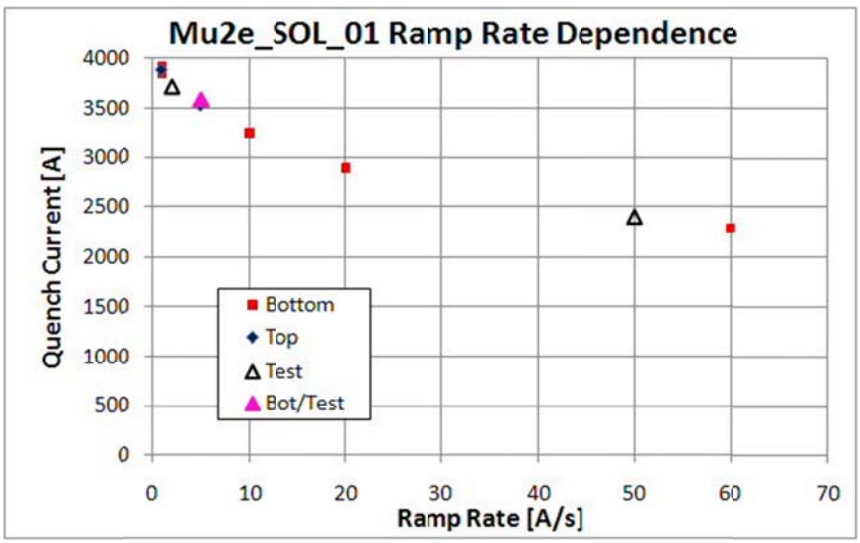


Fig. 2.4 Quench training history, by quench location.

3. MODEL 2 Concept

The main goal of this proposal is to design, build and test superconducting coils based on the newly fabricated aluminum stabilized NbTi superconductor from Hitachi Cable. The crosssection of this cable is shown in Figure 3.1. The conductor parameters are shown in Table 3.1. The MODEL 2 coil should model the technology and achievable parameters of Mu2e and COMET solenoids. The coil should not have the inner support ring. The coil prestress is provided by the outer Al bandage ring. The solenoid should have the possibility for the conduction cooling; for that, an aluminum pipe has been welded to the outer bandage ring surface. The very good thermal contact should be provided. The coil wound from the superconductor 4.7 mm x 15 mm with an Al stabilizer. The solenoid end flanges should provide the coil longitudinal prestress. The whole solenoid system assembly should fit in the 640 mm diameter of FNAL VMTF cryostat.

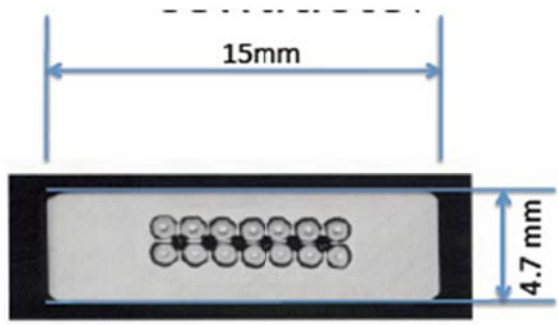


Fig. 3.1 Crosssection of aluminum stabilized NbTi cable supplied from Japan as part of the US-Japan Agreement.

Table 3.1 Design parameters of Hitachi Cable

Item	Value
Cable Dimension	
Without insulation	15 x 4.7 mm
With insulation	15.3 x 5. mm
Strand Diameter	1.15 mm
Strand Number	14
Al/Cu/NbTi	7.3/0.9/1.
Aluminum RRR	500
Copper RRR	50
NbTi Jc at 5 T 4.22 K	2700 A/mm2
Al yield strength	55 MPa
Overall yield strength	150 MPa

3.1 Magnetic Design

The solenoid magnetic model consists of 120 turns having 5 kA current. The total number of ampere-turns is 600 kA. At this current, the peak field on the inner coil surface is 2.55 T. Magnetic field simulation result is shown in Fig. 3.2 - Fig. 3.4.

The proposed coil is shown in Figure 3.5. The coil is mounted between two ferromagnetic plates (recycled from MODEL 1). The aluminum bandage ring is placed on the outer coil surface. The ferromagnetic plates bolted to each should be capable at providing the coil prestress in the vertical, Z-direction. Besides the flange, Lorentz forces compress the coil vertically during excitation. The coil wound on the technological, removable after winding mandrel. The outer bandage ring surface has welded cooling tube for the indirect conduction LHe cooling. The field shown in Fig. 3.2 is calculated without iron flanges. The conductor critical current is 4.27 kA at 5 T and 4.2 K temperature. The coil heaters should be placed on the inner and outer coil surfaces. These heaters should model the heat deposition from the radiation. For that reason the coil inner surface and side surfaces should be efficiently thermally insulated from the LHe bath.

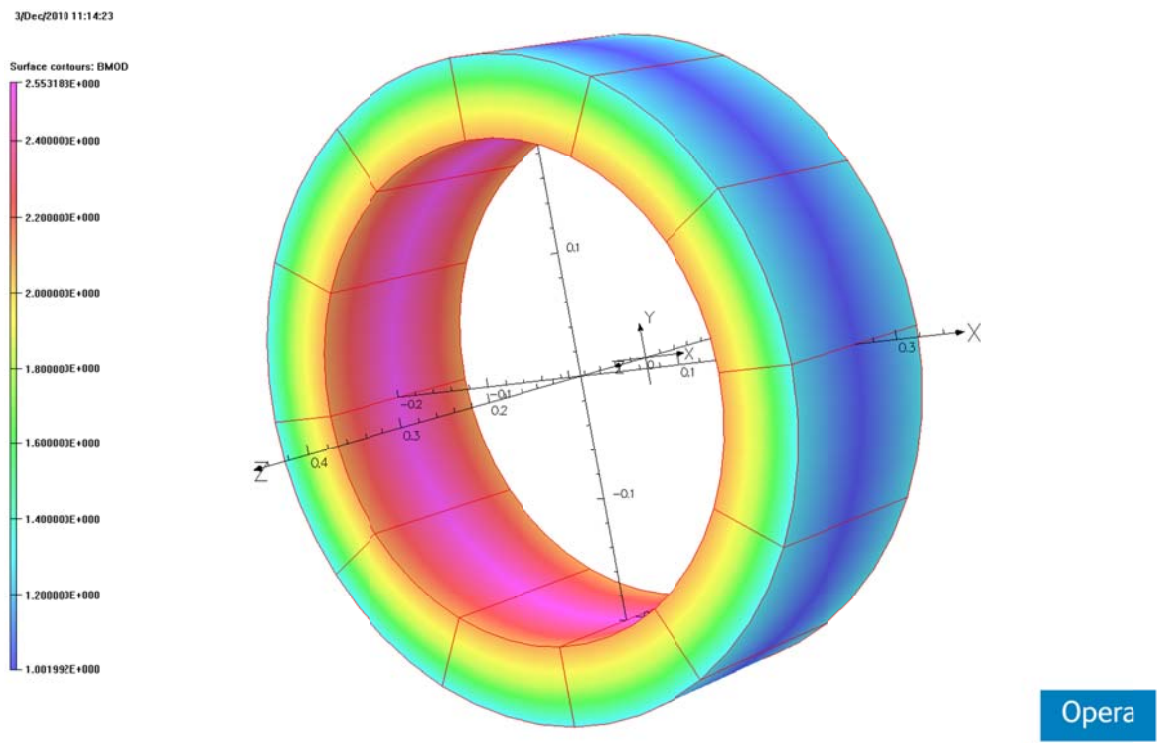


Fig. 3.2 Solenoid geometry and flux density.

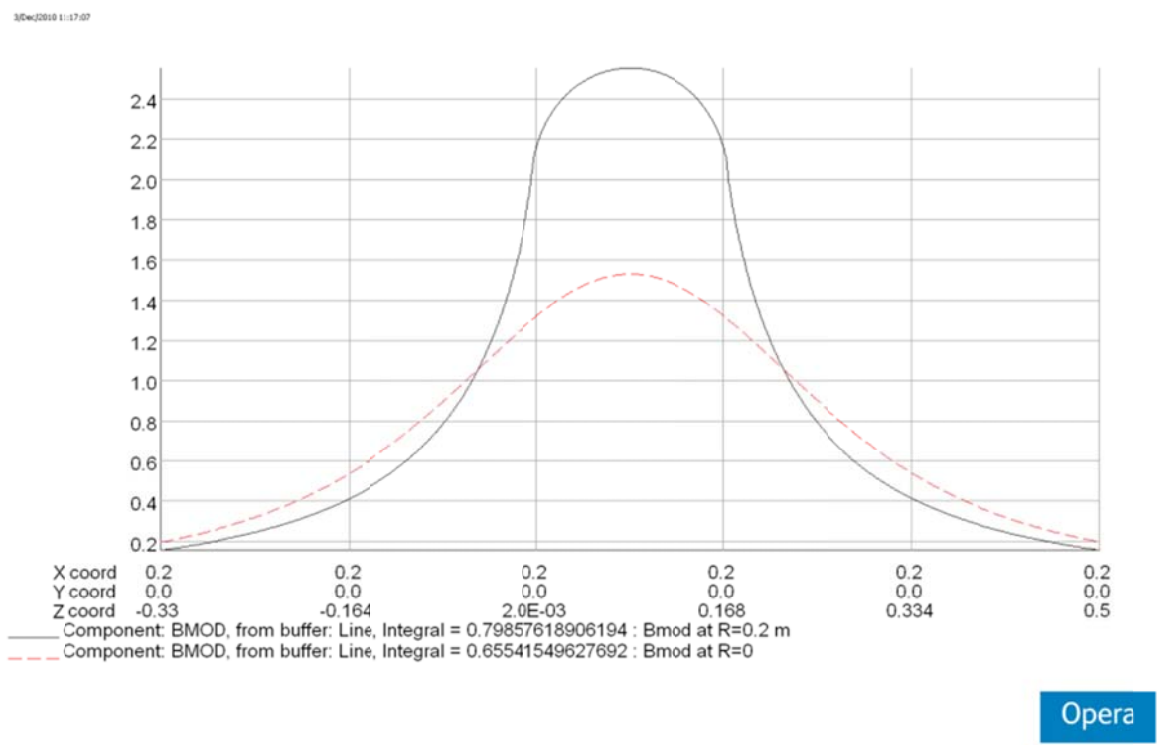


Fig. 3.3. Field distribution along Z-axis.

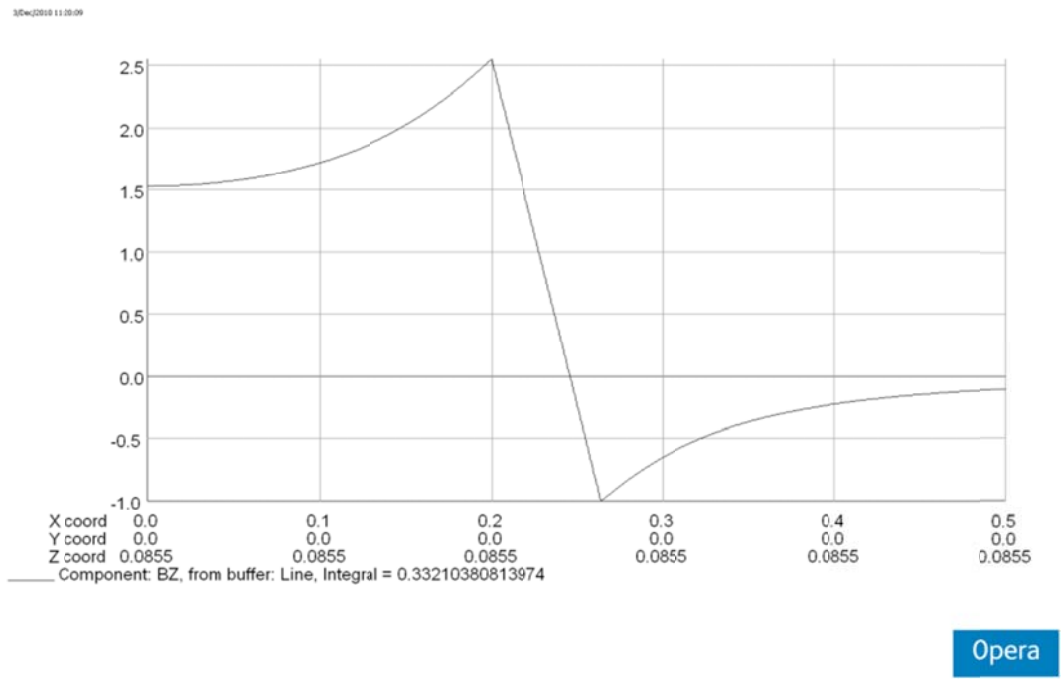


Fig. 3.4. Flux density in the radial direction.

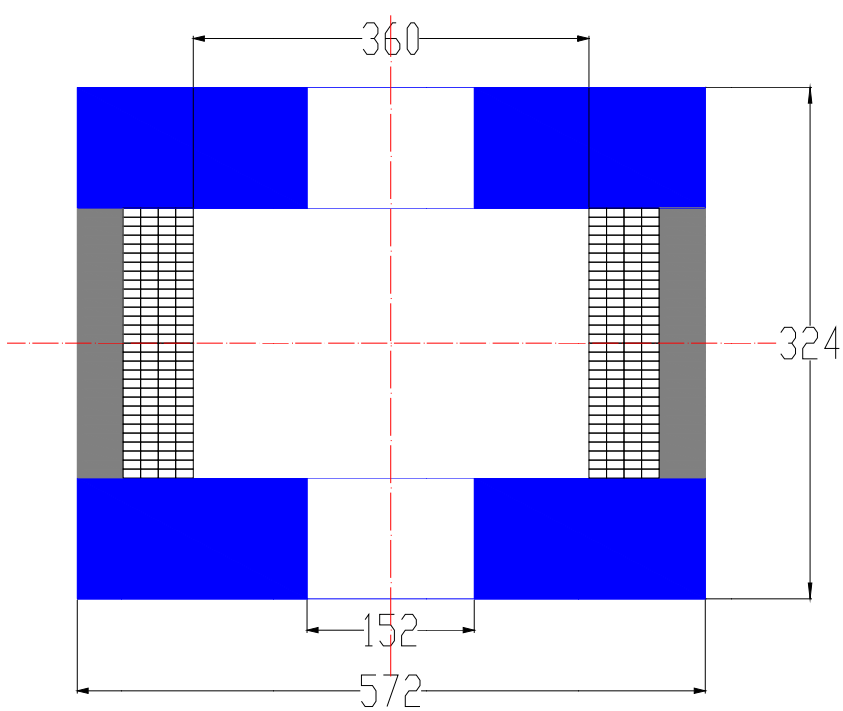


Fig. 3.5 MODEL 2 Solenoid crosssection.

4. Structural Measurements of ATLAS Cable Stacks

The design of a high field/multilayer superconducting coil requires an understanding of the thermal and mechanical properties of the insulated conductor during cooldown and excitation. The superconducting coil consists of aluminum, superconductor, fiberglass insulation and epoxy. Each material has different thermo-mechanical properties as a function of temperature. The composite properties of these material admixtures are dependent on fabrication methods and coil geometry and are therefore difficult to predict.

The purpose of this study was to evaluate the structural properties of vacuum impregnated cable stacks with high strength Al stabilizer and fiberglass insulation similar to what is expected for Mu2e/COMET production/capture solenoids.

For this test, ATLAS central Solenoid Cable was used [5]. The properties of the ATLAS conductor are shown in Table 4.1.

Material/Property	Temp., K	Al stabilizer	Overall cable
Yield strength, MPa	300	81	128
Ultimate strength, MPa		86	184
Maximum allowable stress, MPA		**43**	**85**
Yield strength, MPa	4.2	110	147
Ultimate strength, MPa		294	-
Maximum allowable stress, MPA		**73**	**98**

Table 4.1 Properties of ATLAS Central Solenoid Magnet Conductor. Note: stress shall not exceed 43 MPa during room-temperature operations.

The cable stacks were assembled as follows. The cable was cut into equal pieces of ~90 mm long. The pieces were butt-wrapped with 4 layers of 0.125 mm thick E-glass tape that constituted the nominal insulation for the Mu2e Production Solenoid. Six insulated cable pieces were stacked and impregnated with CTD-101K epoxy under pressure of 40 MPa applied to the broad faces of the cables. This high pressure was chosen to assess the stack performance at the upper limit for the impregnation pressure. The actual impregnation pressure for the Mu2e Production Solenoid was expected to be considerably lower than that.

After impregnation, the stack was sectioned into ~cubic pieces (i.e. ~ 30 mm x 30 mm x 30 mm, 6 layers of conductor cut into 30 mm pieces) using low-speed diamond saw. The samples were instrumented with 4 strain gauges per side, on 4 opposing sides. See Figures 4.1- 4.2. The measurements of elasticity modulus and thermal contraction coefficients were performed at 300 K and 4.2 K using a lower temperature loader.

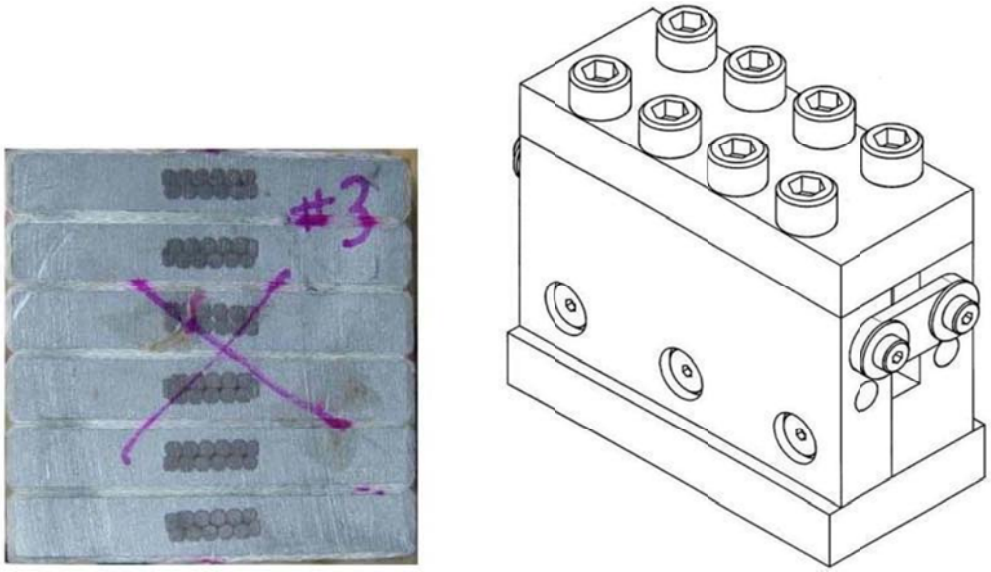


Fig. 4.1. ATLAS Central Solenoid magnet cable stack (left) and cable stack potting fixture (right).

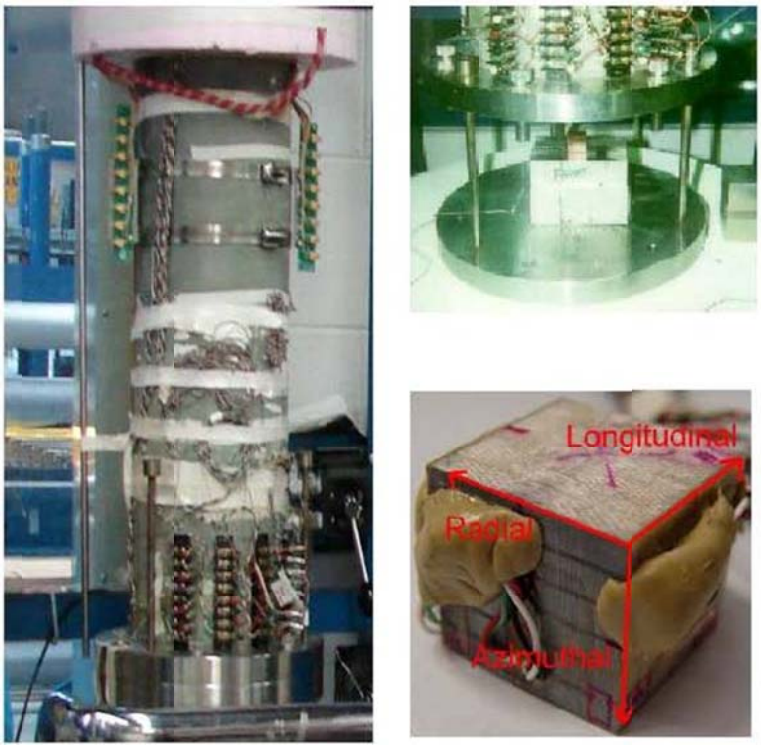


Fig. 4.2 Test set-up for cable stack test.

In order to measure the elasticity modulus, the samples were repeatedly loaded in the axial and azimuthal directions (that refers to the cable orientation in the actual coil assuming the “hard” way bending) at room temperature and 4.2 K. The test results are shown in Figure 4.3.

The elasticity modulus in the axial direction is dominated by the properties of (soft) insulation. Therefore, the measured modulus was relatively low: 39.4 GPa at room temperature and 34.5 at 4.2 K. The reason for the room temperature modulus being higher than the cryogenic temperature is not fully understood.

In the azimuthal direction the elasticity modulus is dominated by the properties of aluminum stabilizer. Thus, the measured modulus is considerably higher than that in the axial direction: 53 GPa at room temperature and 62.7 GPa at 4.2 K. It was not possible to measure the elasticity modulus in the radial direction because the cables started to delaminate at a relatively low applied pressure.

Prior to the measuring of the thermal contraction coefficients, the strain gauges were calibrated using pieces of aluminum and stainless steel of approximately the same dimensions as the cable stacks. Figure 4.4 shows the measured thermal contraction coefficients in the axial, azimuthal and radial directions.

Depending on the calibration coefficient used (either Al or SS), the average thermal contraction coefficient in the axial direction ranges from 3.2-3.4 μm/mm, and in the 3.1-3.4 μm/mm range in the azimuthal direction. The thermal contraction coefficient in the radial direction was out of the feasibility range, perhaps due to the same problem that prevented measurements of the radial elasticity modulus.

The measured thermal contraction coefficients in all directions are lower than that of pure aluminum that it indicates a too high fraction of glass in the insulation. Hence, the impregnation pressure of less than 40 MPa should be used for the actual coils. The impregnation and measurement techniques should be improved to get more reliable data.

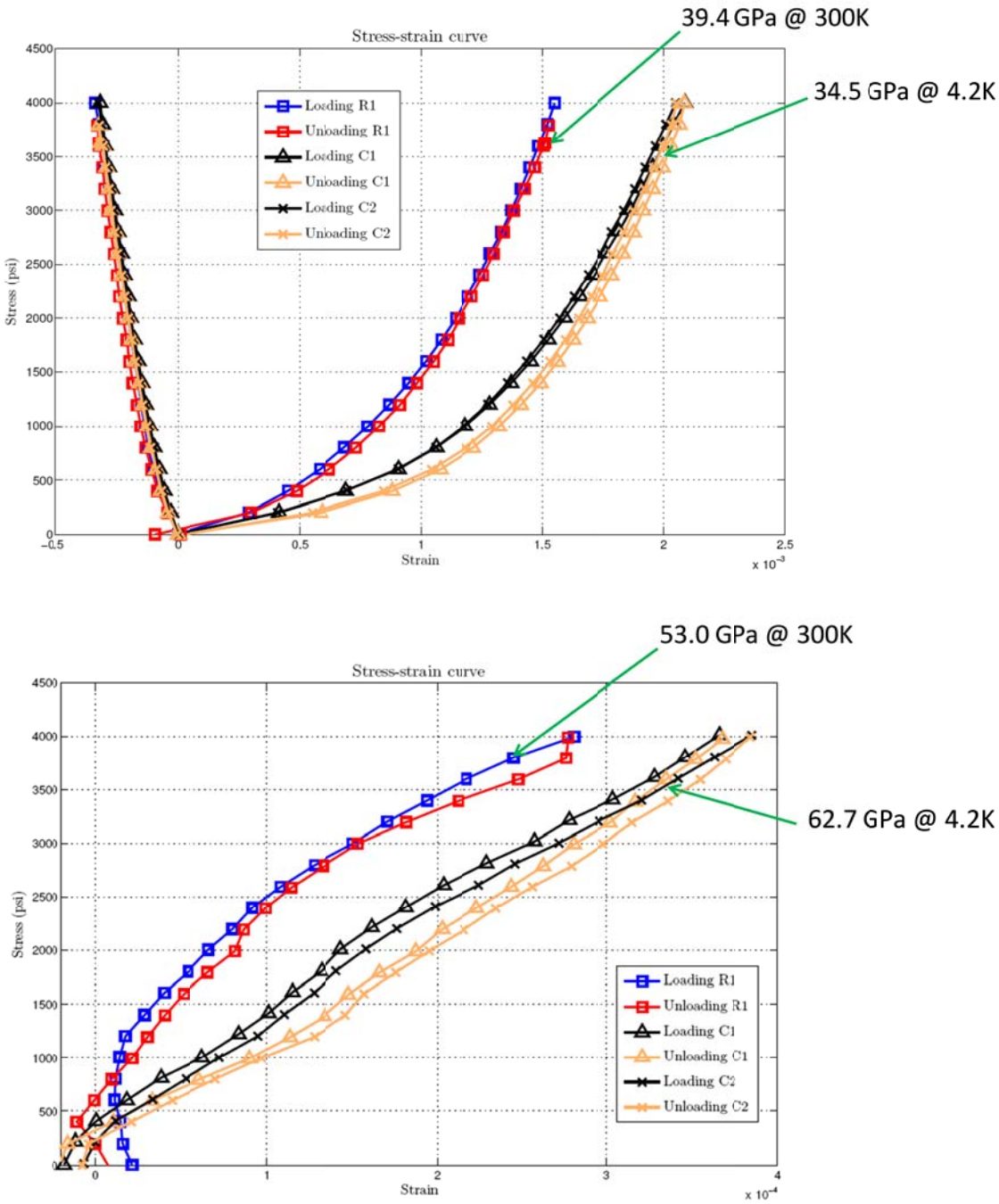
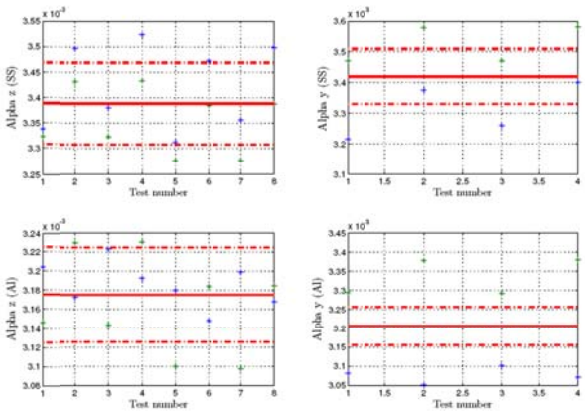


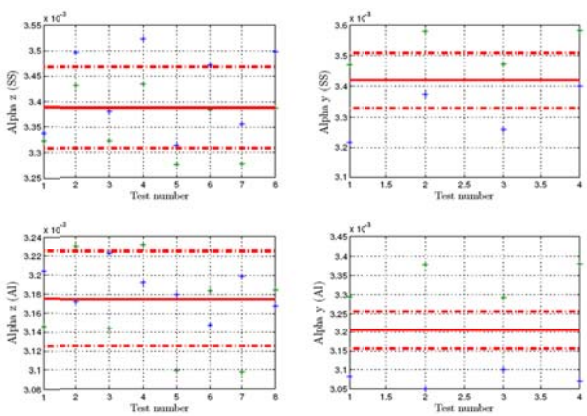
Fig. 4.3 Sample performance under axial loading (top) and azimuthal loading (bottom).



$$\alpha_{z/y} = \alpha_{SS/Al} + \frac{\varepsilon_{z/y} - \varepsilon_{SS/Al}}{\Delta T}$$

Liquid Helium (300K → 4.2K)

	$\alpha_z(\mu m/mm)$	$\alpha_y(\mu m/mm)$
SS	3.39 ± 0.08	3.42 ± 0.09
Al	3.18 ± 0.05	3.21 ± 0.05
FE	$2.9 \div 4.2$	$3.6 \div 6$
	Azimuthal	Axial



$$\alpha_{x/z} = \alpha_{SS/Al} + \frac{\varepsilon_{x/z} - \varepsilon_{SS/Al}}{\Delta T}$$

Liquid Helium (300K → 4.2K)

	$\alpha_x(\mu m/mm)$	$\alpha_z(\mu m/mm)$
SS	1.75 ± 0.08	3.26 ± 0.09
Al	1.53 ± 0.05	3.06 ± 0.05
FE	$3.5 \div 4.4$	$2.9 \div 4.2$
	Radial	Azimuthal

Fig. 4.4 Thermal contraction coefficients between 300 K and 4.2 K.

Conclusion

Studies have been performed on solenoid magnet technology for a possible muon conversion experiments. A coil using aluminum stabilized NbTi conductor was built and tested. A coil using a recently fabricated NbTi cable has been designed but not yet built. The schedule for building and testing this magnet will depend on the priorities of the US-Japan collaboration over the next few years.

Using ATLAS conductor, cable stack studies were performed at room temperature and liquid helium temperatures to measure the mechanical properties of insulated aluminum stabilized NbTi conductor. This information is being used in computer models to understand the mechanical properties of the conductor during operation.

References

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