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ALUMINIUM STABILIZED NbTi TEST COIL ASSEMBLY PRODUCTION REPORT

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1.0 INTRODUCTION

This Aluminum stabilized Niobium-Titanium (Al-NbTi) superconducting test magnet is the first of its kind in terms of the conductor used and mechanical set-up to be built and tested in the laboratory. No previous models are available for this magnet hence all the data collected can be possibly extrapolated to subsequent set-up and tests. The basic premise for the test is to analyze and acquire some comprehension of the Al-NbTi coil (Also known as RIKEN superconductor with Al stabilizer) properties since it has been tentatively and theoretically predicted to have better radiative heat absorption properties than a soldered copper channel copper coil used in a superconducting solenoid while simultaneously maintaining a relatively comparable quench protection (Low resistivity due to Nickel impurity in Aluminum – RRR value > 800) and superconducting properties [1]. The cable also has high mechanical strength, good thermal and electrical stability while achieving light weight and downsizing thereof. 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 test coil consisting of the Al-NbTi cable that is 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 [2]. 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 1.0 below and the cross section of the global mechanical assembly is shown in Figure 1.0.

Table 1.0: Primary features of RIKEN coil Test Magnet

Cable strand type (Main coils)	2 parallel NbTi Rutherford Type SSC cable
Cable strand type (Test coil)	Aluminium stabilized NbTi cable
Cable Insulation(Main Coils)	Fiber glass with 40% overlap, Kapton with gaps
Cable Insulation(Test Coil)	Fiber glass with 40% overlap
Bore Diameter	232mm
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)	?
Coils Fabrication Start Date (Main coils)	?
Cold Mass Completion Date (Main Coils)	?
Overall Cold Mass Completion Date	?

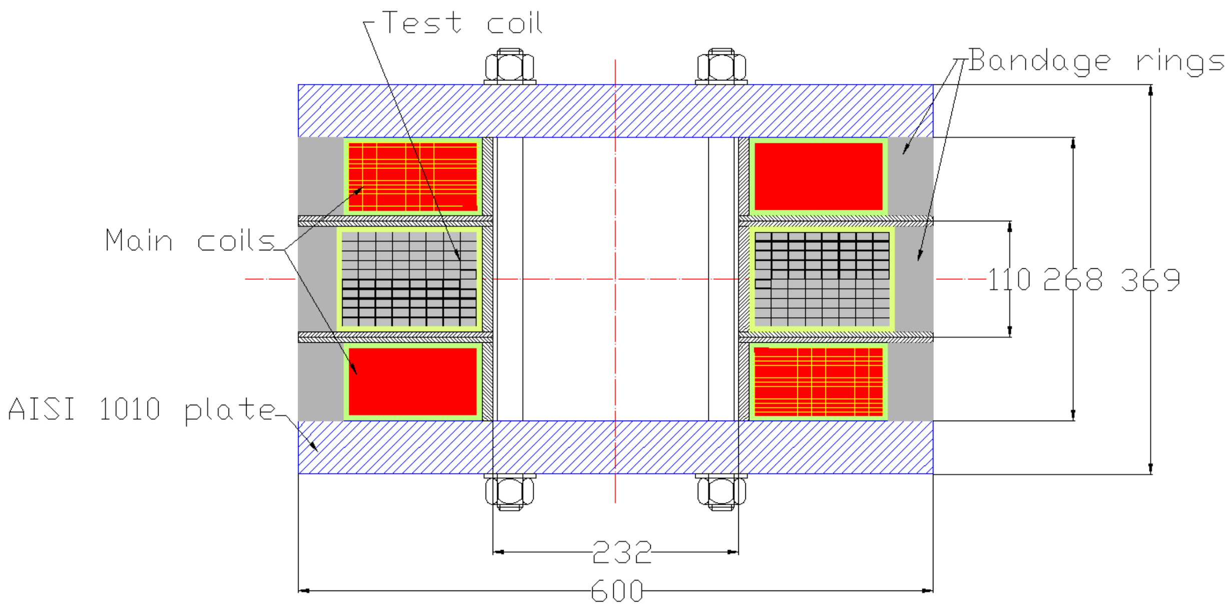

Figure 1.0 Al Stabilized NbTi coil test magnet symmetric cross-sectional of global assembly

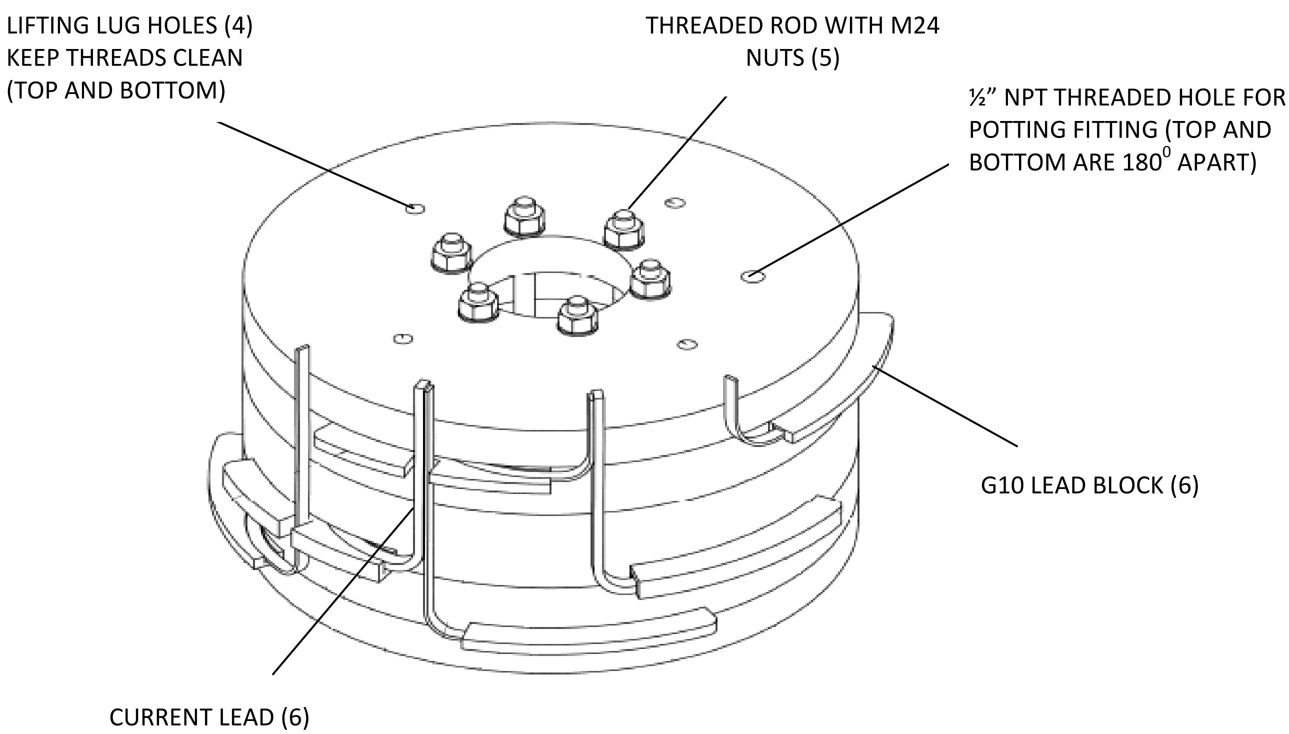

Figure 1.1 Al Stabilized NbTi coil test magnet global assembly isometric drawing

2.0 SUPERCONDUCTING CABLES

The cable types used in the production of the RIKEN coil test magnet set-up are two in number namely the conventional Rutherford type SSC inner cable utilized in the winding of the 2 main coils and an Aluminum stabilized NbTi cable [3](RIKEN Superconductor) utilized in the winding of the actual test coil that is sandwiched between the 2 main coils. The RIKEN superconductor is 8mm X 15mm with Al stabilizer. The cables parameters are given in Tables 2.1 and 2.2 below.

Table 2.1 Rutherford NbTi cable mechanical parameters

Coil ID	SSC-3-U-00214
Strand Diameter, mm	0.81
No. of Strands	30
Filament Diameter, microns	6
Mean Cable Mid Thickness, mm	1.46
Mean Cable Width, mm	12.36
Strand Twist Pitch in Cable, mm	15.0
Cable Lay Pitch, mm	83
Mean Keystone Angle, degrees	1.19
Cable Lay Direction	Left-hand screw thread
Cable Area, mm^2	15.5
Superconductor Area, mm^2	6.7
Cu:SC	1.3

Table 2.2 RIKEN cable mechanical parameters

Coil ID	Unknown
Aluminum outer band cross-sectional dimension, mm	8 X 15
Cable Cross-section, mm	Unknown
No. of strands	Unknown
Strand diameter, mm	Unknown
Pitch length, mm	Unknown
Cable average thickness, mm	Unknown
Cable width, mm	Unknown
Keystone angle	Unknown
Packing factor, %	Unknown

No electrical tests were done on these cables prior to winding. Several electrical tests were carried out after the final windings of the test and main coils. Details of some of these tests are described in Section 4.0 of this production report.

3.0 COIL FABRICATION

The test and main coils assemblies were done independently on their individual mandrels specially designed to meet the mechanical, experimental and test facility requirements to be appropriately fitted as an assembled unit in the 640mm diameter of the FNAL VMTF liquid helium cryostat. Stainless steel bobbins are used for both coil mandrels.

3.0.1 QUENCH HEATER

The winding mandrel of test coil is wrapped around with 3 layers of kapton on its outer diameter, followed by a few layers of fiber glass and then a 316L stainless steel quench heating strip with copper leads sandwiched between 2 layers of kapton as received from the manufacturer. A few layers of fiber glass is then wrapped around the heating strip prior to winding the actual test coils on the winding mandrel. The function of the quench heater is to artificially induce a quench in the magnet as needed during the magnet test at the VMTF. A small thru hole is drilled on the bobbin prior to installing the heating strips as a passage for the insulated electrical conductor wires which are soldered to a small portion (~4" length) of the exposed end copper leads on the heating strips. A sealant (RTV 157) is then added to the thru hole on the winding mandrel inner diameter for subsequent reinforcement as shown in Figure 3.0.1

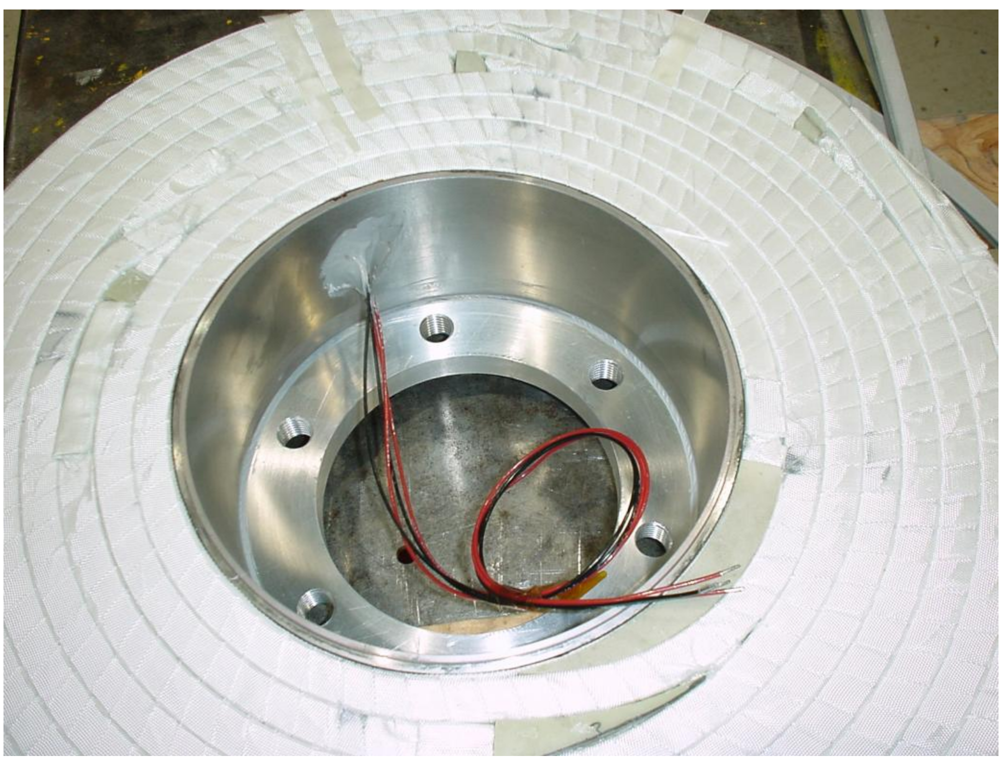

Figure 3.0.1 Test coil quench heating strip added external leads. Picture also shows RTV sealant on thru hole on bobbin

3.0.2 TEST COIL FABRICATION

The RIKEN superconducting cable was used as the winding for the test coil on its mandrel[3]. No known heat treatment was done on the cable prior to winding. The RIKEN cable basically consist of a solid outer rectangular bound of an aluminum alloy that acts as a stabilizer for the 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 [3]. Figure 3.0.2 shows the cable cross section.

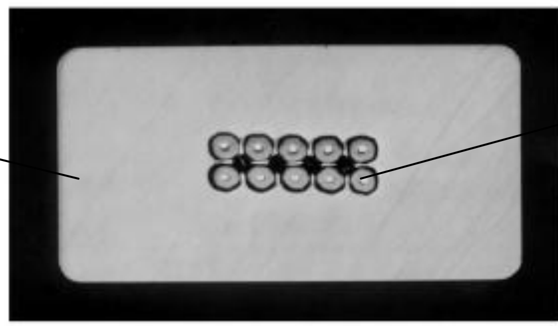

Figure 3.0.2 Cross Section of Aluminum stabilized Nb-Ti superconducting cable

This cable was first sand-blasted and subsequently checked for possible nicks and cracks visually in order to verify the aluminum alloy material outer uniformity. It was further wiped clean with alcohol (Iso-Propanol) prior to insulation. A standard 3 mil fiber glass cloth was used as the cable insulation wound with a 40-45% overlap (6 mil total). This insulation winding was done intermittently by hand. Only a one layer overlay of the cloth was used on the coil and it was wrapped dry. The 120m of cable was wound on a supply spool and linearly back wound from the spool unto another overhanging spool. An initial length of about 25m (82ft) of this insulated cable was initially back wound from the supply spool in order to completely wind the 1st horizontal layer (pancake) in contact with 0.06" (1.5mm) thick G10 strips acting as spacers that are glued with loctite directly to the inner face of a temporary steel bottom plate as shown in Figure 3.0.3. This is a very critical step in the winding process since one of the current leads which is held in place by a G10 lead block in the final assembly emanates from this pancake forming a termination as shown in Figure 1.1 to be eventually spliced with one of the terminations of the main coil. It can be seen in Figure 3.0.3 that all winding are performed using hard bending (turn to turn rotation about the coil thickness) for the coil as against the conventional easy bending technique (turn to turn rotation about the coil width).

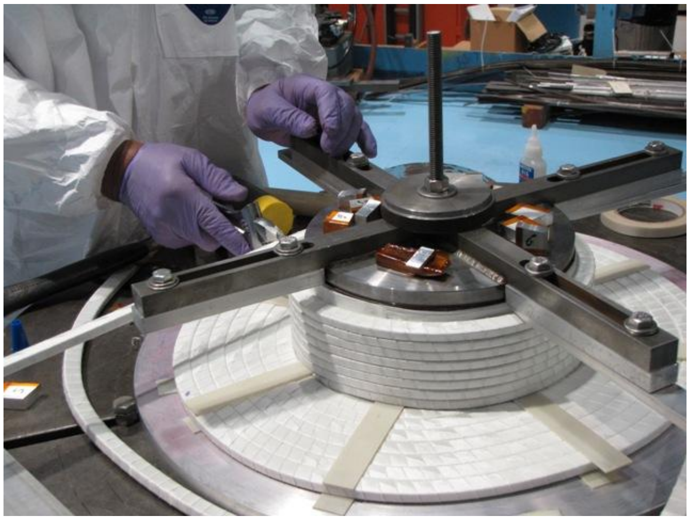

Figure 3.0.3 Picture showing bottom pancake of coil with wound 1st layer.

Subsequent coil windings are done on a vertically stacked turn by turn basis forming vertical layers after the bottom layer is wound commencing from the one layer up of innermost turn In contact with the fiber glass wrapped around the OD of the stainless steel bobbin to the one layer outermost turn that ends with the second current lead at the bottom of the turn close to the 1st wound layer with G10 strips in direct contact with the bottom steel plate. The final wound coil consist of 10 horizontal layers from bottom-up and 9 vertical layers radially hence consist of 90 individual turns for the entire coil made from the 120m length of available RIKEN cable. The schematic cross section of the ideal arrangement of the test coil is shown in Figure 3.0.4 below.

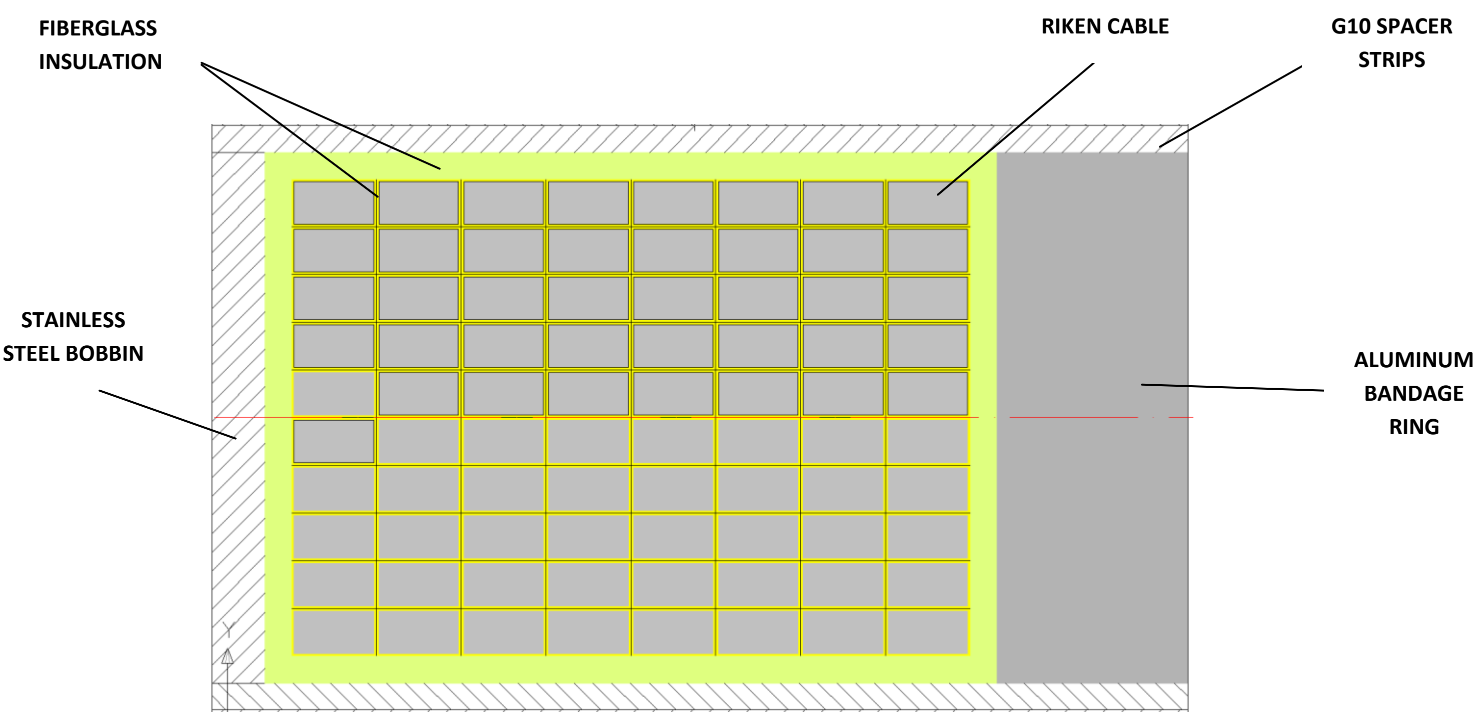

Figure 3.0.4 Schematic of test coil ideal cross-section showing 10 horizontal layers X 9 vertical hence a grand total of 90 turns for the coil

Temporary specially sized chamfered aluminum wedge pieces with kapton tape laminates were used to keep each turn by turn layer in close contact intermittently with the aid of stacked up pieces of G10 strips wherever needed as shown in Figure 3.0.5. Loctite was also used wherever needed to hold turn to turn coils in place and the aluminum wedge is subsequently removed after the loctite seal is obtained.

Figure 3.0.5 Coil showing specially shaped kapton-covered aluminum blocks used intermittently in holding turn to turn transitions between layers during coil winding

Specially shaped G10 blocks were used to fill voids and also facilitate tension in the cable at the vertical layer to layer transitions as shown in Figure 3.0.6

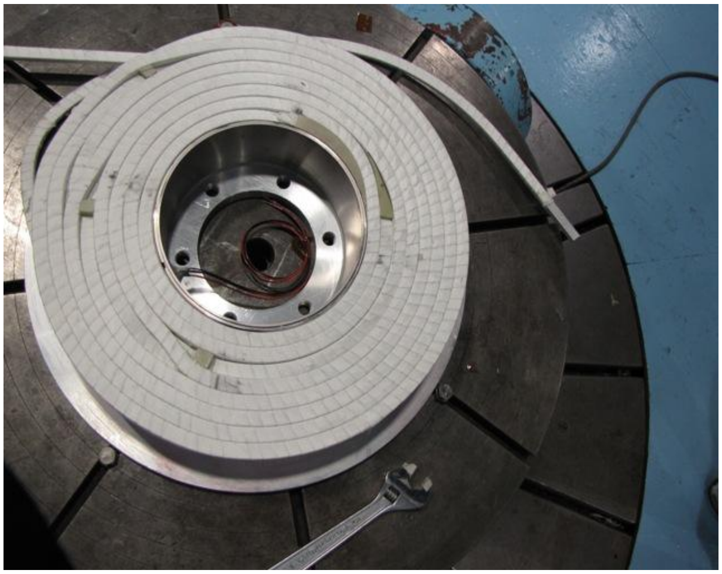

Figure 3.0.6 specially shaped G10 blocks used as wedges in coils during winding

Some additional apertures and openings in the wound coil are filled with fiber glass cloth on the fly as shown in Figure 3.0.7 in order to create a tight fit for the vacuum epoxy impregnation.

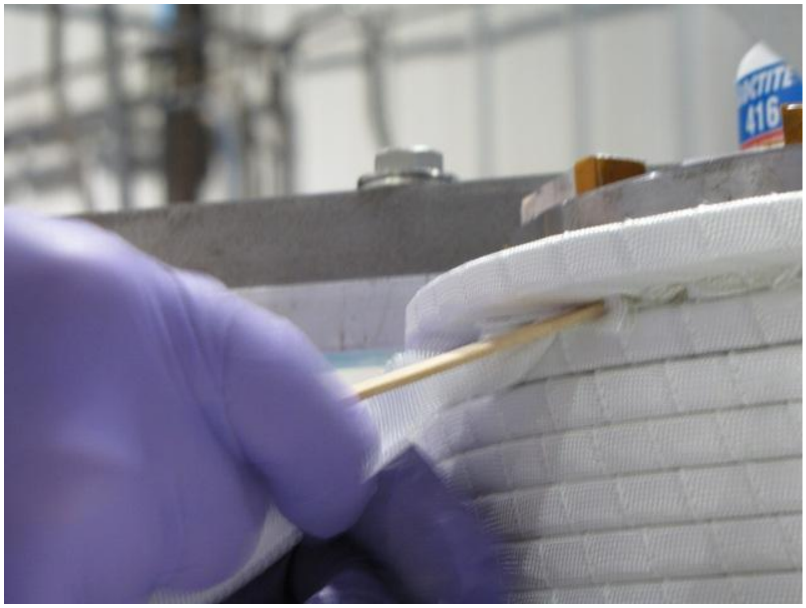

Figure 3.0.7 Wound coil voids filled with fiber glass cloth

Final assembly has the current leads one layer apart emanating from the bottom of the assembly structure and supported by slotted and uniquely shaped G10 blocks to hold the leads in place as shown in Figure 3.0.8 below. These terminations were spliced in the final assembly as depicted in isometric drawing in Figure 1.1 of section 1.0.

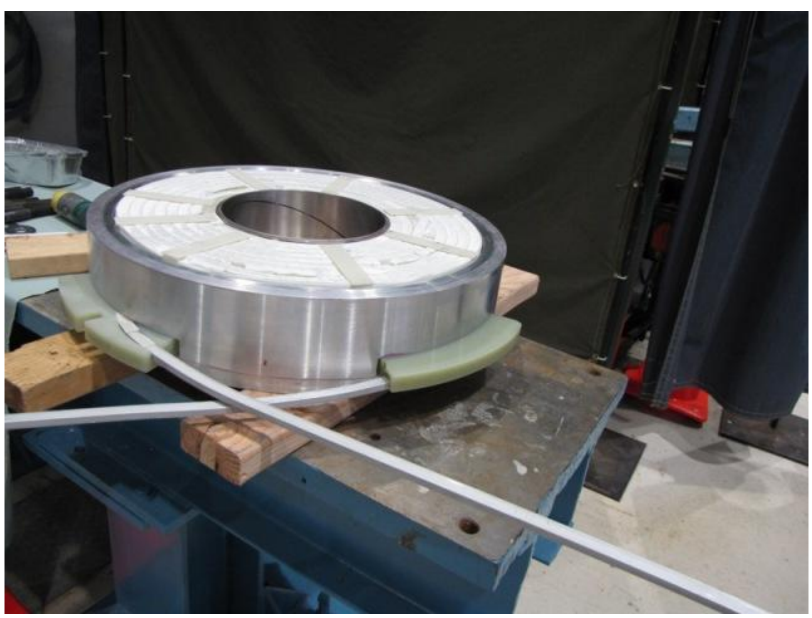

Figure 3.0.8 Final test coil assembly with AISI1010 steel top plate removed

3.0.3 MAIN COILS FABRICATION

The assembly fabrication of the main coils was very similar to the test coil, the main difference being the coil type and the tooling set-up. The main coils were wound from two parallel SSC inner cables lapped together along their length in such a way the thinner of the tapered crossed section (keystone) of each coil are on opposite sides of one another so as to obtain a rectangular cross-section for the lapped coils. The stainless steel bobbin was first wrapped with 3 layers of 5mil kapton tape and 4 layers of 7mil fiberglass cloth prior to the coil winding. Two feed spools each containing the appropriate length of 740m of the Rutherford-Type superconducting cable horizontally fed the insulating winding machine. This machine has its own rotary internal feed of 3mil fiber glass cloth on its first spindle and 1mil kapton on its second spindle. The angular speeds on the spindles were set in such a way that the first spindle revolves 1.5 times faster than the second in order to simultaneously insulate the superconducting virgin cable with 40-45% overlap of the fiberglass cloth and ~20% gaps between the kapton insulation on the fiberglass cloth already on the cable. Hence total insulation thickness was 7mil. An initial length of about 192m (630ft) of the insulated cable was loosely wound out around the bottom steel flange and subsequently hard bent around the fiber glass insulated bobbin to form a terminating pancake in direct contact with G10 strips attached with loctite glue to the bottom of the steel flange. This pancake was secured in place after the winding with 0.06" (1.5mm) G10 rectangular strips in a circular fashion around the coils as shown in Figure 3.1.0 Additional windings were done with the insulation simultaneously and sequentially on a vertical turn by turn basis from the 2nd layer to the 16th layer by hard bending the cables accordingly. The schematic cross section of the ideal arrangement of the main coils is shown in Figure 3.0.9 below.

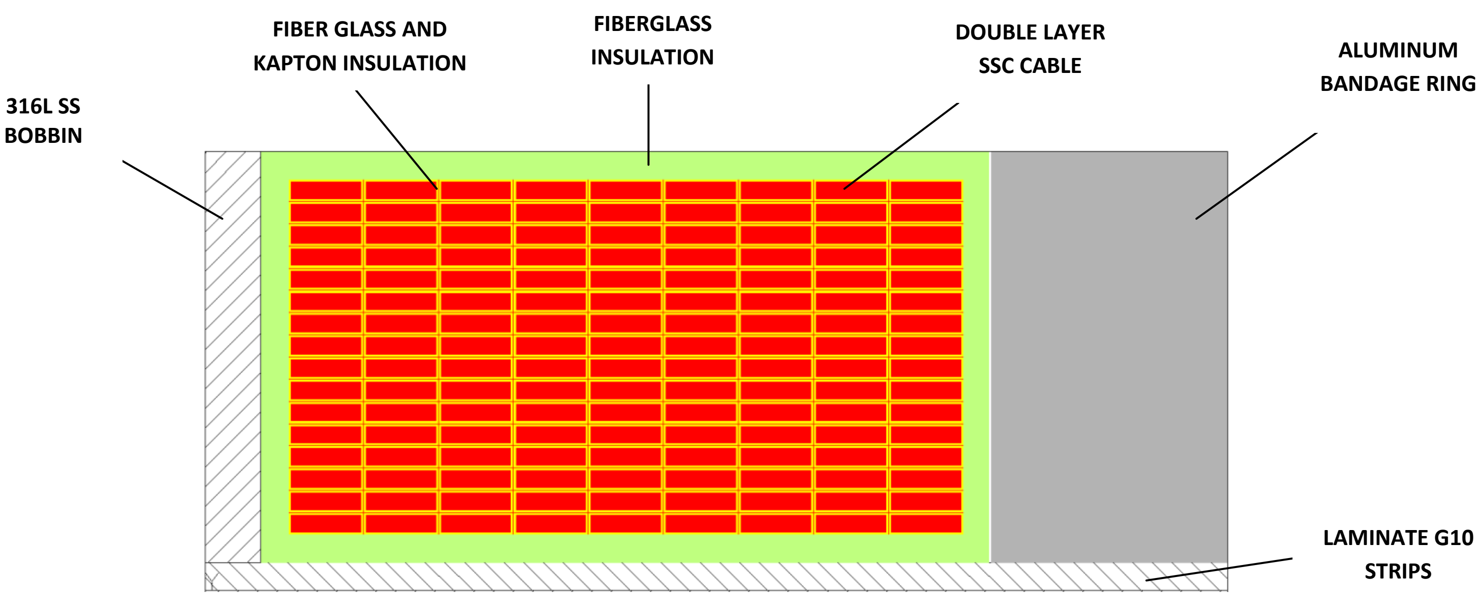

Figure 3.0.9 Schematic of main coils ideal cross-section showing 16 horizontal layers X 10 vertical layers hence a grand total of 160 turns for the coil

Similar to the winding of the test coil, each vertical turn to turn winding was done with the aid of specially shaped kapton tape covered aluminum wedges using the 8 rib clamps on a rotating flat table as shown in Figure 3.1.0 This set-up facilitates a close spaced wedge turn to turn coil pressing for better contact to control and eliminate cable twists. These aluminum wedges were pressed firmly against the turns intermittently to flatten each turn and keep it in close contact with each preceding turn. Loctite glue was appropriately applied under the coil turn for the wedges to achieve this close contact and untwisting even after the wedge was removed.

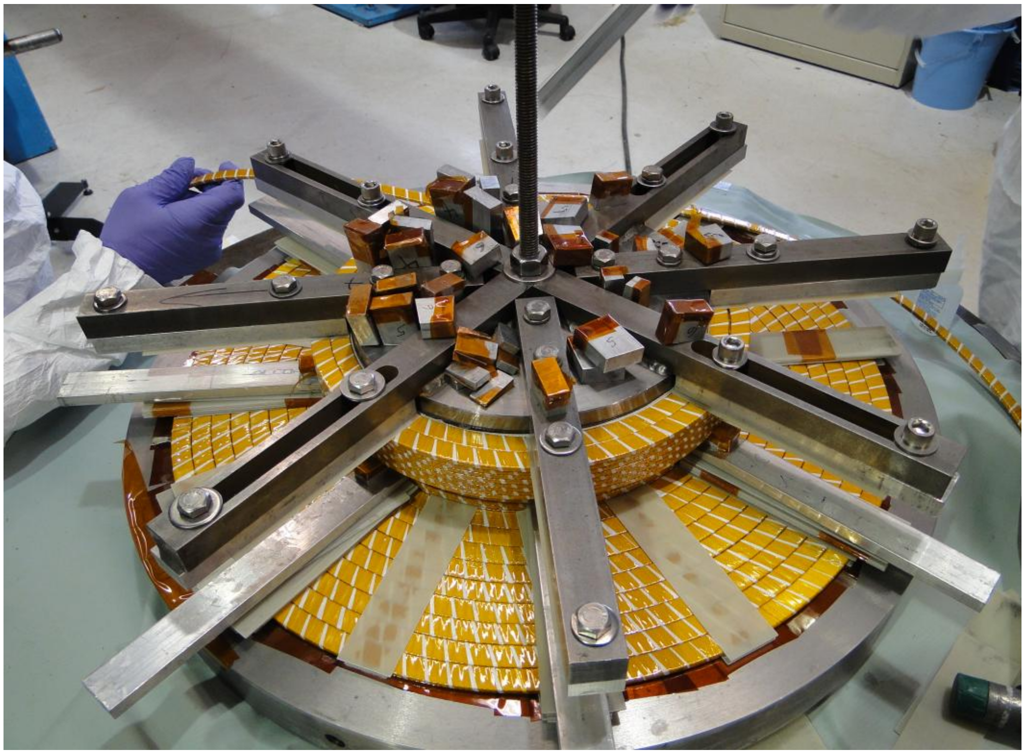

Figure 3.1.0 Coil with 1st pancake wound showing termination on far right of coil. The clamping 8 ribs are also shown on the flat rotating table

Additional kapton tape was manually used to trace the vertical layer to layer transitions and the 5mm rectangular G10 strips were used to hold the coil in place with some loctite after the winding was completed with the 2nd termination. Figure 3.1.1 below shows the layout of the insulating machine in IB2 of Fermilab for simultaneously wrapping the fiberglass and kapton insulation on the double layer SSC cable while winding the cable on the mandrel. The cloth and kapton insulation winding tension is set by regulating the voltage level on the side of the winding machine. Figure 3.1.2 shows the finish wound coils with the current leads.

Figure 3.1.1 Insulating machine layout for fiberglass and kapton wrapping and tensioning on main coils. Picture show cloth spindle on far right and kapton spindle on left

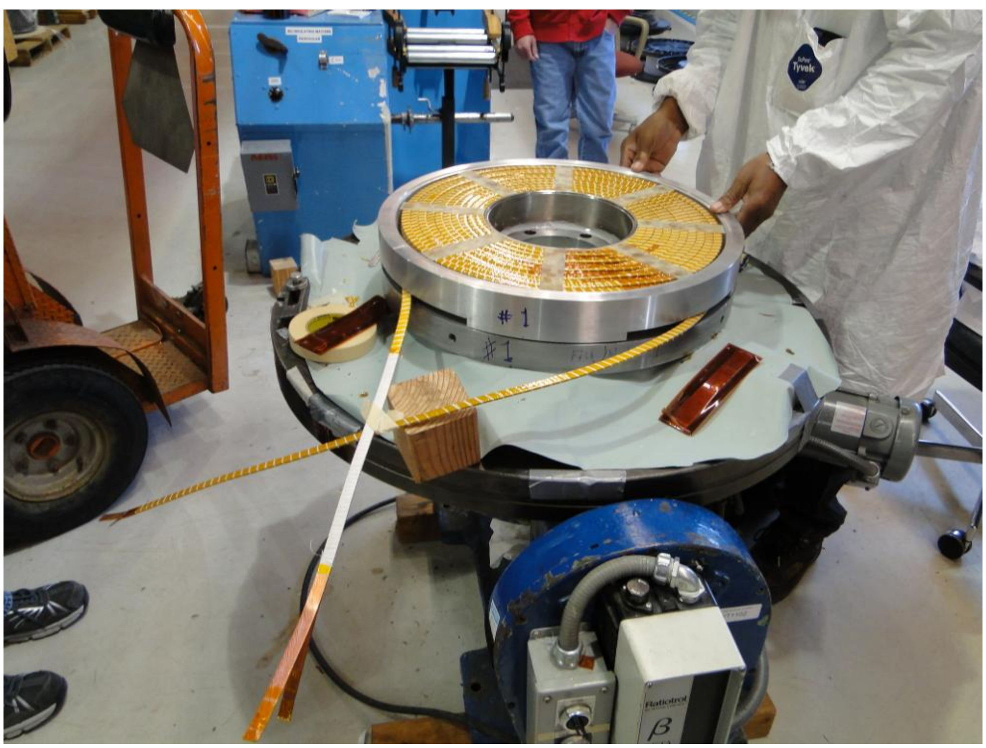

Figure 3.1.2 Picture of finished wound coil showing terminations, aluminum outer bandage ring, top G10 strips and vertical layer to layer transition kapton tape trace

4.0 ELECTRICAL MEASUREMENTS

Several electrical tests were carried on main coils after winding to verify the non existence of short circuits in the coil. These tests were mainly the HI-POT (ground) test and the RING test. There were 4 iterations of the coil windings done on the main coils stainless steel mandrel as a result of turn-to-turn shorts that were obvious from the ring test inductance readings on the previously wound main coils. As a result, the final insulation detail had to change from a previously used fiber-glass only insulation to a double insulation consisting of kapton insulation wound over the fiber glass as stated in Section 3.0.2 above. This additional layer of insulation eventually resulted in the inductance measurements difference between the two main coils to a less than 14% value which was acceptable for the test. In order to summarize this production report, the various electrical measurement values and curves were omitted for all the different coil winding iterations and only the final 2 main coils electrical inductances are shown in Figures 4.0.1 and 4.0.2 below

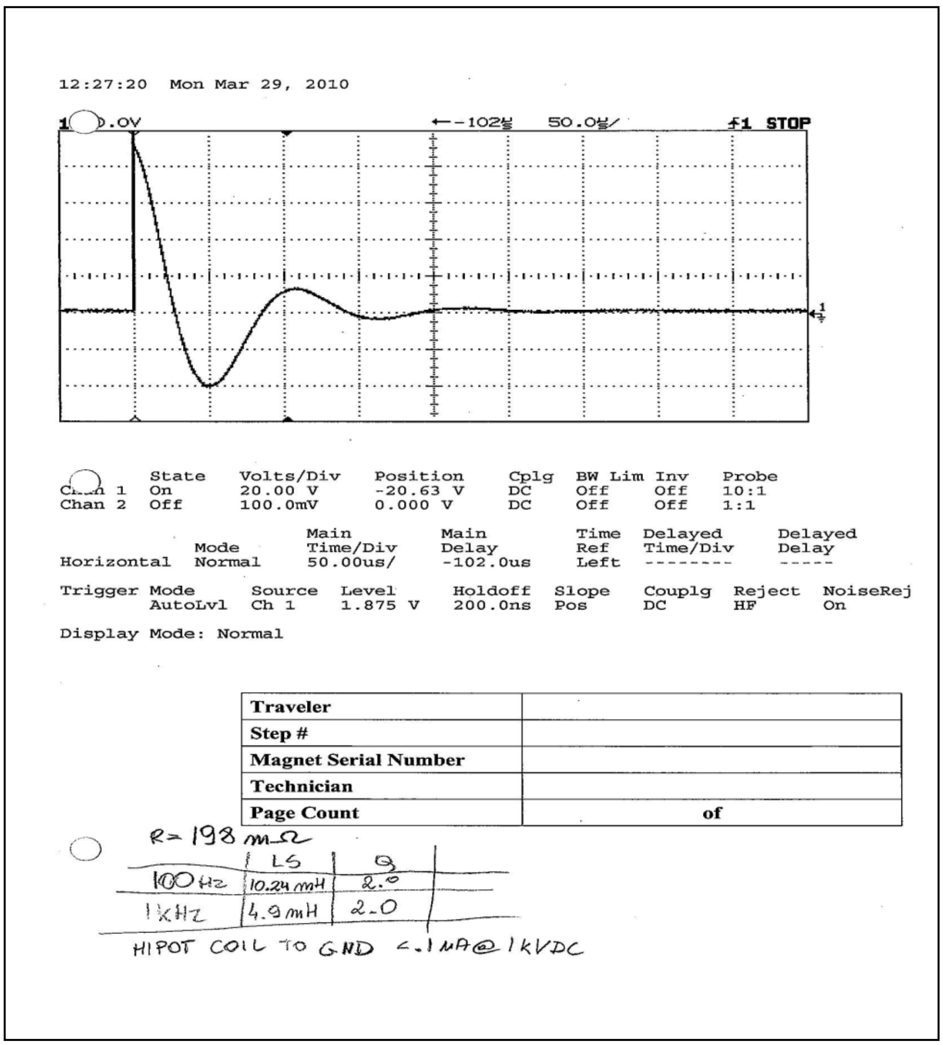

Figure 4.0.1 Final electrical inductance measurement values for the for the RING test of the 1st main coil at different frequencies and quality factors at 198mΩ.

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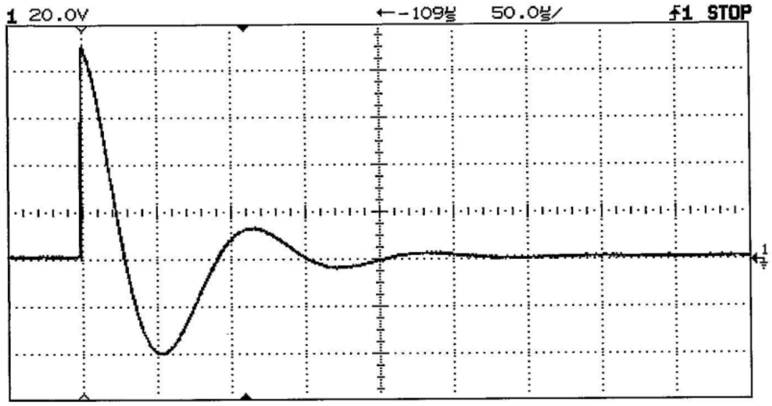

	State	Volts/Div	Position	Cplg	BW Lim	Inv	Probe
Chan 1	On	20.00 V	-20.63 V	DC	Off	Off	10:1
Chan 2	Off	100.0mV	0.000 V	DC	Off	Off	1:1

	Mode	Main Time/Div	Main Delay	Time Ref	Delayed Time/Div	Delayed Delay
Horizontal	Normal	50.00us/	-109.0us	Left	--------	-----

Trigger Mode	Source	Level	Holdoff	Slope	Couplg	Reject	NoiseRej
AutoLvl	Ch 1	1.875 V	200.0ns	Pos	DC	HF	On

Display Mode: Normal

Resistance	LS @ 100 Hz	Q @ 100 Hz	LS @ 1 kHz	Q @ 1 kHz	Hi-pot
204 mΩ	11.62 mH	2.4	5.47 mH	1.9	<1μA @ 1kVDC

Traveler	
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Figure 4.0.2 Final electrical inductance measurement values for the for the RING test of the 2nd main coil at different frequencies and quality factors at 204mΩ.

As seen in the above tables, the difference in electrical inductance between the 1st and 2nd main coils is 1.38mΩ (within 13.5%) at 100Hz and 0.57mΩ (11.6%) at 1000Hz. There were some uncertainties in the theoretically calculated value for the coil inductance because of the presence of the iron in the assembly hence the above values were the best estimates based on actual measurements of the coils end-to-end lead connections after the completed coil windings.

5.0 EPOXY IMPREGNATION

The test and main coils were impregnated separately. The test coil was the first to be fabricated and vacuum epoxy impregnated. Subsequent impregnation was carried out on the main coils after fabrication. The CTD101K epoxy was used for the vacuum impregnation process and was common to both the main and test coils. The impregnation fixture was placed in a large oven and heated to 60^0C and evacuated to ~23microns. It took about 48hours to create the needed vacuum in the vacuum chamber before the epoxy was administered to the coil. The epoxy container was placed outside the vacuum vessel and connected via flexible rubber hoses to the coil in the chamber. The epoxy was flow was done in steps of 6inchesat regular 15 minutes intervals until the coil was saturated. The impregnation process for each of the 3 coils lasted for approximately 10 hours. After impregnation, the fixture was placed in an oven and cured at 125^0C for 10 hours subsequent to a ramp step of heating the impregnated coil in the oven to ~90^0C for an initial 2 hours. Figure 5.0.1 shows the pictures of the test coil and the bottom main coil after impregnation.

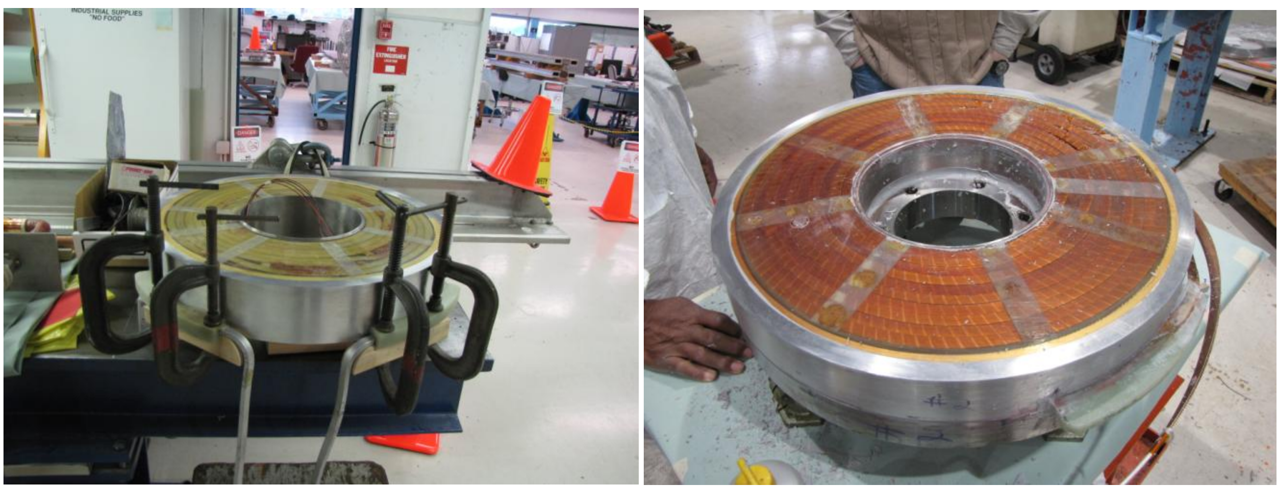

Figure 5.0.1 Picture of the cured epoxy impregnated test coil (left) and cured epoxy impregnated bottom main coil (right)

The coils were surface prepped after the curing in order to achieve the flat mating surfaces that were necessary for the coils prior to bolting all 3 coils together in the final assembly. There were no relevant mechanical measurements done on the coils after the curing process.

6.0 FINAL ASSEMBLY

The detail of the final assembly included the coupling of the test coil and 2 main coils held together as shown in the bolting detail in Figure 1.1. The bottom flange has tapped holes which serve as Female NPT stoppers for the partially threaded M24 hex head bolts that come in from the top flange thru holes. A picture of the final assembly is shown in Figure 6.0.1

Figure 6.0.1 Picture of the final structural assembly showing the splices between the main and test coils. The current leads (main coils terminations) are also shown

7.0 SUMMARY

This is the first test of this kind in the laboratory in terms of the conductor used for the test coil and the solenoidal global assembly mechanical configuration. The final assembly had a bore diameter of ~232mm and an overall height of ~369mm measuring from the top face of the top flange to the bottom face of the bottom flange. The conductor used for the test coil was a leftover from a superconducting ring cyclotron [3] and it was given to the lab by the RIKEN RI Beam Factory in Japan via a collaboration effort. The final coupled global assembly was delivered to the Fermilab VMTF facility for testing.

REFERENCES

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[3] H. Okono, K.Yamada et al " Commissioning of the Superconducting Ring Cyclotron for the RIKEN RI Beam Factory" IEEE Transactions on Applied Superconductivity, Vol. 18, No. 2, June 2008