NCSX Modular Coil Fabrication

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Abstract— **The modular coils for the National Compact Stellarator Experiment (NCSX) presented a number of significant engineering and manufacturing challenges due to their complex shapes, requirements for high dimensional accuracy and the high current density required in the modular coils due to space constraints. Some of these challenges included developing techniques to manufacture highly shaped coils which utilize copper rope conductor, dimensional control, and Vacuum Pressure Impregnation [VPI] operations. Production style manufacturing operations were introduced in order to maintain schedule and contain costs. This paper will discuss those challenges and manufacturing steps that were taken to successfully manufacture the Modular Coils. A general description of the tooling and equipment necessary to manufacture the modular coils will also be presented.**

I. Introduction

The National Compact Stellarator Experiment has a total of eighteen modular coils- six each of three coil types. These coils are being fabricated at the Princeton Plasma Physics Laboratory for the NCSX project. The coils are constructed by winding insulated copper cable onto a stainless steel winding form that has been machined to high accuracy, so that the current centroid of the winding pack is within ± 1.5 mm of its theoretical center. The overall fabrication processes per coil takes approximately 138 shifts of effort from receipt of the winding form through final electrical tests.

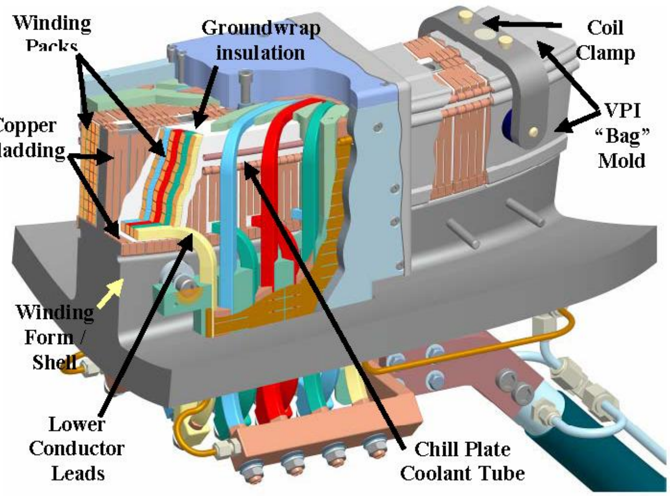

Figure 1- Cross-Section of Typical Modular Coil Lead Area

II. Winding Form Preparation

When the modular coil forms are delivered from the manufacturer, they are QC inspected for surface defects and measured for magnetic permeability. They are then shipped to the Modular Coil manufacturing facility for processing. The individual winding forms are mounted to a support ring that remains with the coil through completion. The support ring is an essential part of the coil turning fixture and serves as a lifting fixture for transporting the coils from station to station.

A. Surface Measurements

Additional fiducial points are added to the winding form to enable measurements to be made throughout the manufacturing process. Using these points, a complete scan of the winding surfaces is made using a coordinate measuring machine [CCM]. These measurements are necessary to establish a baseline for determining the position of the turns and centroid throughout the manufacturing process.

Figure 2- Measuring Winding Surface using CMM "Romer" and Template

Once the baseline has been established, the basic winding strategy is to wind "into the box" by setting the side winding clamps to predetermined positions before the start of winding.

B. Miscellaneous Tasks

Approximately 200 Inconel studs are mounted to the winding form that will be used with the coil winding clamps needed to hold the turns in position during winding. The winding form is cleaned and several layers of mold release are then applied to the winding surfaces to minimize the bonding

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between the coil bundle and winding form during the epoxy fill [VPI] of the coil.

C. *Cladding Installation*

Approximately [750] pieces of Kapton backed copper cladding are then positioned onto the winding surfaces. Once completed, this provides the inner wall cooling for the coils. The copper cladding is temporarily held in position using a 2-part 3M-adhesive.

The individual pieces of cladding must be electrically isolated from each other as well as from the winding form. It is essential that the cladding fits tightly to the winding form to ensure accurate tolerances and positioning of the copper conductor.

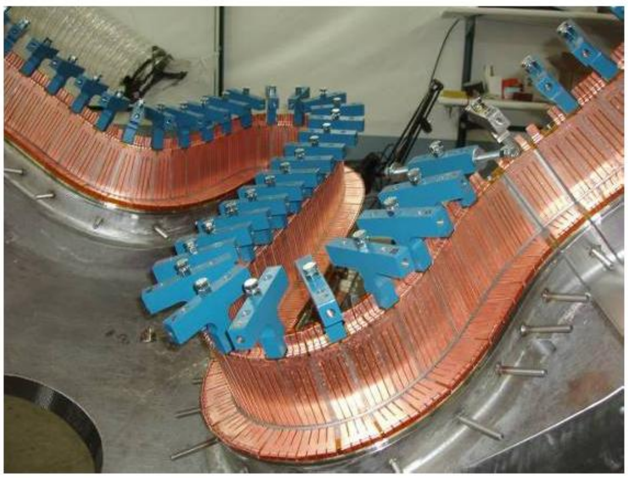

Figure 3- Cross-Section of Typical Modular Coil Lead Area

III. Coil Winding Activities

Once the copper cladding has been installed, the coil is transferred to a winding station. In this station the groundwrap insulation is positioned and coil turns are wound onto the winding form.

A. *Groundwrap Positioning*

Since the coil is wound directly onto the coil structure, it is necessary to pre-position the multiple layers of groundwrap insulation. Nearly 1000 individual pieces of 18 inch long insulation are pre-positioned onto the copper cladding. The groundwrap insulation scheme is comprised of:

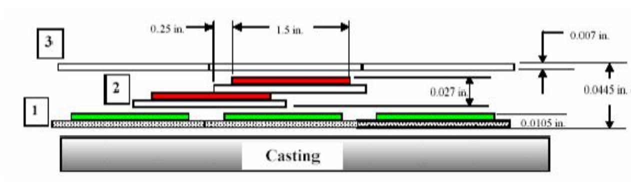

Figure 4- Groundwrap Insulation Scheme

- **Layer 1 [Inner- against winding form]-** (1) butt lapped layer of composite insulation [0.007 inch thick S-2 glass x 2 inch wide plus 0.0035 (HN) Kapton tape x 1.5 inch wide with adhesive back
- **Layer 2 [Middle layer]-** (1) half-lapped layer of composite insulation [0.007 inch thick S-2 glass x 2 inch wide plus 0.0065 (HN) Kapton tape x 1.5 inch wide with adhesive back
- **Layer 3 [Outer- against coil]-** (1) butt lapped layer of 0.007 inch thick x 2 inch wide S-2glass tape

B. *Lacing Strips*

Individual glass cloth strips "lacing" are positioned on top of the groundwrap. The purpose of these lacing strips is to bind the bundle turns together after final adjustments to minimize changes in the height and width of the pack when the top and side clamps are removed to complete the ground wrap and add the chill plates, cooling tubes, and bag mold.

C. *Winding Operations*

The coils are wound using pre-insulated rectangular compacted copper rope conductor. The rope conductor is constructed of 34-gauge oxygen free copper wire [12 x 5 x 44 x 34] with an external 0.004-inch thick nylon serve. Once cabled, the copper rope was compacted to dimensions of 0.350 in. x 0.391 in. +/- 0.010 inches.

The conductors are wound 4-in-hand with copper lugs brazed onto the ends of the each conductor. During the winding operation 4 to 5 side clamps are removed to allow the copper turn to be hand positioned. The side clamps are then returned to pre-shimmed positions, and the top winding clamp screws are torqued to 30 inch-lbs. This process is repeated until the entire coil bundle has been wound. The coil is then flipped and the process is repeated for the "B" bundle pack.

Figure 5- Coil Winding Operation

D. *Metrology and Bundle Positioning*

After winding, the positions of the coil bundles are measured using the CMM arm. These measurements are then reviewed by the engineering analysis group who generate a listing of repositioning requirements. The copper rope conductor is then repositioned by adjusting the top and side clamp bars. This process generally takes several iterations until the current centers are within the ± 0.020 inch allowance. Once the winding packs are complete, the position of the turns are secured by overlapping and gluing of the glass cloth "lacing" strips that were installed prior to winding. Securing of the turns is necessary so that the groundwrap, chill plates and bag mold can be installed with change in bundle position.

E. Final Groundwrap

Once the "lacing strips" and bundle have been secured the groundwrap insulation [GW] is completed. Each individual piece of GW is mated and secured in position using Kapton insulation. Extra care is taken to ensure proper overlap of the Kapton insulation layers.

F. Chill Plate Installation

Approximately 750 copper chill plates are then installed over the completed GW. This forms the outer wall of the coil cooling system. The chill plates connect to the inner wall cladding that was installed prior to positioning the GW insulation. Pre-tinned copper tubing is then positioned and soldered to the chill plates providing a flow path for the liquid Nitrogen used to cool the coils.

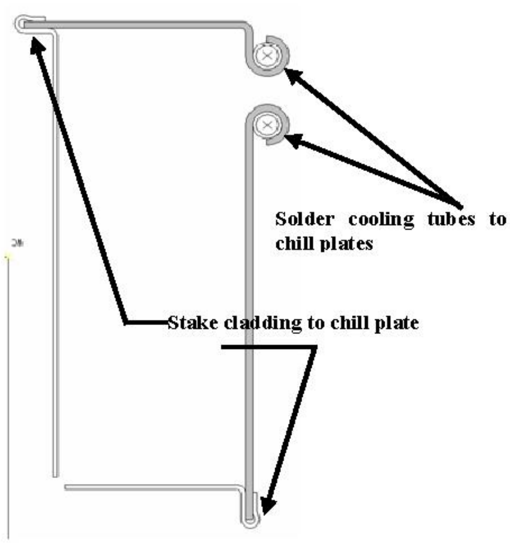

Figure 6- Cladding/Chill Plate Cooling Scheme

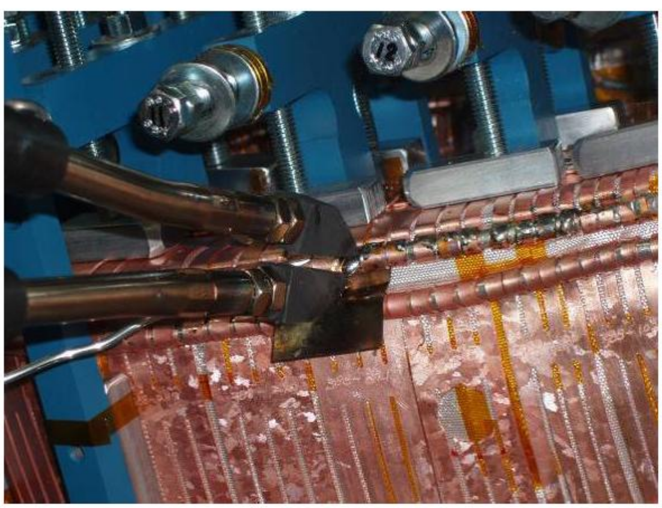

Figure 7- Soldering of Cooling Tubes to Chill Plates

IV. MOLD AND VPI OPERATIONS

A. Installation of Bag Mold

The bag mold is now ready to be installed. Two layers of silicone vulcanized rubber tape are applied over the coil bundles. The ends of the bags are held in position using silicone RTV and copper tubing that is pushed into a pre-machined groove in the winding form. The copper tubing works similar to a spline that is used to hold screening in place.

Once installed, the bag mold is pumped down using a vacuum pump. A layer of RTV is then painted onto the outside surface to fill any small leaks. A mixture of chopped fiberglass and 2-part room cured epoxy is the mixed and applied over the bag mold, providing the structural element of the mold design.

Figure 8- Bag Mold under Vacuum

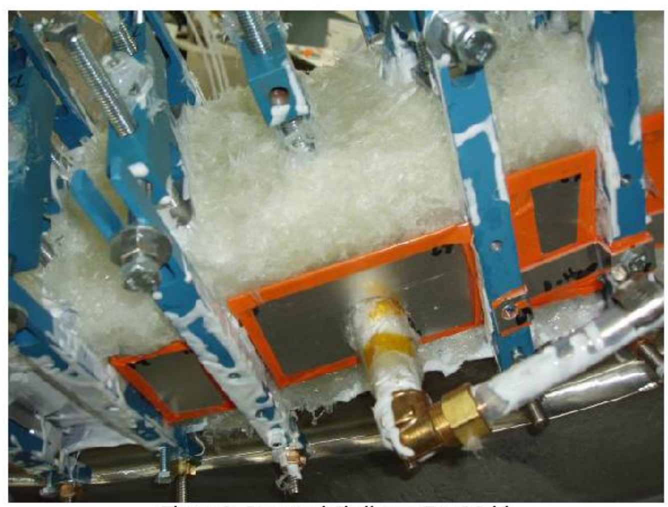

Figure 9- Structural Shell over Bag Mold

Once the epoxy shell has cured, the entire coil and ring assembly is then lifted from the winding station and positioned inside of the autoclave [vacuum-pressure oven] for preparation of the epoxy filling [VPI] operation.

Figure 10- Installation of Modular Coil into Autoclave

B. VPI Operations

Once in the autoclave, the coil is plumbed to the epoxy delivery system using heat resistant tubing. Nearly 40 feed lines and a dozen thermocouples are connected to the coil assembly.

Twenty four gallons of epoxy are weighed and prepared for the VPI operation. Only eleven gallons of the total epoxy mix actually fills the coil. The remaining epoxy is for filling the feed lines and maintaining a reserve quantity of resin in case it is needed during the VPI filling operation.

The VPI cycle takes nearly 60 hours to complete the cycle. This includes the epoxy mixing operation, filling the coil, plus the heat cure cycle [110º C for 5 hours and 125º C for 15 hours] and cool down steps.

Once the VPI operation has been completed [coil is filled and cured] the coil is removed from the autoclave and prepared for final testing and assembly.

V. POST VPI OPERATIONS

Once the VPI operation has been completed [coil is filled and cured] the coil is removed from the autoclave and transported to the post VPI station for processing. At this station the Inconel studs that were used for the winding clamps are removed as well as the epoxy shell mold and bag mold. The final coil clamps are then installed and the final electrical and pneumatic tests completed. The coil is now ready for installation.

VI. SUMMARY

The NCSX Modular Coils manufacturing operations introduced a number of technical manufacturing challenges that were all addressed. Each coil took approximately 138 shifts [2-3 technicians] to complete. This was primarily due to the large number of individual parts and components that had to be handled during manufacturing and the high degree of dimensional accuracy that was required.

The project was able to achieve the required tolerance of ± 0.020" by careful winding, many in-process measurements, use of clamps to re-position turns as required, and lacing to hold turn positions. To date a total of 12 modular coils have been successfully epoxy impregnated and 2 additional coils are in process. The last coil is schedule to be completed by early 2008.

Carefully developed manufacturing procedures, high levels of Quality control coverage, intense use of metrology and input from the manufacturing technicians were all contributing factors for success.

Figure 11- Finished Modular Coil

ACKNOWLEDGMENT

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