MANUFACTURING DEVELOPMENT OF THE NCSX MODULAR COIL WINDINGS

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***Abstract*— The modular coils on the National Compact Stellarator Experiment (NCSX) present a number of significant engineering 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. In order to address these challenges, an R&D program was established to develop the conductor, insulation scheme, manufacturing techniques, and procedures. A prototype winding named Twisted Racetrack Coil (TRC) was of particular importance in dealing with these challenges. The TRC included a complex shaped winding form, conductor, insulation scheme, leads and termination, cooling system and coil clamps typical of the modular coil design. Even though the TRC is smaller in size than a modular coil, its similar complex geometry provided invaluable information in developing the final design, metrology techniques and development of manufacturing procedures.**

In addition a discussion of the development of the copper rope conductor including "Keystoning" concerns; the epoxy impregnation system (VPI) plus the tooling and equipment required to manufacture the modular coils will be presented.

I. INTRODUCTION

The National Compact Stellerator 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.

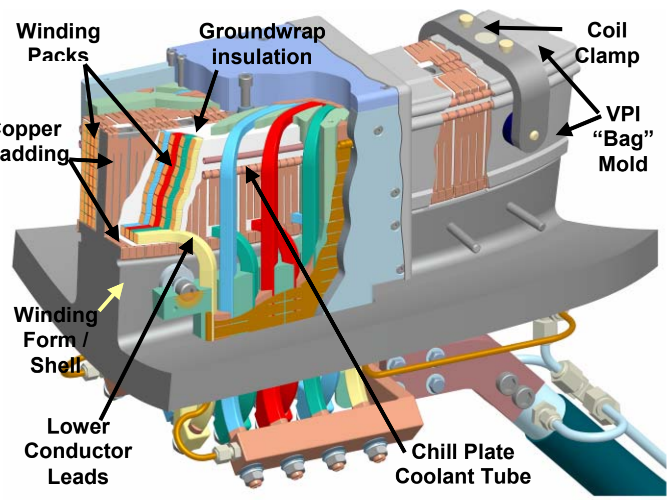

Figure 1- Cross-Section of Typical Modular Coil Lead Area

II. CONDUCTOR

The modular coils will be wound using continuous length compacted copper rope conductor that was developed during a joint design effort by New England Electric Wire Co. and the NCSX project. A total of (7) conductor designs were manufactured and evaluated. Variations in conductor cross-section, wire gauge, lay length and direction of lay were all incorporated into the development program. The primary requirements were to maximize the packing fraction; maintain conductor tolerance and minimize conductor keystoning.

The copper rope conductor selected has a dimensional cross-section of 0.390 ±0.010 inches x 0.350 ±0.010 inches. It has a total of 3240 strands of AWG 34 (nom. 0.063 inch) OFHC copper with a minimum packing fraction of 75%. Its construction is 12/5/54/34 bare strands with an overlay of 0.004 inch thick nylon serve that is used to contain the strands during cable compaction, and minimizes any loose strands the could cause a turn to turn short. Several of the manufacturing challenges relating to the conductor were keystoning during winding, and epoxy impregnation of the rope conductor.

This type of conductor offered many challenges in respect to winding the coil. The copper rope conductor did allow easier positioning of the turns onto the winding form. However, this conductor has a tendency to swell during handling thus increasing its cross-section.

A. Keystoning

Keystoning is a term used for the cross-sectional changes that occurs to a conductor during the winding operation. Due to the winding current centroid tolerances [+/- 0.020 inches] it was important to minimize keystoning in the conductor. A number of R&D trials were performed using various conductor designs as discussed above. The results from these tests were then included in the design and manufacturing procedures. Some of the findings included:

- Reducing the layers of turn insulation added flexibility to the conductor as well as reducing keystoning.
- Increased the number of clamps during winding. Winding clamps on 3 inch centers were required to fully support and hold the turns in position. The rope conductor reacted like a "water balloon" where pushing in one section caused severe movement in adjacent areas. [Figure 2]

- “Setting” or repositioning of the conductor turns after they have been wound onto the winding form. Special tools were used to gently tap the turns against the winding form to reshape and reduce the degree of keystoning. [Figure 3]

Figure 2- Coil Winding Clamps

Figure 3- Setting Turns in Position

- As a result of these steps the keystoning of the conductor and excessive bundle growth was not as great of a problem as was anticipated.

B. Vacuum Impregnation (VPI)

The second technical issue associated with the copper rope was epoxy filling the copper rope strands using a vacuum-pressure process. The analysis for the coil conductor assumed that the conductor was epoxy filled. A 3-part epoxy system [product CTD-101k] developed by Composite Technology Development Co. was selected for the modular coils. An extensive R&D program was then completed with good test results. The impregnated rope met the design requirements, and as shown in Figure 4, a good epoxy fill was achieved. The photo’s show a sequential magnification of an epoxy filled conductor (0.0065 in. thick). Numerous VPI tests demonstrated that the conductor can be successfully filled using a VPI process.

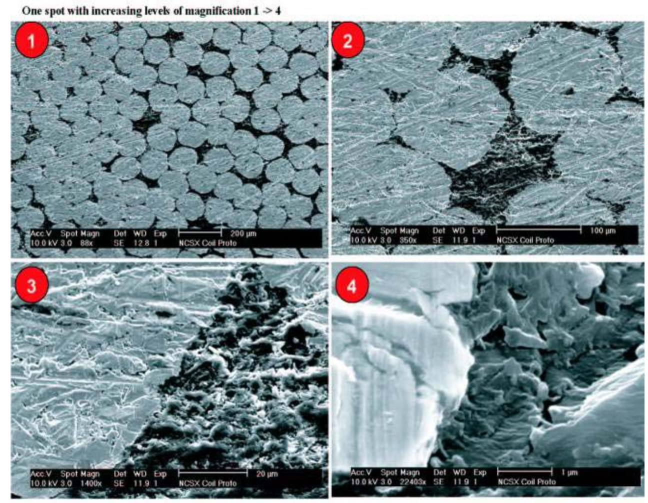

Figure 4- Electron Microscope Photo of Epoxy Filled Conductor

III. DIMENSINAL CONTROL AND METROLOGY

In order to minimize field errors in the NCSX plasma, the current centroid of each coil must be within the design value in the completed NCSX device. To achieve this it is necessary to establish dimensional control steps throughout the manufacturing process. Each winding form has a number of fiducial points that will be used along with a coordinate measuring machine [CMM] to determine the position of turns and the centroid throughout the manufacturing process. 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. The side clamps will be returned to these positions after being removed to add each layer of conductor. The top winding clamp screws will be set to a specific torque value [30 inch-lbs] when they are replaced after a layer of conductor is added. Once the winding packs are complete and have been adjusted to put the current centroid in the desired location, they will be stabilized by binding them between the winding clamps with glass cloth strips. The purpose of these binding strips is 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. The measurement tools to be used include the CMM arm and gauge blocks.

IV. TWISTED RACETRACK COIL (TRC)

The Twisted racetrack Coil (TRC) was the third test article in the modular coil R&D program, and the first to demonstrate a prototypical coil winding. The TRC assembly included many of the modular coil design features including a winding form with typical machined “tee” profile, identical conductor, insulation, leads, termination, cooling system, instrumentation, vacuum-pressure epoxy impregnation (VPI) features and final coil clamps.

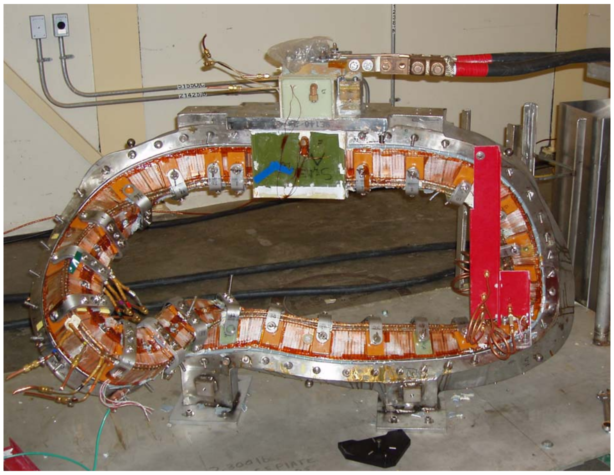

Figure 5- Twisted Racetrack Coil

The manufacturing of the TRC helped the finalization of tolerance control; manufacturing procedures; final tool development; verification of the VPI plan utilizing the autoclave; verification of thermal performance and training of key personnel.

V. MANUFACTURING EQUIPMENT

The manufacturing of the modular coils introduced several unique manufacturing challenges. Due to the complex coil geometries including hairpin bends it was decided to wind the modular coils in the vertical position. Vertical turning fixtures [Figure 6] allowed access from both sides and made easier handling of the coil assemblies. The individual winding forms are mounted to support ring assemblies that are used during manufacturing as part of the turning fixtures, and as lifting fixtures to transport the coils from station to station.

Figure 6- Modular Coil Turning Fixture

The pre-insulated conductors are wound 4-in-hand using a payout spool system that allows direct positioning of the turns onto the winding form while minimizing any keystoning of the conductor. Additional concerns with the copper rope conductor are the copper whiskers that may be present and could penetrate the turn insulation causing a turn to turn fault. A detector was designed and fabricated that can detect any copper whiskers as the conductor is being layed onto the winding form. An audible alarm is activated if any copper whiskers are detected. [Figure 7]

Figure 7- Copper Whisker Detector

Once wound the coils the coils are then placed in a mold and vacuum-pressure impregnated with epoxy in the autoclave a pressure/vacuum coil oven that was designed and fabricated at PPPL. [Figure 8] The overall VPI cycle is approximately 60 hours as shown in Figure 9.

Figure 8- Autoclave used for VPI of Modular and TF Coils

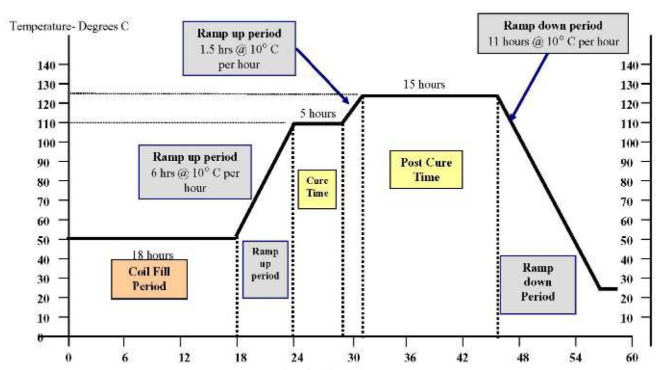

Figure 9- Modular Coil VPI Cycle

VI. MANUFACTURING DEVELOPMENT

A number of manufacturing developments were required in order to complete the final manufacturing process plans and procedures. Some of these included the finalization of the internal cooling system, termination of the conductor leads, development of a VPI process and mold system. Included below are just a few of those activities.

A. Lead Brazing

The lead connectors were attached to the copper rope conductor via a brazing operation. A procedure using a flameless resistive heating method was developed for heating the specimens to the braze temperature. Once the copper connectors were cleaned using ethanol, the rectangular shaped copper conductor was then reshaped using phenolic form blocks to provide a proper fit between the cable and terminal block. The outside of the connectors were then painted with Nicrobraz to protect the threads and electrical contact surfaces. Chill blocks were used to protect the copper rope conductor from the advancing heat and argon gas flowed across the braze joint to minimize oxidation. The joint was heated using the "Nibco" carbon tongs. Once at temperature, the Sil-Fos rod was fed through the feedhole at the threaded end of the terminal. The carbon tongs were then repositioned to fill the backside of the connector. The samples were successfully tested and process was qualified.

Figure 10- Brazing of Conductor Leads

B. VPI Mold

Due to complex geometry of the modular coils it was decided to utilize a "Bag" mold instead of procuring a rigid machined mold. The "Bag" mold is constructed starting with layers of a silicone rubber tape that encloses the coil bundle. A vacuum is then applied to this bag as shown in figure 11. The bag is then painted with a layer of 2-part RTV12 to help seal any small leaks that may occur. An epoxy/glass shell is then applied over the bag to provide mechanical strength [Figure 12]. This method was successfully demonstrated on the Twisted Racetrack coil. The "Bag" mold was less expensive to fabricate and can be customized to fit any imperfections on the coil.

Figure 11 -VPI Bag under Vacuum

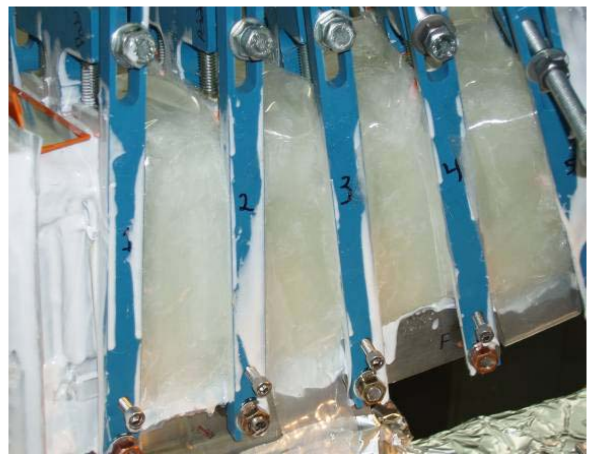

Figure 12 – Epoxy Shell Mold

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REFERENCES

[1] T. Kozub, J.H. Chrzanowski and S. Jurjinski, "Measurement of NCSX Modular Coil Composite Conductor Material Properties" presented at 21st. SOFE Conference in Knoxville, Tenn., October 2005. *(in press)*

[2] I. Zatz and J.H. Chrzanowski, "Test Program to Determine the Mechanical Properties of the NCSX Modular Coils" presented at 20th. SOFE Conference in San Diego, Ca. October 2003.

[3] G. Neilson, "NCSX Construction Progress and Plans" presented at 21st. SOFE Conference in Knoxville, Tenn., October 2005. *(in press)*

[4] P. Fogarty, "Manufacturing of the Modular Coil Winding for NCSX presented at 21st. SOFE Conference in Knoxville, Tenn., October 2005. *(in press)*

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