The TPX Superconducting Magnet Fabrication Process

15th IEEE/NPSS Symposium on Fusion Engineering

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ABSTRACT

The TPX Toroidal Field (TF) and Poloidal Field (PF) Coils use both Nb_3Sn and Nb-Ti internally cooled, cabled superconductor (ICCS). A prime consideration in the design of the coils was the minimization of joints in the conductor cable to save space, reduce heating losses and increase reliability. Therefore, the traditional double pancake approach was discarded in favor of the continuously wound coil. The recently developed use of the roll bender in winding the coils permits the backwinding, which is required in this geometry. The Nb_3Sn TF coils, the central solenoid coils and inner-most PF coils require the wind-react-insulate sequence. The Nb-Ti outer PF Coils are also insulated after the coils are wound because the insulation system used in all the coils requires the insulation of rigid polyimide sheet between turns and pancakes before Vacuum Pressure Impregnation (VPI) of the glass epoxy system.

This paper proposes and discusses a manufacturing plan based upon the use of the roll bender in the winding of the

coil, and a special fixture to spread apart the turns of the coil and permit the application of the insulation materials prior to VPI.

I. INTRODUCTION

The TPX is a tokamak designed for long pulse operation and will be the first tokamak with both superconducting TF and PF coils. The TPX has completed the conceptual design stage. It is anticipated that the design will soon be transferred to industrial partners who will complete the design and fabricate the magnets. Fig. 1 illustrates the magnet system. There are 16 magnets in the TF system and 7 pairs of magnets with horizontal mid-plane symmetry in the PF system. Four of the PF pairs constitute the central solenoid. The TF coils, the central Solenoid coils, and the PF5 coils use Nb_3Sn superconductor in an internally cooled cable in conduit design. PF6 and PF7 use NbTi superconductor, also in a cable in conduit design. A more complete description of the TPX magnet system can be found in [1] and [2].

The manufacturing process proposed here is an evaluation

Fig. 1 TPX Magnet System

MASTER

Fig. 2 TF Coil

of the fabricability of the present design and may be changed by the industrial partner who will actually manufacture the magnets. However, certain design features dictate a departure from the more traditional procedures followed in manufacturing normal magnets. The high reaction temperatures of the Nb_3Sn require the insulation material to be applied after reacting the Nb_3Sn and before vacuum impregnation of the coil. There is also a strong desire to not have joints within the winding of a coil. The reason for this is to save valuable space (especially in the case of the central solenoid), reduce heat loads from the normal joints and increase the reliability of the system. This requirement eliminates double pancake designs with transitions at the inside diameter and joined at

the outer diameter. The need to spread apart the turns of the coil to apply the turn-to-turn insulation eliminates layer-wound coil concepts. The recently developed use of the roll bender facilitates the manufacture of a continuous layer-wound coil in which the conductor is wound from the inside diameter to the outside diameter, then transitions to the next layer and is backwound to the inside diameter. The process repeats as often as the design requires. The use of the roll bender avoids the heavy fixturing required for coils wound under tension because of the low "spring back" resulting from this technique. All the coils in the TPX are of the continuous pancake design.

II. TOROIDAL FIELD COIL FABRICATION PROCESS

The Toroidal Field Coil conductor is Nb_3Sn in an Incoloy 908 conduit. The length of the conductor is slightly over 1 km. There are 12 pancakes with 7 turns per pancake. All transitions and crossovers take place at the top of the coil. This permits a compact array of conductors in the front and rear legs of the coil. The liquid helium coolant is fed into and removed from the coil at feed-throughs welded onto the conductor sheath. These feed-throughs are located in the crossovers on the low field side at the top of the coil. Fig. 2 shows the TF coil.

A. Coil Winding

The conductor will be received from the manufacturer with sufficient conductor on a spool to wind a complete coil. A concept of what a coil winding station might look like is shown in plan in Fig. 3 and in elevation in Fig. 4. Note that in using the roll bender to bend the conductor, the bending rollers must be close to the final location of the conductor on the coil at the time the conductor is bent. In the case of a "Dee" shaped coil, this requires relative motion between the winding table and the roll bender, as illustrated in Fig. 3. In the concept for the winding station shown, the spool of conductor is close to the roll bender, minimizing the distortion of the Incoloy sheathed conductor as it comes off the spool. If the conductor were

Fig. 3 TF Coil Winding Station, Plan View

Fig. 4 TF Coil Winding Station Elevation

straightened as it comes off, the spool could be located at a distance from the winding table. This would simplify the design of the winding station, but the extra work hardening of the Incoloy must be evaluated.

After winding, the helium feed-throughs will be installed by cutting through the conductor sheath and TIG welding the feed-throughs in place. The coil will then be thoroughly leak checked.

B. Reacting the Superconductor

The coil will be reacted in a vacuum oven to minimize Stress Activated Grain Boundary Oxidation (SAGBO) in the heat treated Incoloy 908. The heat treatment cycle is 175 hours at 220 C, 96 hours at 340 C, and 200 hours at 650 C. All tooling and fixturing will be fabricated from Incoloy 908 to minimize differential thermal expansion between the coil and the tooling.

C. Application of Insulating Materials

After heat treatment, the coil will be transferred to the cleaning and insulating station. At this station, the coil shall be fixtured so that the turns can be individually separated. Fig. 5 is an illustration of this operation. Once separated, each turn shall be cleaned to remove any residue that may remain after the heat treatment. During the separation of the turns, the Incoloy strips and sheets between the turns and layers are removed. The conductor shall be wrapped with two half lapped layers of dry glass insulation. Strips of polyimide, or cryogenic grade G-11, will be placed between turns and sheets of the same material will be placed between layers as the coil is rebundled. Glass roving will also be installed in the voids formed by the radius of the corner of the conductor and the sheet insulation.

Fig. 5 Application of Insulating Materials

Fig. 6 PF Coil Location

The coil will then be ground-wrapped using a number of half lapped layers of sandwiched Kapton/glass insulation.

D. Vacuum Pressure Impregnation (VPI)

The coil will be vacuum pressure impregnated with a heat cured epoxy resin in an autoclave. The coil is placed in an open-topped mold in the autoclave. A vacuum is drawn and the epoxy resin is allowed to flow into the mold to wet the dry glass insulation. The autoclave is then pressurized to force the epoxy into the voids. The vacuum-pressure cycle is repeated a number of times. The top is then placed on the mold and the sides are pressed to the final dimensions, squeezing out the excess epoxy resin. The coil is then heat cured.

E. Final Testing and Inspection

After being impregnated and cured, the coil will be removed from the mold and a conductive ground wall will be applied to the outside surfaces of the coil. This will be followed by extensive leak checking and electrical tests. These will include DC hipot tests, tan-delta and induced voltage tests.

III. POLOIDAL FIELD COIL FABRICATION PROCESS

The locations and designations of the poloidal field coils are shown in Fig. 6. There are 7 pairs of coils. PF coils 1 through 5, both upper and lower sets, use Nb_3Sn superconductor. PF6 and PF7 upper and lower use NbTi superconductor. All the PF coils are of the continuous pancake wound design similar to the TF coil, and require the back winding process using the roll bender.

A. Fabrication of the Nb_3Sn Poloidal Field Coils

The manufacturing steps and procedures of the Nb_3Sn PF coils is exactly the same as that of the TF coils. The difference is that the PF coils are round and the translational motion of the roll bender with respect to the winding table, is smaller. This will result in a simpler design for the winding station.

B. Fabrication of the NbTi Poloidal Field Coils

The NbTi PF coils differ in fabrication procedure from the Nb_3Sn coils in that the NbTi does not have to be reacted. The cleaning of the conductor and the application of the insulating materials takes place at the winding station just after the conductor passes through the roll bender. The coil winding is also interrupted whenever the location of a helium feed-through is reached. The feed-through is installed and the insulating and winding process will continue.

The vacuum pressure impregnation and testing is also identical to the other coils.

IV. CONCLUSIONS

Both the Toroidal Field coils and the Poloidal Field coils require the use of the roll bender and the back winding technique to fabricate the continuous pancake wound coils. The Nb_3Sn coils also require the wind-react-insulate sequence and the need to spread apart the turns of the coil to apply the insulation. The manufacturing plan has been reviewed by three coil manufacturers who are in general agreement with the feasibility of the approach. However, there is general agreement with the need to do manufacturing R&D in the areas of winding, heat treatment and VPI to develop the tooling and procedures that are required.

ACKNOWLEDGMENT

Work supported by U.S. DOE Contract DE-AC02-76-CHO3073.

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