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A Small Rectangular Edge Localized Mode Control Coil Design able to Withstand a 400°C Environment*

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***Abstract*—Recently, an Edge Localized Mode (ELM) control coil was developed for use on the DIII-D tokamak. The coil design represented a significant challenge due primarily to the requirement for the coil insulation to withstand bakeout temperatures of 400°C for extended periods. This requirement ruled out most common organic insulating systems and necessitated a significant prototyping and development effort, leading to the selection of an advanced high temperature glass/polyimide resin system. The development included developing a heating mechanism that provided the discrete temperature ramp cycles and cure cycles required by this exotic resin. To complicate matters, the resin had a limited shelf life. Additionally the coil was small and rectangular in shape with rather small corner radii. This created a corner buildup that was not previously encountered and made dimensional control difficult. Another unique design requirement was the need to apply a sufficient internal pre-load to the wound and cured coil to insure there will be no relative motion between the coil and the Inconel case due to Lorentz forces from the 4 Tesla toroidal field on the vessel center post. This led to development of very unique leaf springs and a significant research and development effort coupled with an equally arduous finite element analysis effort. A satisfactory prototype was produced. This paper will focus primarily on the manufacturing challenges and discuss the prototyping effort.**

Keywords-Edge Localized Mode; ELM; Coil; Polyimide; resin

I. INTRODUCTION

Edge Localized Mode (ELM) control coils can range in size from small picture frames to several meters across. Recently a small picture frame ELM coil was developed for the DIII-D tokamak at General Atomics. These coils were compact measuring 6.75" x 16.12" overall including their Inconel 625 case. The internal magnet measured only 14.89" x 5.8". The design requirements include a vacuum tight Inconel 625 coil case, 12 turns (nominal) - 1667 amps/turn - 20 kAT conductor system operated at 20 Hz and capable of withstanding high current magnetic forces and baking temperature to 400°C. Electrical insulation is a combination of Polyimide resins, Kapton film, and Vespel in spaces that are usually filled with stagnant nitrogen but can be evacuated for system leak checking. The coil windings are bonded together with high temperature pre-impregnated (pre-preg) polyimide material. While there were several challenges during their design, this paper describes a few of the manufacturing challenges of parts to meet the design.

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II. MANUFACTURE CONSIDERATIONS

A. Coil Manufacture

The magnet coils themselves posed several manufacturing challenges including a unique winding arrangement; precisely placed transitions from one layer to the next; structurally strong insulation capable of very high temperatures.

1) The coil winding configuration shown in Fig. 1 required the leads to exit the magnet in a specific pattern to allow the coils to be connected in series. The conductor was provided precoated with a thin layer of polyimide.

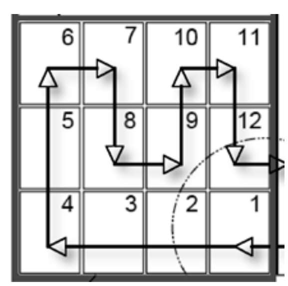

Figure 1 Coil winding configuration

2) In order to achieve the specified winding configuration precise placement of transitions were required. An example is shown in Fig. 2.

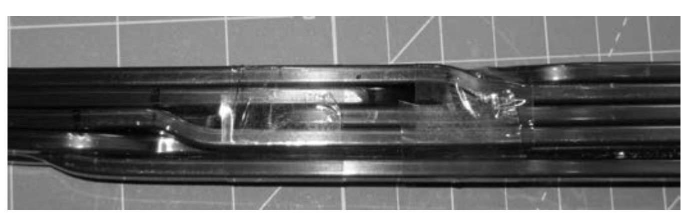

Figure 2 Winding transitions nested

3) A hydraulic forming tool shown in Fig. 3 was crafted that allowed pre bending of the transitions precisely where needed. This tool was also used to press the inner radius of the turn flat to eliminate keystoning.

Figure 3 Hydraulic conductor transition bender

4) In order to achieve the structural requirements it was determined that a bonded coil design would be required. Fortunately, an advanced high temperature glass/polyimide pre-preg resin system was discovered called 900HT manufactured by Performance Polymer Solutions Inc. (P^2SI) 2711 Lance Drive, Moraine, OH 45409. Tests showed that this material once cured provided greater than 1000 psi shear strength. 900HT is normally used for thin flat laminate sections that are very different from our 12 conductor rectangular cross sections. However, the manufacturer thought that it could be used for both our turn-to-turn insulation as well as the over all ground wrap. The pre-preg material has a limited shelf life and requires refrigeration until use. P^2SI was very cooperative and provided our limited quantities as needed. The turn-to-turn insulation layer was ½ lapped by hand. At first this seemed daunting but the technician became quite adept and was able to wrap sufficient conductor in a day, refrigerate overnight in a Nitrogen bag and wind the coil the following day. Then the leads were torch brazed and finally, the ground layers were applied. The coil was ready for curing. The 900HT had a unique complicated cure cycle. Five (5) individual coils were made to develop the cure cycle with the cooperation of P^2SI. The 900HT has several discrete temperature steps where unique chemistry occurs. Ramp rates, hold times, and pressures were critical. It became evident that a specialized mold would be required to apply required pressure as well as uniformly heat the coil shown in Fig. 4. The curing cycle required the 900HT resin to be heated under slight vacuum to remove the volatiles that allowed the pre-preg tape to be pliable. Once the volatiles were released, the mold pressure was applied to allow the resin to bond properly. This required the mold to be removed from the vacuum chamber at a temperature of 250°C; four internal blocks adjusted outward and finally the top tightened down to the bottom. The mold appeared to work well to control dimensions. A layer of copper was added to distribute heat more quickly and evenly. Excess resin material was observed flowing out of the coil as shown in Fig 5. that made it very difficult to free the coil from the Teflon and glass breather overwrap. Several conversations were held with P^2SI to adjust the percentage of resin impregnated in the glass. This needed further development.

Figure 4 Coil Curing Mold

Figure 5 Mold opened revealing cured coil, four inside mold pusher blocks, copper sheet, and excess resin

5) Inexpensive yet powerful controllers were used to precisely control the curing cycle found below.

1. Reduce pressure by 2-5" Hg (NOTE: No mold pressure)
2. Heat at 0.25°F/min from RT to 350°F (177°C)
3. Heat at 0.5°F/min to 482°F (250°C)
4. Hold for 3 hours at 482°F (250°C)
5. Apply mold pressure
6. Reheat at 5°F/min to 482°F (250°C)
7. Heat at 2°F/min to 536°F (280°C)
8. Hold for 30 minutes at 536°F (280°C)
9. Heat at 2°F/min to 700°F (371°C)
10. Hold for 2 hours at 700°F (371°C)
11. Heat 0.5°F/min to 752°F (400°C)
12. Hold for 2 hours at 752°F (400°C)
13. Cool 0.5°F/min to 650°F (343°C)
14. Cool at 1°F/min to 600°F (317°C)
15. Cool at 2°–5°F/min to below 500°F (260°C)
16. Cool to room temperature

6) During case assembly it was noticed that the various prototypes fit the case bottom (see Fig. 7) with varying amounts of snugness and in two cases there was an interference that did not allow the coil to fit over the inside edge of the bottom. This lead to an investigation which discovered that the four internal blocks were unable to compress the inside corners sufficiently to provide pressure against the inside side flats. At first it was thought that the mold simply needed to apply more pressure but after further investigation it was learned that, in fact, there were several contributing factors. The inside corner radius was sharper than any other coil previously made. During the wrapping of the coil with the pre-preg ground wrap, the material effectively ¼ lapped each layer instead of the anticipated ½ lap. This doubled the amount of material on the inside corners causing them to bulge inwardly. A careful dimensional analysis quickly showed that the fundamental issue was that the original coil winding form radius needed to be even sharper. This seemed counter intuitive but by making the radius sharper (reduced number), it provided additional room for the additional material on the inside corner. This in turn, would allow the internal mold pusher blocks to fit tightly up against the straight part of the inside surfaces without butting against the corners first.

B. Case Manufacture

A high tolerance Inconel 625 case was required curved exactly to conform to the diameter of the DIII-D center post and had to have even contact with a layer of Grafoil to provide sufficient and uniform heat transfer. Initially a brazed construction was considered to minimize distortion. However, because of the high stresses involved and the requirement for the case to be only 0.093" thick due to space restrictions, a welded construction was specified. The weld distortion of the curved case was quite a challenge. Eventually an elaborate fixture shown in Fig. 6 was developed that held the parts firmly in place while providing access for the welder to sufficiently tack the parts in place. Then the fixture was opened and the welding was completed. A thermal anneal cycle was also incorporated to relieve the stress and resulted in a predictable and acceptable amount of only 0.020" of distortion.

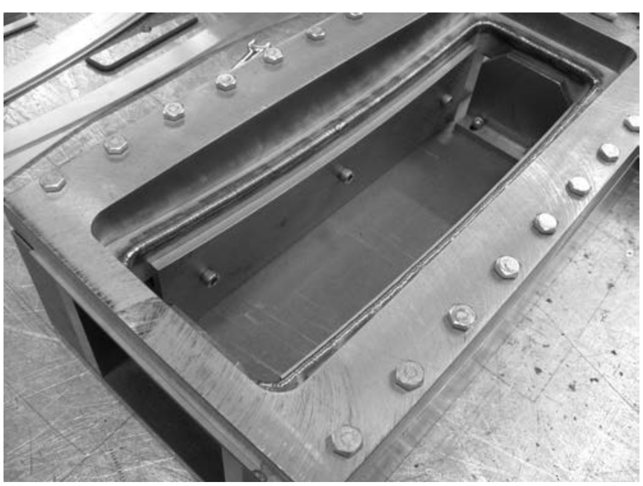

Figure 6 Welding fixture

Figure 7 Case bottom

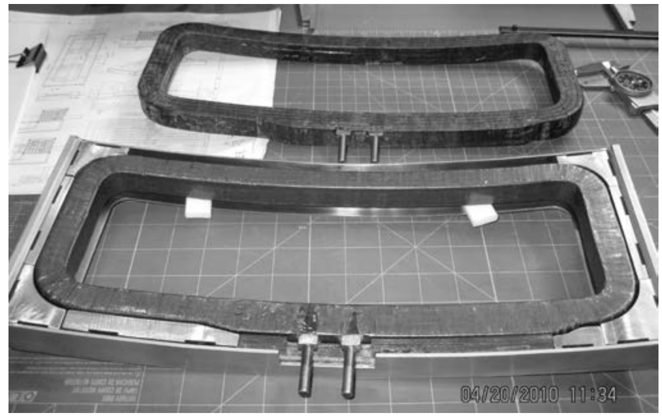

Figure 8 Cured coil wrapped in Kapton positioned into the case top

C. Coil Assembly

Once the coil was cured it was fit over the case bottom shown in Fig. 7 to verify a snug fit. As mentioned previously, this proved difficult. Then the coil was fit into the case top shown in Fig. 8 to assemble all the side pusher blocks along with their corresponding side springs. Because the coil was to be operated at 20 Hz in a strong magnetic field, springs were developed to apply sufficient pressure to stabilize the coil and prevent rocking within the case. A clever design was established that provided a high repeatable spring rate within a very low profile. The spring plate shown in Fig. 9 was placed within the case on top of the cured coil. A hydraulic press was used to apply the required force to press the case top down onto the case bottom thus compressing the springs. The springs deformed plastically at first but then performed elastically within the desired range of force and motion as shown in Fig. 10. Similar springs were also placed around the outer edge of the coil to maintain the required side load. During the compression, the lead block insulators were monitored closely to assure that they engaged the case and each other to provide the required insulation. The case was tack welded while under compression to sufficiently hold it together. Then the case was removed from the hydraulic press and the weld was completed. Finally the lead block was installed and welded into place. The coil was electrically tested including both impulse testing and DC hi-pot tests to 3 kV and was also subjected to a shaker test to assure that the springs would perform as expected throughout its life cycle. The coil successfully passed all required tests.

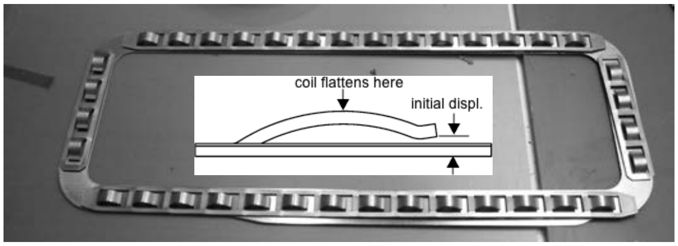

Figure 9 Spring plate (insert shows deflection)

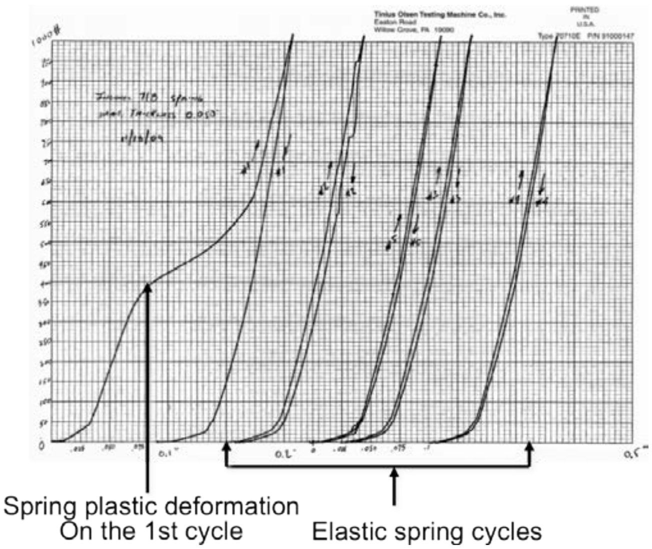

Figure 10 Spring deformation

Figure 11 Completed coil

III. Summary

This was an extremely challenging collaboration between very talented engineers and physicists of both the Princeton Plasma Physics Laboratory and the General Atomics DIII-D staff. A state-of-the-art ELM coil was developed that was both ultra high vacuum and 400°C bakeout compatible and capable of operating at high alternating current. In order to achieve this extraordinary coil, a significant amount of research and development including several prototyping efforts was required. At the onset the design criteria seemed challenging and the amount of R&D required was underestimated. Future projects that require research and development should be budgeted in two phases. First, a research and development phase should be planned that allows for realistic prototype development and has ample contingency to allow for design improvements. Second, the design should be frozen and the production phase should be planned that takes advantage of the prototyping efforts to establish low risk cost estimates.

Acknowledgment

Special acknowledgment should be given to the extraordinary cooperation of the Princeton Plasma Physics Laboratory and General Atomics staff which yielded this amazing ELM coil shown in Fig. 11.

References

[1] P.Titus, "ELM and in-Vessel Coil Programs at PPPL for ITER, DIII-D, and JET" 23rd IAEA Conference October 9-17, 2010, Daejeon South Korea

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