Princeton Plasma Physics Laboratory

PPPL- 4923

PPPL- 4923

Design Analysis and Manufacturing Studies for ITER In-Vessel Coils

M. Kalish, et. al.

June, 2013

PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

Design Analysis and Manufacturing Studies for ITER In-Vessel Coils

M. Kalish[1], A. Brooks[1], P. Heitzenroeder1, C. Neumeyer[1], P. Titus[1], Y.Zhai[1], I Zatz[1] M. Messineo[1], M Gomez[1], C Hause[1], E. Daly[2], A. Martin[2], Y. Wu[3], J. Jin[3], F. Long[3], Y. Song[3], Z. Wang[3], Zan Yun[3], J. Hsiao[4], J. R. Pillsbury[5], T. Bohm[6], M. Sawan[6], Jiang[7]

[1]Princeton Plasma Physics Lab, Princeton, NJ, USA
[2]ITER Organization, Route de Vinon, 13115 St Paul-lez-Durance, France
[3]Chinese Academy of Sciences - Institute of Plasma Physics, Anhui, China
[4]Vector Resources Annandale VA, USA
[5]Sherbrooke Consulting, Arlington, VA, USA
[6]Fusion Technology Institute, University of Wisconsin-Madison, Madison, WI, USA
[7]Southwestern Institute of Physics, Chengdu, China

mkalish@pppl.gov

Abstract—ITER is incorporating two types of In Vessel Coils (IVCs): ELM Coils to mitigate Edge Localized Modes and VS Coils to provide Vertical Stabilization of the plasma. Strong coupling with the plasma is required so that the ELM and VS Coils can meet their performance requirements. Accordingly, the IVCs are in close proximity to the plasma, mounted just behind the Blanket Shield Modules. This location results in a radiation and temperature environment that is severe necessitating new solutions for material selection as well as challenging analysis and design solutions. Fitting the coil systems in between the blanket shield modules and the vacuum vessel leads to difficult integration with diagnostic cabling and cooling water manifolds.

The design of the IVCs is now progressing towards a final design scheduled for late CY 13. The project is a collaboration between the Princeton Plasma Physics Laboratory in Princeton NJ, the Chinese Academy of Sciences (ASIPP) in Hefei China and the ITER Organization. An extensive thermal and stress analysis to evaluate the effects of the high temperatures and electromagnetic loads on the In Vessel Coils has been undertaken. Manufacturing development is underway at ASIPP to develop the processes necessary to build ELM coil and VS Coil prototypes. This paper will outline the design and analysis issues as well as review the manufacturing development required to address these requirements and plans for prototypes.

Keywords— ITER, Edge Localized Modes, ELM, Vertical Stabilization, VS, Magnesium Oxide Insulation, MgO, In Vessel Coils, IVC, Stainless Steel Mineral Insulated Conductor, SSMIC, Mineral Insulated Conductor

I. DESIGN AND ANALYSIS SUMMARY

The IVC system is shown in Fig. 1. It consists of an array of 27 ELM coils arranged in an orientation that forms a cage around the plasma and two VS coils located above and below the plasma. The coils are mounted on the vacuum vessel wall, behind the blanket/shield modules.

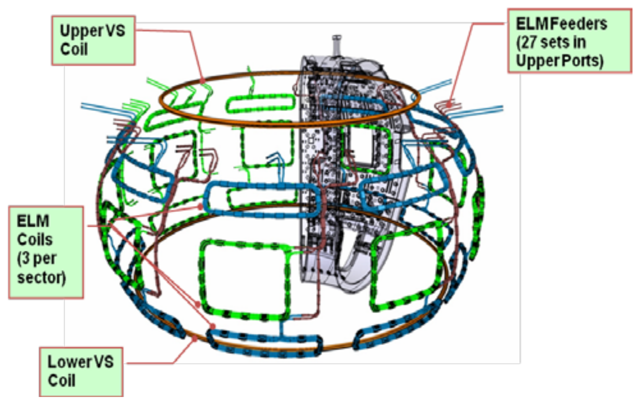

Figure 1 ELM and VS Coils

This location places high demands on the coil design: The vessel temperature during operation is 100 C, and bakeout temperature is 240 C. Nuclear heating is in the range of 1.12-0.86 MW/m3 in the ELM coils and 1.4-0.7 MW/m3 in the VS coils. Mineral insulated cables, shown in Fig. 2, were developed to operate in this severe environment and to provide the structural characteristics needed to meet the performance requirements. The cable details are listed in Table 1. Note that there are two cable types: C18150 CuCrZr conductors with Inconel 625 jackets for the ELM coils, and C10200 Cu conductors with SS316 (LN)-IG jackets for the VS coils.

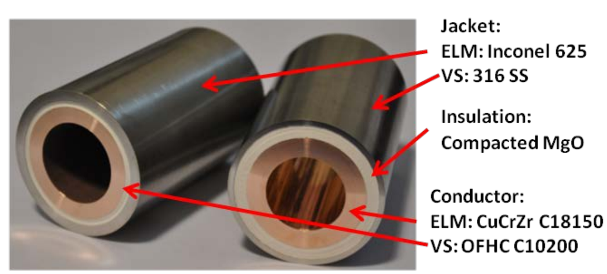

Figure 2 Mineral Insulated Cable

Work supported by U.S. DOE Contract No. DE-AC02-09CH11466

	ELM	VS
SS [316 LN (IG)] Jacket Outer Diameter	59 mm	59 mm
SS [316 LN (IG)] Jacket Inner Diameter	51 mm	55 mm
Conductor Material	CuCrZr [CDA 18150]	Cu [CDA 10200]
Conductor Outer Diameter	46 mm	45 mm
Conductor Inner Diameter	33.3 mm	30 mm
Mineral Insulation thickness	2.5 mm	5.0 mm
Test voltage (2*E+1kV)	1.4 kV	3.4 kV

Table 1. Mineral insulated cable details

A. ELM Coil Overview

The ELM coils each have 6 turns and operate up to 15 kA, at frequencies ranging up to DC-5Hz. The coils are designed to last for the lifetime of ITER, 30,000 pulses, at pulse durations up to 3000 s. From the fatigue point of view, this requires designing for infinite life. A fracture mechanics analysis method is used, with the fatigue design allowable being set at less than the threshold stress level for a flaw size no greater than 0.3 mm^2. The analyses considered both the thermal stresses due to Joule heating and nuclear heating, and electromagnetic loads for (18) states of operation. All results were found to be within the design allowables. The coils are designed for reliability, with all conductor joints being induction silver brazed and inspected (x-ray, ultrasonic, visual, and helium leak tests) and welded jacket joints which will also be visually, x-ray, and helium leak tested. If a braze did leak in service, it is expected that a ground fault system will detect the increase in leakage resistance so that the coil can be safely de-energized and continue to be cooled. Since the power supplies will be floating, two ground faults would be required for a damaging level of energy release. ELM Coils are assembled into the vacuum vessel by adjusting their position with shims and bolting them to rails on the vacuum vessel wall. After they are bolted in position, feeders which supply current and cooling water will be attached by brazing and welding the joints. The feeders are made of the same MgO insulated cable as the coil.

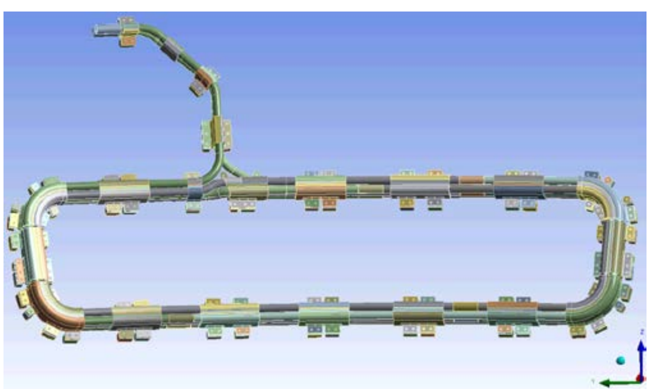

Figure 3 Six Turn Lower ELM Coil with Brackets

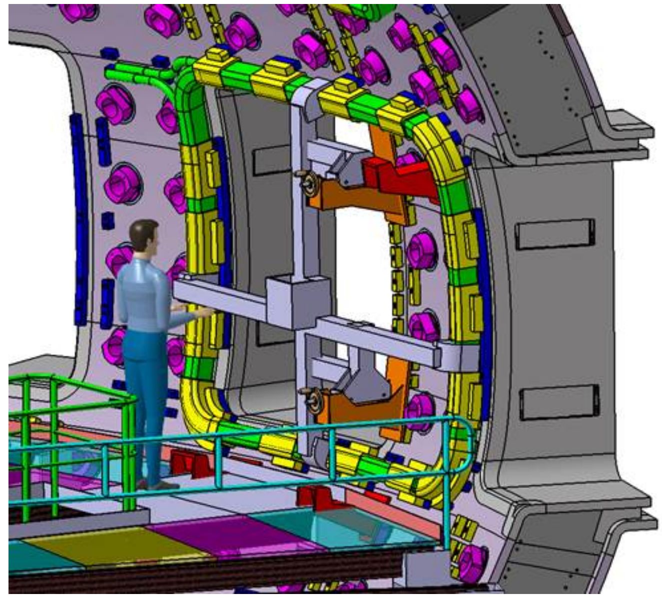

Figure 4 Equatorial ELM Coil Installed on Vacuum Vessel Wall

B. VS Coil Overview

The design and analysis approach for the VS coils is much different than the ELM Coils because of their circular geometry and rigid attachment to the vacuum vessel wall. Each coil contains 4 turns, with each turn being individually powered to permit bypassing failed turns, if they occur. The coils are designed for a maximum current of 60 kA peak per turn. The circular geometry of the coils and rigid attachments puts the coils in a compressive stress state when heated by current flow and nuclear heating. This is a favorable condition because cracks will not grow with material in compression. Consequently a more traditional S-N fatigue design criteria is used. In addition, the fatigue life requirement at high stress for the VS is limited to 30,000 cycles rather than the infinite number of cycles for the ELM coils The most demanding design situation for the VS coils is the design of the lead-out regions and feeders, since their 60 kA currents are being crossed by PF and TF fields. Analyses to date indicate that the coils meet the design stress allowables for all 17 operating design states.

The VS production coils will be fabricated and tested in 120 degree segments in a manufacturing facility. The segments would be installed, joined, and submitted to final testing inside ITER's vacuum vessel.

II. Manufacturing and Prototype Development

A. A. Mineral insulated cables

All of the mineral insulated cables required for the prototypes have been manufactured and are shown in Figure 5.

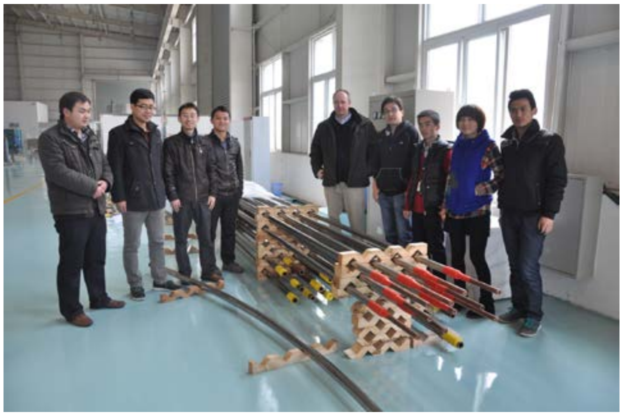

Figure 5 ELM Conductor for Protype Coil at ASIPP

Conductor cable is fabricated by sliding preformed magnesium oxide, MgO, blocks over the copper tubes These blocks are formed by mixing Polyvinyl alcohol binder with pure MgO, compressing the mixture into forms at pressures in the range of 500MPa and then sintering the MgO blocks at over 1000 degrees C (see Figure 6). It is important to control the density of the preformed blocks. If the preformed block is too dense initially it cannot be properly compacted to its final required density. A density of 2.2gm/cm^3 to 2.3 gm/cm^3 was found optimal. After running the conductor through the compaction machine and compressing it to its final dimensions the density of the MgO is increased to roughly 3 gm/cm^3.

Figure 6 MgO Preperation and Molded Preform Insulation

MgO is hygroscopic. For the MgO to maintain its electrical insulating properties it must be kept away from moisture. Nitrogen filled troughs in the assembly areas were used to keep the MgO preforms in a dry atmosphere as they were slid over the copper conductor and inserted into the Inconel or SS sleeves. The assemblies were then compacted by the ITER PF compaction machine. Figure 7 is a picture of the mineral insulated conductor inserted into one pair of compaction rollers and a view of the compaction machine. The cable was pulled through 14 pairs of rollers for compaction and 4 pairs of rollers for straightening. The R&D team effort at ASIPP succeeded in optimizing many parameters including pressure, temperature for sintering the MgO and the diameter of the outer mineral insulated conductor sleeve before compaction.

Figure 7 Pair of Compaction Rollers and Compaction Machine

The conductor development effort included studies on composition and compaction of the magnesium oxide, physical properties of the fabricated cable, and forming trials to determine mechanical tolerance limits.

B. Testing

During development of the conductor prototype samples the electrical performance of the conductor was tested at PPPL and ASIPP. Parameters tested included DC current leakage at 1kV DC, the dissipation factor (insulation power factor), the voltage endurance, and the DC breakdown voltage. In Figure 8 the DC breakdown voltage is plotted for some of the samples tested at PPPL. The operating voltages are 2400V for the VS conductor and 180V for the ELM conductor. Breakdown during testing always occurred at the ends of the test samples which is not representative of actual operating conditions. When the ends were insulated well enough so that breakdown did not occur at the end of the sample test voltages went as high as the 15kV power supply would allow with no breakdown evident internally in the mineral insulated conductor. If more conservative values for the breakdown at the ends of the test samples are used the VS conductor exceeds the operating voltage by a factor of 4 and the ELM conductor exceeds the operating voltage by a factor of 20.

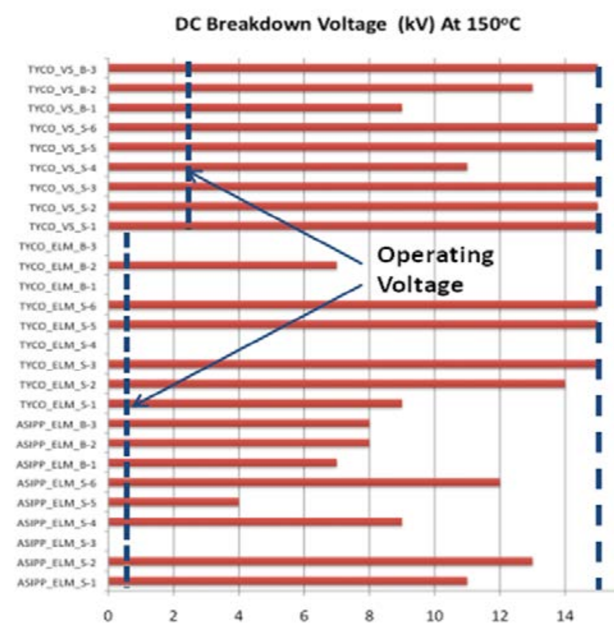

Figure 8 DC Breakdown Test Results

Mechanical tests of the prototype mineral insulated conductor were also performed. These tests determined the viability of the conductor after bending and provided information on the compressive strength of the MgO, as well as the strength of the shear connection between the central conductor and outer jacket through the MgO. A cyclic loading test was also performed. Details of this testing are outlined in "ITER In-Vessel Coil Design and R&D" ref #7 and "Mechanical Performances of ITER In Vessel Coils Conductors" ref #8. Figure 9 shows a test fixture used for fatigue testing of the mineral insulated conductor. This cyclic load U-bend testing successfully demonstrated that as the mineral insulated conductor is loaded axially around the coil corners the MgO insulation remains intact and the copper conductor does not migrate to one side or fail the MgO insulation. Electrical testing was repeated after the mechanical testing to verify the integrity of the MgO insulation.

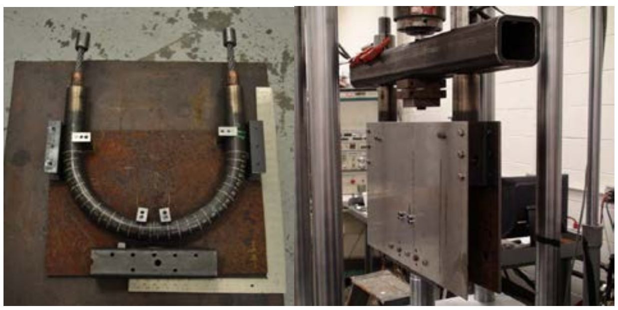

Figure 9 Conductor Cyclical U Bend Testing

C. Joint development

The in-vessel locations of the coils behind the first wall require that the coils be manufactured to not require maintenance and to be highly reliable. For that reason, all joints, including those within sections of the coil and in the feeder-to-coil connections are brazed and welded. Due to limitations on the available length of conductor from suppliers, multiple conductor lengths will are required per coil. Each ELM coil has seven joints, plus the feeders. Each VS coil contains 12 joints to connect the 120 degree sections plus 8 joints for connecting the feeders. A developmental joint assembly is shown in Figure 10.

The first step in a joint is to induction braze the copper conductor ends together using BCuP-5 brazing filler. Tentative plans are to examine the joints ultrasonically and by X-rays along with a helium leak test. After the brazed joint is made and inspected, the gap between the conductor and jacket is filled with insulating MgO preforms which are cut in half for assembly. The MgO serves three purposes. It is the electrical insulation, it provides a load path between the conductor and jacket, and it conducts nuclear heat absorbed in the jacket to the water-cooled copper conductor. Next, a stainless steel or Inconel sleeve, depending on if it is a VS or ELM joint, is slid over the exposed MgO preforms covering the length of the joint. This sleeve is then compacted using a specially designed compaction machine to locally compress the joint sleeve to provide good interface pressure for the MgO to perform its functions. During compaction the MgO filler pieces are compressed crushing the preforms and distributing the MgO evenly within the joint. Lastly the sleeve is welded using an orbital welder applying circumferential welds at either end completing the joint. Tentative plans are to use die penetrant, ultrasonic, and X-ray inspections to test the joints.

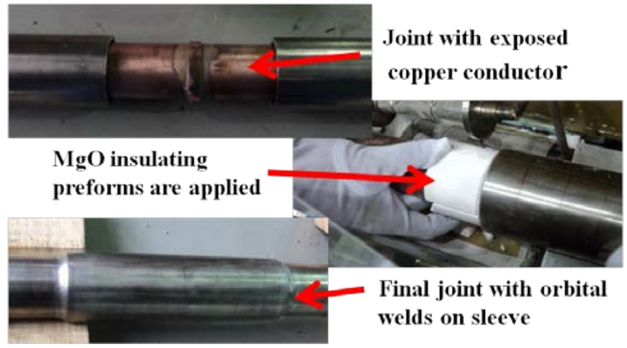

Figure 10 Joint Assembly

D. Bending and Forming

The manufacture of the ELM and VS coils involves a variety of cable bends. Fortunately, the MgO insulated cable maintains good electrical insulation characteristics even after bending to a radius of 215 mm (R/d ratio of 3.6). The coils must conform to the toroidal and poloidal contours of the vacuum vessel walls, requiring gentle, large radius bends. Corner bends are required for the ELM coils. Turn-to-turn and layer-to-layer transitions must be precisely formed. Lead-out regions and the feeders require a variety bends, often with 3-dimensional shaping. Figure 11 shows examples of some of the bends required. ASIPP is developing a variety of forming methods to fit these requirements.

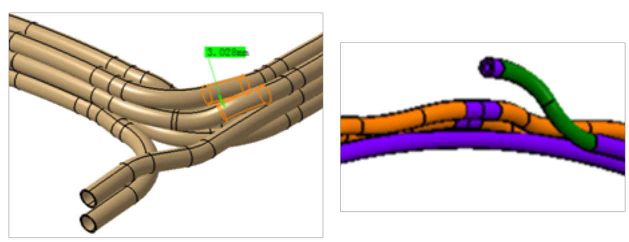

Figure 11 Example of 3D Bending for ELM and VS

Hydraulic press forms were initially used for the corner bends and to form the transitions. This process worked for the ELM cables, providing bends with smooth surfaces. However, ripples formed on the inside of the bends of the VS cable jacket, which is thinner and weaker than the Inconel used on the ELM coils. ASIPP developed a "clam shell" sleeve or bushing shown in Figure 12 which was applied over the conductor before bending. This eliminated the wrinkles on the inner diameter after bending.

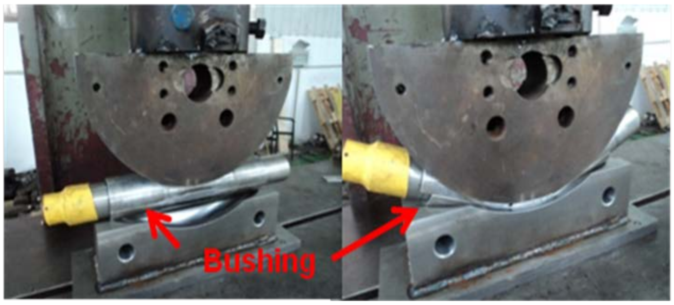

Figure 12 "Clam Shell" Busing in Press Form

A three roller bending machine shown in Figure 13 is used for large radius bends needed to form the coils to the toroidal and poloidal curvatures of the vacuum vessel. In lieu of hydraulic presses a CNC tube bender, shown in Figure 14 is now used for the tighter radii corner bends, lead-out bends, and 3D layer-to-layer transition bends. Many trials were made to determine the exact parameters required for each bend so that the final shape after spring back was within design tolerances. Due to the restricted clearances to the vacuum vessel wall on one side and the blanket shield module on the other side tolerances for both the ELM and VS Coils are +/- 4mm across their major dimensions.

At the time of this writing bending trials are ongoing to improve tolerances. ASIPP is also performing additional bending trials with the CNC tube bending machine to determine if it can be used to advantage for some of the other forming operations.

Figure 13 One ELM Coil Turn Using 3 Roller Forming

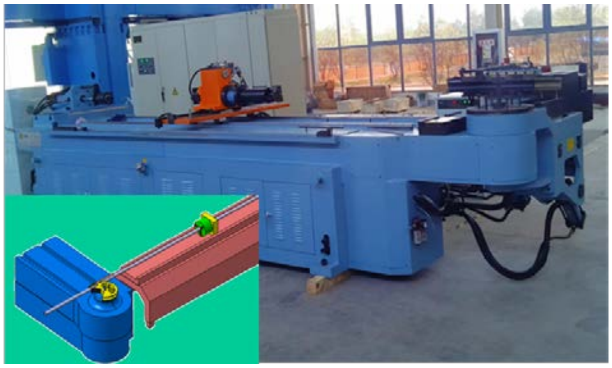

Figure 14 The CNC Bending Machine

E. Structural components

Figure 15 shows a mid ELM coil with the mounting brackets required. These brackets will be made in 3 pieces, as shown in the larger figure of a typical bracket on the left. Prototype brackets are being precision vacuum cast of Inconel 625 for use in the prototype ELM coil. However, for assembly purposes it will be necessary to segment the center spar. These changes will be developed as part of the prototype program. The brackets will be fitted to the finished coils, brazed to the coil while being clamped, and then welded along the top and bottom (yellow stripes).

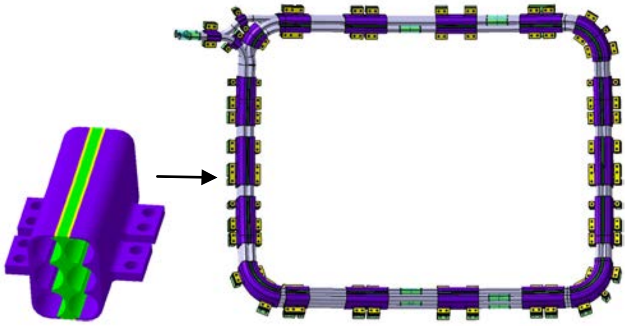

Figure 15 Mid-ELM Coil With Brackets

The VS coil support "spine", will be fabricated from 316 (LN) stainless steel plate. The plate will be press formed and then machined to provide the required surface contours, with intermediate stress relieving as required. It should be noted that the VS coils are conical in shape to fit the contours of the vessel.

F. Prototype Coils

Now that the manufacturing R&D and tooling preparations are nearing completion, manufacture of prototypes is getting underway. The prototypes includes a full Equatorial ELM Coil, complete with mounting brackets as shown in Figure 16, and a 120 degree section of an Upper VS Coil to develop and demonstrate the necessary manufacturing techniques for the Final Design Review shown in Figure 17.

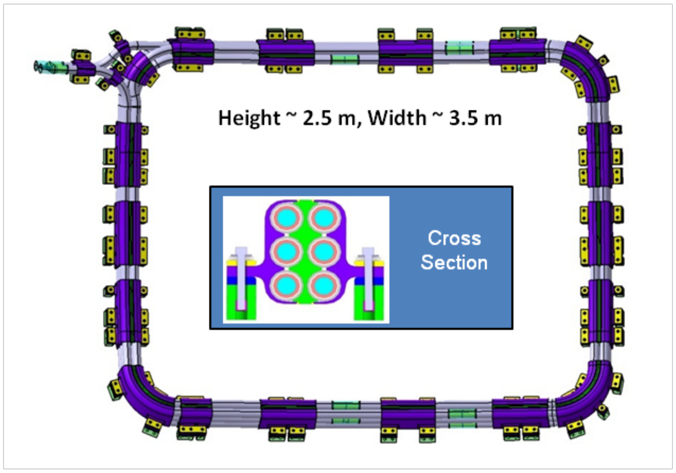

Figure 16 ELM Coil Prototype

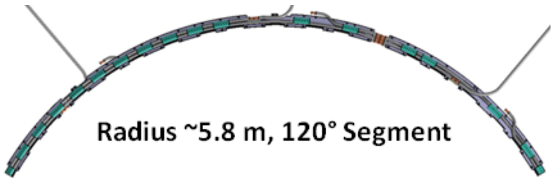

Figure 17 VS Coil Prototype

The VS prototype section chosen includes a field assembly joint. Four conductor joints must be made, structural "bridge" pieces added, and then the conductor and structural parts must be brazed.

It is planned to perform a series of mechanical, thermal, and electrical tests on the prototypes. The details of these tests will be developed in the next few months.

III. SUMMARY

In conclusion prototype IVC cable has been fabricated and tested with good results. ELM and VS Coils have been designed and integrated into the vacuum vessel. Analysis is almost complete and design iterations have produced a final design with stresses that meet allowable limits. Work on the VS and ELM Coil prototypes is progressing with good progress made in forming, shaping, brazing and welding the MgO insulated cable. This work will be completed under the continuing collaboration between Princeton Plasma Physics Laboratory in the US and ASIPP in China under a task agreement arranged with the ITER International Organization.

References

[1] System Requirement Document (not under Configuration Control or publicaly abvailable) SRD-15-IVC "Project Communication"

[2] P. Titus "DESIGN AND ANALYSIS OF THE ITER VERTICAL STABILITY(VS) COILS" "TOFE2012 Proceedings " Fusion Sci. Technol. ,Vol.64 (2013).

[3] R. PILLSBURY "Calculation of forces on the In Vessel Coils for the ITER Alternate Design using Vector Fields OPERA" -- ITER TASK ORDER #2 , October 6, 2009.

[4] R. PILLSBURY Impact of additional steel in the VS structure on the induced currents, March, 2011.

[5] MOHAMED SAWAN Nuclear Heat in Upper and Lower VS Coils, 2012, Power points and data on file with ITER "Project Communication", M. SAWAN et al., "Neutronics Analysis of ITER Blanket Modules with Impact on Vacuum Vessel Shielding, "TOFE2012 Proceedings " Fusion Sci. Technol. ,Vol.64 (2013).

[6] Final Report on the Preliminary Design of the ITER In-Vessel Coil System, June 14, 2011, Princeton Plasma Physics Laboratory

[7] M. Kalish "ITER In-Vessel Coil Design and R&D" Proceedings from SOFE 11 Chicago USA (2011)

[8] Huan Jin, "Mechanical Performances of ITER In Vessel Coils Conductors" Proceedings from ICONE21, Paper # 16887

[9] Peter Titus "Axisymmetric Simulations of the ITER Vertical Stability Coil" Proceedings from SOFE 13 San Fransico USA (2013)

[10] Arthur Brooks "Thermal and Structural Analysis of the ITER ELM Coils" Proceedings from SOFE 13 San Fransico USA (2013)

[11] Shanwen Zhang "Mechanical analysis of the ITER Upper ELM Coil" Proceedings from SOFE 13 San Fransico USA (2013)

[12] P. J. Heitzenroeder, A. W. Brooks, J. H. Chrzanowski, et al., "AN OVERVIEW OF THE ITER IN-VESSEL COIL SYSTEMS," in 2009 23rd Ieee/Npss Symposium on Fusion Engineering, 2009

[13] M. Z. Lei, Y. T. Song, S. M. Liu, et al., "Primary Design and Analysis of Feeder for ITER Poloidal Field," Plasma Science & Technology, vol. 13, pp. 623-626, 2011

ACKNOWLEDGMENT

This work is Partly supported by US DOE Contract No. DE-AC02-09CH11466. Additional Support is Provided under a Work For Others Contract with the Chinese Participant Team and ASIPP. "The views and opinions expressed herein do not necessarily reflect those of the ITER Organization"

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2245
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov