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ELM and in-Vessel Coil Programs at PPPL for ITER, DIII-D, and JET

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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT.

Erosion and damage caused by Edge Localized Modes (ELMs) is a major hurdle on the route towards achieving magnetic fusion energy. Presently the most promising method of mitigating, or even completely suppressing ELMs is to apply Resonant Magnetic field Perturbations (RMP) to the plasma. Princeton Plasma Physics Laboratory (PPPL) is providing design of RMP coil systems for JET and ITER, and has designed CenterPost (CP) or ELM coils for DIII-D. These programs are collaborations with the organizations responsible for installation and operation of the coils. Within PPPL, the programs represent an opportunity to work with other laboratories in a coordinated effort to develop acceptable performance, mechanical design, materials, analyses and manufacturing techniques, for ELM and Vertical Stability (VS) coils. To date, many engineering issues have been identified and resolved.

1. INTRODUCTION

Present scaling predicts that the ELM energy in ITER, if not mitigated, will exceed the acceptable level by a factor of 20. The technique of ELM suppression by application of Resonant Magnetic Perturbations (RMP) was discovered on DIII-D, and experimentation continues on DIII-D and several other machines. Because of the importance of mitigating ELMs, a set of RMP coils is being designed for ITER, based on empirical criteria developed on DIII-D. A system of RMP coils in JET is being considered. These will provide additional information towards our understanding of ELM control by RMP, and extend the dataset for extrapolation towards ITER-like plasmas. The DIII-D experiments were to be augmented with a set of centerpost mounted coils. These passed a prototype evaluation stage. As of Fall 2010, the DIII-D ELM system has been postponed based on cost, schedule, and physics issues. More detailed discussion of each project may be found in references [1] for ITER [3,4] for JET and [5] for DIII-D

2. THE ITER IN-VESSEL COIL SYSTEM

Design of the ITER coil system has progressed to the preliminary design stage, and a Preliminary Design Review is scheduled for October, 2010. This program includes vertical stability (VS) coils as well as ELM coils. ITER's operating environment is more demanding than the others. Longer pulse operation and nuclear heat require active cooling of the coils. Placement behind the blanket and the necessity for remote servicing puts a very high premium on reliability. The operating life for ITER is 20 years. The coils are intended not to require any in-vessel repair or maintenance. Radiation damage of insulators has been an active area for R&D. MgO or Spinel insulated conductors have been successfully used in the past in high radiation environments, but are not presently available in the sizes needed. Accordingly, prototypes are currently being manufactured. A negative characteristic of MgO is that it is hygroscopic and its electrical insulation properties degrades with the absorption of moisture. Spinel is less sensitive to moisture but has a lower thermal conductivity and is more sensitive to radiation-induced conductivity changes. At present, a circular hollow MgO insulated conductor is specified. Full size manufacturing studies are underway. Early R&D efforts included ceramic polymer which was found to have inadequate radiation resistance for use in ITER, but which remains a candidate for the JET ELM coils, Figure 12.

Mechanical behavior of the compressed MgO powder is a performance and analysis concern. The ELM coil corner bends and the lead bends in the VS coils experience concentrations of differential expansion between the Joule heated conductor and stainless steel jacket. This raised a concern that cyclic compression of the MgO powder in the corner would lead to migration of the MgO and shorting of the conductor to the jacket. This was simulated with a cyclically loaded U bend test, shown in figure 2. The sample is a sub-scale commercial conductor. Loading was based on a fully constrained center conductor. After 30,000 cycles there was no discernable displacement of the conductor with respect to the jacket. These tests also provided properties for use in analysis models, some of which are shown in figure 3. The significant design and analysis challenge is to obtain a system that can support the Lorentz forces while allowing thermal growth due to the conductor Joule and nuclear heat. The design concept employs supports that are selectively flexible in directions parallel to the vessel wall while providing strength and rigidity in directions normal to the vessel wall. Primary Lorentz loads come from normal and disruption driven currents crossed with the toroidal field. Poloidal field contributions are significantly smaller. With active cooling provided, the normal thermal environment in ITER is more benign than in JET or DIII-D. The operating temperature of the vessel wall is 100C, peak coil temperatures are 130 to 150^{o}C, and the bake-out is at 240^{o}C. The bake-out temperature is sufficiently high to anneal out radiation damage in the CuCrZr conductor. For the faulted, loss of coolant condition, the ITER environment is the worst of the three systems, leaving only poor thermal conduction paths and radiation to remove nuclear heat. Among the significant effects of limited space allocation for the ITER in vessel coils are the implications on thermal hydraulics and temperature control. Reliability concerns simultaneously require that temperature differentials remain below in the range of 40-50^{o}C to maintain fatigue life, and flow rates of ~3m/s, for which there are many examples of coils with long service life. The copper cable for the ELM coils was increased from 45mm OD/30mm ID to 50MM OD /30mmID design to allow 3m/sec and low erosion rates. Nuclear heating adds 2.52 (poloidal leg) and 1.68 (toroidal leg) W/cm^{3} to the heat load which is readily removed from the conductor and structures via conduction to the water. Adoption of MgO insulated conductors with adequate thermal conductivity has eliminated the actively cooled case included in the conceptual design. Analysis of the ITER ELM coils require quantification of the normal operating electromagnetic loads, and disruption analysis. The shielding of the blankets necessitates electromagnetic simulation of the ITER vessel and blankets in models similar to those used for the larger components. OPERA and SPARK simulations have been used to quantify electromagnetic loads on the ELM and VS coils for normal operation and a family of disruption loads derived from the ITER vessel load specification. During initial assembly, the VS coils will be built in-situ after assembly of the vessel. The ELM coils will be brought in through the vessel ports. A significant effort has been expended to ensure the doubly curved ELM coils will pass through the ports. The conductor fabrication process limits Conductor lengths, thus requiring joints.

The vertical stability coils serve a Welded These are intended to be positioned at low stress points in the winding, i.e. away from the corners. and brazed copper joints with welded stainless steel sheath joints are being considered. The winding joints and joint locations are shown in figure 5.

The VS coils have a different purpose [6] than the ELM coils but share many of the engineering challenges. The MgO insulated cable is similar except for the MgO thickness being increased from 2.5 to 5 mm because of the higher operating voltage.

Stress behavior is nearly axisymmetric except at the break-out and cross over for the leads. These share similar geometry as the ELM coil corners and the U bend test. Similar support provisions are anticipated. Analysis models of the axisymmetric area and of the cross-overs are shown in figures 6, and 7

3. THE DIII-D CP COIL SYSTEM

PPPL provided design, analysis and fabrication functions in the collaboration with General Atomics (GA). GA provided review and system integration functions.

Unlike the ITER and JET ELM coils, which are positioned on the OD of the vessel, the DIII-D coils are positioned on the center post (CP), to allow extended physics studies of how the magnetic field spectrum affects ELM suppression and plasma behavior. Figure 8 shows the coil array on the centerpost. Both the DIII-D and JET coil systems are passively cooled. Heat removal needed to avoid thermal ratcheting is accomplished by conduction through nitrogen gas filled gaps inside the cased coil, and through in-vacuum contact resistance between case and vessel to the water cooled centerpost which has a corrugated construction providing strength and coolant flow paths. Contact thermal resistance between the coil case and the vessel wall is reduced through the use of compressed Grafoil (t.m.) under the coil cases which are preloaded to the vessel with studs spot welded onto the vessel shell. The compliance of the Grafoil helps to assure thermal contact but increased elastic strains in the case and plastic strains in the coil. Fatigue life was reduced. This was reduced by the addition of shims under the clamped corners shown in Figure 9. The 350-390^{o}C bake-out temperature requirement was initially thought to preclude any kind of impregnation, requiring dry wound coils preloaded in the case radially and horizontally by high force springs Conductors were coated with polyimide (with the same chemistry as Kapton) then wound on the case which also served as a mandrel. Tests showed larger motions under compression than expected; consequently, a more conventional bonded coil system was developed. A prepreg polyimide system produced by Performance Polymer Solutions, Inc. was identified that had the required high temperature resistance and structural strength required to stabilize the windings. Case weldment distortions (Figure 11) were investigated throughout the project. Weld, fixturing and annealing procedures were developed at PPPL and passed to the case manufacturer who continued to develop weld procedures to obtain acceptable welds with respect to fatigue sensitive NDT indications.

Two prototype coils were built and tested. The first was the dry wound coil. The second used the high temperature prepreg system. Some of the components and assembly fixture are shown in Figure 10. The second prototype was tested at PPPL and at GA This included verification of conduction cooling. Measured thermal results matched the analysis predictions. Compression of the array of springs that restrains the magnet against the case can be globally verified by measuring the closure force in the assembly press, but individual spring loads could vary. Depth gauges were used to measure spring compression, verifying the individual preload application. A full range of electrical tests were performed, and the coil passed. The coil was tested on a shake table to demonstrate the reliability of the spring loaded internal case support, and to confirm that the higher frequency accelerated cyclic testing planned in the tokamak would not damage the coil. When mounted inside of DIII-D, initial charging was successful, but the tests had to be terminated when a lead connection failed.

4. THE JET COIL SYSTEM

A RMP system on JET is proposed to extend the performance of the JET machine, and is essential in developing ITER relevant scenarios. JET's solution requires an array of local saddle coils, distributed toroidally and poloidally around the machine, but only coils above the mid-plane are used, as opposed to the DIII-D and ITER coils which have coverage at the equatorial plane. JET coils have successfully undergone a feasibility study including a detailed analysis of equipment removal and installation by remote handling. Pre-conceptual design efforts continue. Ex-vessel coils were considered due to the obvious benefits of their location. Ultimately they were rejected due to the crowded conditions in these areas and the high currents required due to their far location from the plasma. Inside the vacuum vessel, the coils can be located within 10cm of the plasma surface and the physics criteria and flexibility goals can be satisfied with reasonable currents (60kA-turns). Feasibility issues associated with equipment removal and installation by remote handling were judged to be resolvable. An in-vessel approach was therefore chosen. The coil configuration adopted in September 2009 for the feasibility study consists of a 32-coil array arranged in two toroidal belts around the plasma, an upper one with 8 large coils and a lower one with 24 small coils. Both rows are located above the midplane. Another early study addressed the method of cooling the coils. The ELM coils must withstand vacuum vessel bake out at 350^{o}C for extended periods, and must operate with the vessel at 200^{o}C. Pulsed coil heat loads due to joule heating of the conductors and radiation from the plasma are removed by passive cooling. Passive cooling was chosen because its risks were judged to be the more manageable than active water cooling. Passive cooling means that the design must rely almost exclusively on radiation to the vacuum vessel walls for removal of pulsed heat loads between pulses. Coil overheating protection is provided by control of the vessel temperature, the coil current and pulse length. The performance and lifetime of insulating materials operating close to manufacturer's limits are being tested via R&D and are supported by the DIII-D experience with high temperature polyimide insulation Two candidate materials are being considered: Performance Polymer Solutions, Inc. (P2SI) - LM700 polyimide (well characterized, commercially available, widely used in high-temperature aerospace applications) and Starfire System's RD-212 Ceramic Polymer (simpler, room temperature process; but greater uncertainty due to limited experience.)

Coil support provisions have evolved from a distributed system employing existing mounting points for saddle coils and mushroom tiles, to coils mounted to a box beam system attached near corners of main vertical ports. This produces loading near bellows at octant mid points that add stress to the vessel bellows. Because of the cyclic operation of the ELM coils, this adds many more cycles to the bellows stresses and potentially could reduce operational life of the bellows and require difficult repair. Re-positioning of the support attachments is being investigated to reduce the influence on the bellows. Fatigue evaluations are on-going.

Remote handing tooling and operational requirements for installing these coils were developed, based on many years of remote handling operations on JET, based on past success installing wave launchers of comparable complexity. The plan takes advantage of existing boom manipulators and tooling to transport equipment into and out of the vessel and to perform some of the required operations. However, it was necessary to also design special-purpose adapters and manipulators to perform the series of maneuvers and fastening operations necessary to install the coils. The remote handling analysis established the maximum payload weight of 170kg, which constrains the weight of any single part or sub-assembly in the coil design. The study found that equipment removal to accommodate the ELM coils could be a significant schedule driver, and identified opportunities for modifying the design to allow existing in-vessel equipment to remain in place.

CONCLUSIONS

The three systems have similar goals in terms of understanding and suppressing ELMs. This introduces some commonality in the designs, but the differences in operational characteristics and space constraints of the three tokamaks have dictated different design solutions. All three projects are driven by the difficulties of back fitting complex electrical components close to the plasma where the environment is especially demanding, and space allocation is a severe issue. Even though ITER is still in its design phase, addition of the in-vessel coils has similar space and interface challenges as fitting coils into the operating tokamaks. These problems are compounded by the necessity of using remote handling in JET and ITER. All three projects have benefitted from the collaborative efforts of all the laboratories involved. All three projects include significant R&D programs that are a benefit to the other efforts, but the degree to which R&D is necessary makes cost estimating and cost control difficult. All three require assessments of the physics value weighed against the cost and difficulty of the coil addition, but based on work up to this point, all three systems are feasible.

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Table 1: Comparison of Design Parameters

Parameter	**ITER**	**JET**	**DIII-D**
Number of coils	27 (Upper, mid, lower)	32 (Above mid)	36 (Upper, mid, lower)
Vessel operating temperature	100 ^{0}C	200 ^{0}C	20 ^{0}C
Bakeout temperature	240 ^{0}C	350 ^{0}C	350-390 ^{0}C
Max. coil pulse duration / time between pulses	500-1000 s / 1200 -9000s (depending on operating condition).	8-17 s (depending on operating condition) / 1800 s	3 s / 600 s
Max. coil op. temp.	120^{0}C	350 ^{0}C	75 ^{0}C
Primary cooling method	Water at 3 m/s	Radiation to the vacuum vessel	Conduction to the vacuum vessel
Max. nuclear heating	2.52 W/cm^3 (Poloidal) 1.68 W/cm^3 (Toroidal)	minimal	negligible
Conductor / insulation	SS jacketed MgO insulated hollow copper conductor	Kapton / fiberglass insulated CuCrZr potted with polyimide.	Polyimide film insulated Cu bonded with prepreg polyimide; coils spring loaded in casings.
Installation / servicing method	Hands on + RH / RH	RH / RH	Hands on / hands on
Operating frequency	5 Hz.	<20 Hz.	DC and 20-200 Hz.
Fatigue life requirements	30,000 experimental pulses / 1x10^6 fatigue pulses	TBD	50,000 experimental pulses / 1x10^6 fatigue pulses
Max. end of life radiation fluence	3000 MGy	(not a significant driver)	(not a significant driver)
EM loads	Normal +disruption	Normal + disruption + halo	Normal +disruption

Table 1: Comparison of Design Parameters.

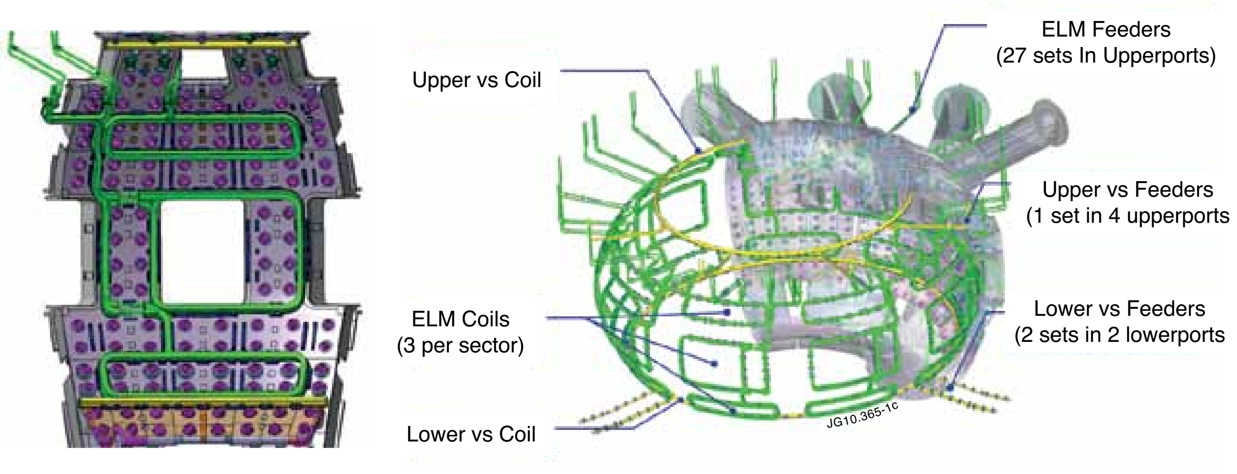

Figure 1: ITER In-Vessel Coil System.

Figure 2: Above: Sections Cut from the U bend test, Below the U-Bend test fixture.

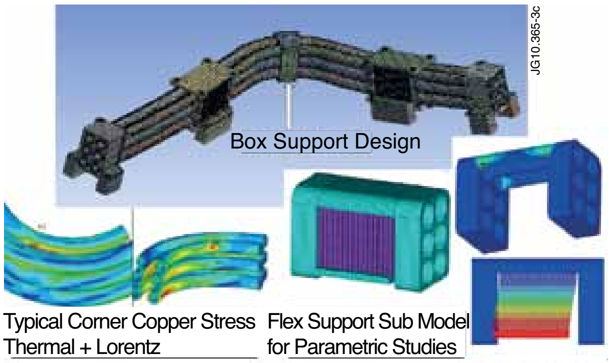

Figure 3: ELM Corner Model and Flex Support Bracket.

Figure 4: ELM Coil Winding and Joint Location.

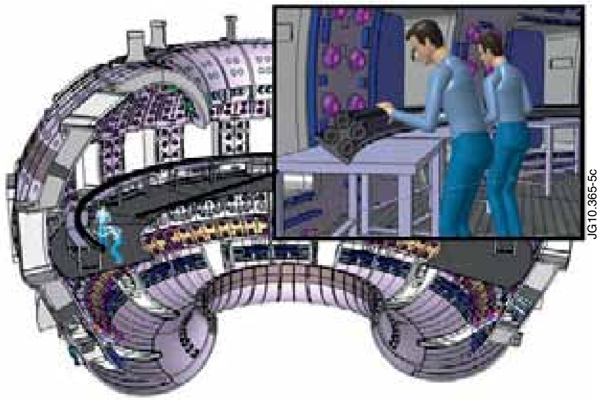

Figure 5: Vertical Stability Coil Assembly.

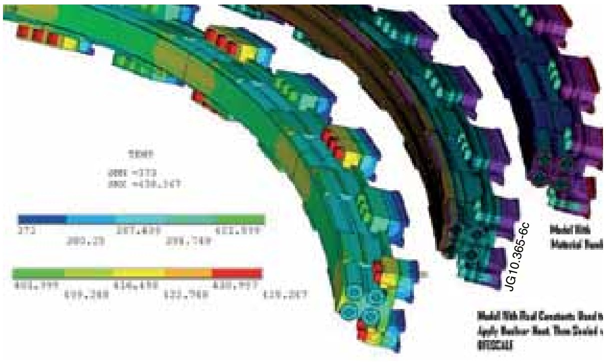

Figure 6: *Vertical Stability Coil Analysis Model*.

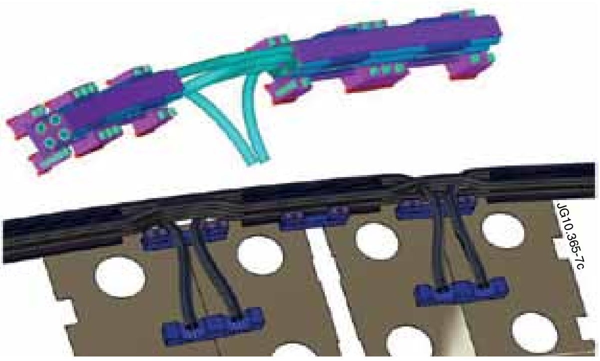

Figure 7: *Vertical Stability Coil Lead, Analysis Model Above, CAD Model Below.*

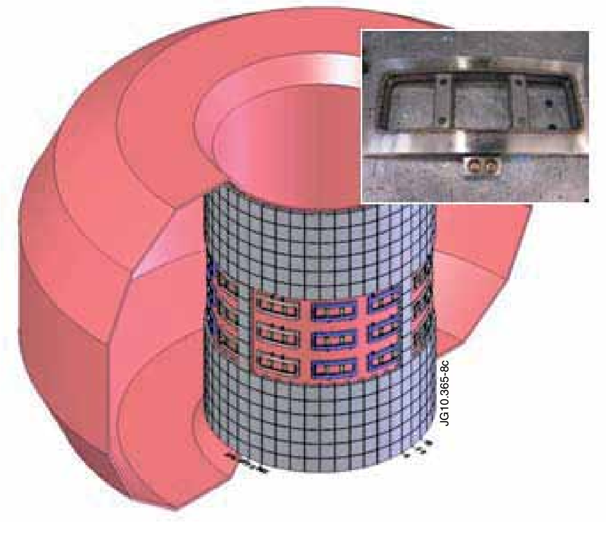

Figure 8: *GA DIII-D ELM Coil Arrangement with an Inset Showing the prototype coil built by PPPL*.

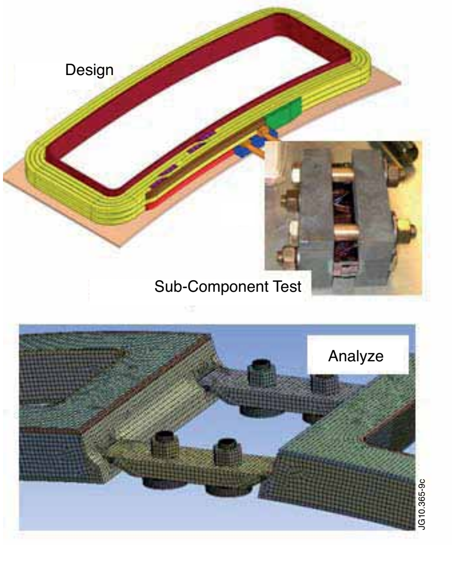

Figure 9: *PPPL Design and Analysis Scope in the DIII-D Centerpost/ELM coil effort*.

Figure 10: DIII-D CP Coil Components. At Left: Coil cover and one of the four strips of Inconel 718 springs, the Bonded Coil At Right, the Preload Assembly Fixture.

Figure 11: Welding Trials for the first prototype.

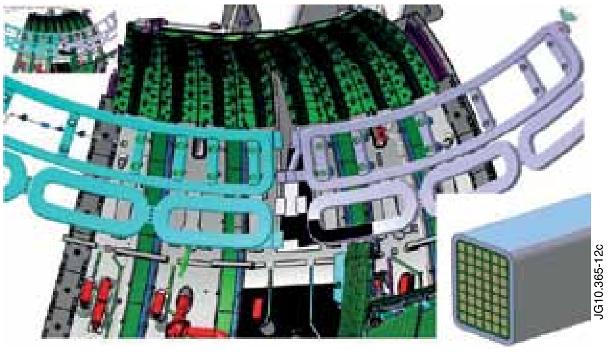

Figure 12: JET ELM Layout with an Inset Showing the Coil Cross Section.

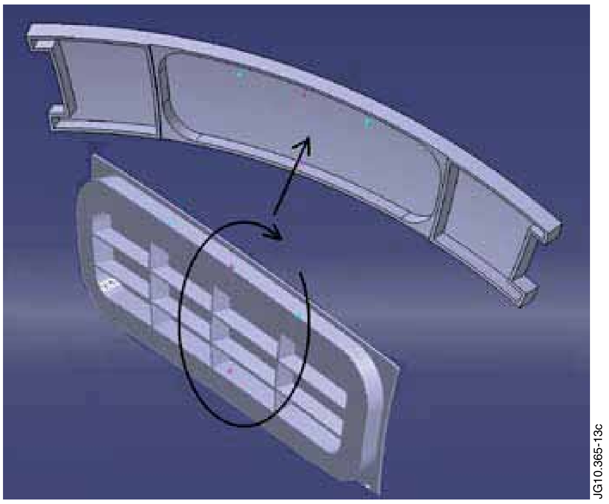

Figure 13: JET Upper Coil Box Frame.