DESIGN OF THE ITER IN-VESSEL COILS

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The ITER project is considering the inclusion of two sets of in-vessel coils, one to mitigate the effect of Edge Localized Modes (ELMs) and another to provide vertical stabilization (VS). The in-vessel location (behind the blanket shield modules, mounted to the vacuum vessel inner wall) presents special challenges in terms of nuclear radiation (~3000 MGy) and temperature (100^{o}C vessel during operations, 200^{o}C during bakeout). Mineral insulated conductors are well suited to this environment but are not commercially available in the large cross section required. An R&D program is underway to demonstrate the production of mineral insulated (MgO or Spinel) hollow copper conductor with stainless steel jacketing needed for these coils. A preliminary design based on this conductor technology has been developed and is presented herein.

I. PURPOSE OF IN-VESSEL COILS (IVCs)

The ITER Science and Technology Advisory Committee (STAC) has identified a list of physics issues needing attention. Amongst these are two which may be solved by the deployment of “In-Vessel Coils” (IVCs) with strong coupling to the plasma. The first issue concerns “Edge Localized Modes” (ELMs) and the second concerns “Vertical Stabilization” (VS).

An ELM is a disruptive instability occurring in the edge region of a tokamak plasma due to the quasi-periodic relaxation of a transport barrier previously formed during an L to H transition. ELMs result in impulsive bursts of energy deposition on to the “Plasma Facing Components” (PFCs) causing a reduction in their lifetime through processes including erosion, thermal fatigue, and cracking. Without mitigation the ELM energy deposition on ITER can potentially exceed the allowable level by a factor of 10-20. Various experiments have shown that the application of “Resonant Magnetic Perturbations” (RMPs) produced by in-vessel non-axisymmetric “ELM Coils” can be used to suppress the ELMs (Ref. 1).

The elongated plasma of ITER is inherently unstable and requires feedback control to maintain vertical position. Vertical stabilization (VS) is nominally provided by eddy currents in passive structures which resist plasma motion along with feedback control of the “Poloidal Field” (PF) coils which produce a radial component of field and vertical force on the plasma. However, analysis indicates that the capability of these features, measured by the ability to recover from an initial displacement in vertical position, is not reliable or robust. Considering that loss of vertical plasma position control in ITER will cause large thermal loads on PFCs and can lead to plasma disruption events which produce large electromagnetic loads and other undesirable consequences, the need for a set of in-vessel “VS Coils” to provide additional vertical stabilization capability has been recommended. (Ref. 2).

II. IVC CONFIGURATION

The coil configuration is shown in Figure 1.

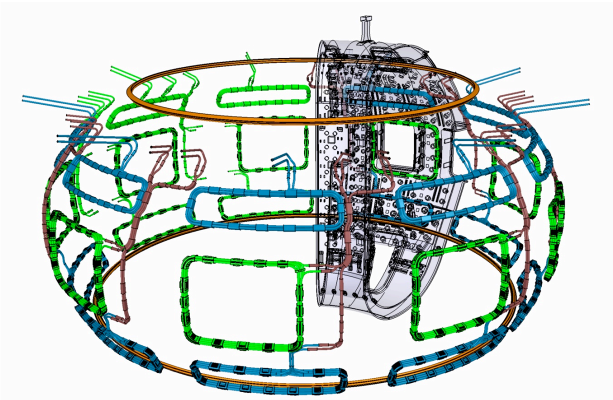

Fig. 1. IVC Configuration with 9 sectors of 3 ELM coils and an upper/lower VS coil pair

The coils are mounted on the ITER vacuum vessel (VV) behind the Blanket Shield Modules (BSM). Following the basic 40^o symmetry of the ITER tokamak there are nine sectors of ELM coils, each consisting of upper, equatorial, and lower rectangular "picture frame" coils, amounting to a total of 27 coils which are individually fed by 27 power supplies. For VS, a pair of upper and lower solenoidal coils are connected in anti-series with 2 interleaved power supplies.

III. IVC REQUIREMENTS

The IVCs must fit in the gaps between the BSM without interference with the BSM water manifolds or the BSM mounting features. This is a challenging design integration task (Ref. 3).

The IVCs must withstand the severe in-vessel environment including an intense radiation field and high temperature. Although some shielding is provided by the BSM and its water manifolds the average flux is ~ 100Gy/sec with local peaks up to 500Gy/sec for ITER plasma operation at P_{fusion}= 500MW (Ref. 3). As a result the peak dose after 0.54FPY is of order 8500MGy. During plasma operations when the IVCs are energized the VV temperature is 100^oC, which sets the initial condition of coil and cooling water temperature. During bakeout when the IVCs are not energized the temperature is 200^oC.

Because of the difficulty of repair/replacement the IVCs are required to withstand the in-vessel environment including nuclear heating if abandoned in place without water cooling. Under these conditions partial system functionality in terms of ELM mitigation and vertical stabilization shall be maintained. In the case of ELM a 20% margin in the individual coil requirements has been included such that the loss of up to three coils can be tolerated with performance still maintained to an extent dependent on which coils in which positions are lost. In the case of VS the individual coil turns are brought out of the VV and routed to the power supply area so that faulted turns may be excluded from the circuit. The design is required to anticipate this condition and be sized for delivery of rated amp-turns with one turn absent.

The ELM coils as a system are required to produce a non-axisymmetric field perturbation with toroidal mode number n > 1 which can be rotated up to 5Hz in order to equalize ELM energy deposition on the divertors. As a result the individual ELM coils are required to deliver 90kA-turns from DC to 5Hz conditions for the duration of the plasma burn which is in the range 300-3000 seconds depending on the type of operations underway.

The VS coils are required to respond to "Vertical Displacement Events" (VDEs) where the plasma drifts vertically and feedback control of the in-vessel VS power supplies, in conjunction with feedback control of the external "Poloidal Field" (PF) coils, is required to restore vertical position. The VS coil requirements are determined by a simulation where the feedback control is turned off, the plasma drifts upward 16.5 cm, and the feedback control is restored. The VS coil and power supply requirements provide for recovery from this event, and also to drive a background current attributable to noise in the magnetic diagnostics. The design-basis current waveform derived from physics analysis is shown in Figure 2. The system is required to supply three such pulses in a row, and a total of 30,000 over the lifetime of ITER. The required waveform has a duration of 10s, a peak current of 240kA-turns, and an RMS current of 36kA-turns. The corresponding voltage requirement is 575 volts per turn with a response time of 1mS.

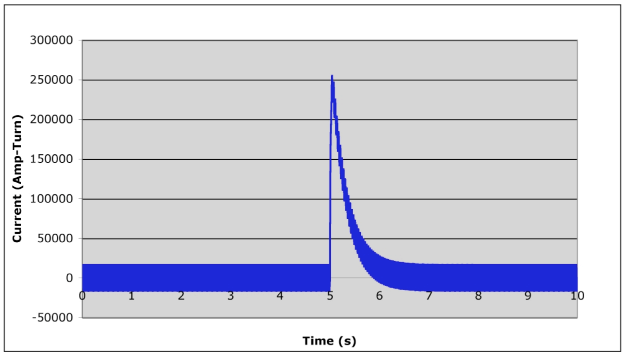

Fig. 2. VS Current Waveform (Amp-turn vs. Time)

IV. IVC CONDUCTOR TECHNOLOGY

"Mineral Insulated Conductor" (MIC) is the key enabling technology for the IVCs.. The use of MIC for "radiation hardened" magnets was pioneered by the accelerator community in the 1970's (LAMPF, SIN, TRIUMF) and is being carried forward by modern devices (JHC, SNS). Good overviews of the issues and early work are given in Ref. 4 and 5. MIC has been considered in various studies of fusion devices (NET, MARS, FED) in the past and is presently being developed for the JT-60SA project.

While MIC is radiation tolerant there are various phenomena which must be addressed including Radiation Induced Conductivity (RIC), Radiation Induced Electrical Degradation (RIED), and swelling. An overview of the radiation effects is given in Ref. 6. For the IVCs the preliminary assessment in regard to these issues is favorable.

MIC may employ Magnesium Oxide (MgO), Spinel ($MgAl_2O_4$), Alumina (Al_2O_3), or other materials. The first preference for the IVCs is MgO which is the most common material in large scale MIC production and it has a high thermal conductivity. A disadvantage is its hygroscopic nature which requires heating to drive out moisture prior to sealing the conductor ends in order to maintain electrical properties. Also its RIC is relatively high.

An additional feature of MIC is its tolerance for high temperature. Industrial power cables using MIC are typically rated for 250°C continuous operation, and other applications such as heaters operate even higher.

V. IVC CONDUCTOR AND COIL DESIGN

Trade studies were performed to optimize the conductor cross section for the ELM and coils. Calculations included ohmic and nuclear heating of conductor and structure to be removed by water cooling. Variables included number of turns, conductor shape (circular or rectangular), conductor material and conductivity, conductor area, coolant channel area, insulation thickness, etc. Constraints were applied on coolant flow velocity, temperature rise, pressure drop, etc. The final selection for the "Stainless Steel Jacketed Mineral Insulated Conductor" (SSMIC) is given in Table I. The ELM and VS conductors have the same jacket but differ in insulation thickness, copper dimensions, and copper alloys.

TABLE I. SSMIC Conductors

	ELM	VS
Jacket OD	59 mm	59 mm
Jacket Thickness	2 mm	2 mm
Insulation Thickness	2.5 mm	5 mm
Conductor OD	50 mm	45 mm
Conductor ID	33 mm	30 mm
Conductor Alloy	CuCrZr	Cu

The above conductor sizes are matched to a 6 turn ELM coil and a 4 turn VS coil. A summary of coil and circuit parameters (including feeders and DC bus bar) is given in Table II.

TABLE II. Summary Coil Parameters

	ELM	VS
Coil Turns	6	4
Coil Current Per Turn	15kA peak/ 11kA rms	60kA peak/ 9kA rms
Circuit Loop Voltage	180V	2400V
Number of Interleaves	1	2
Peak Voltage to Ground	90V	600V

VI. IVC LOADS

VI.A. Electromagnetic (EM) Loads

EM loads are generated during normal operation and plasma disruption events. OPERA was used to evaluate the various design-basis operating scenarios and disruption scenarios. Results are summarized in Figure 3 in terms of the maximum force per ELM coil leg (i.e, top, bottom, left, or right coil segment) or for a 40° sector of a VS coil for normal operation and a variety of disruption events.

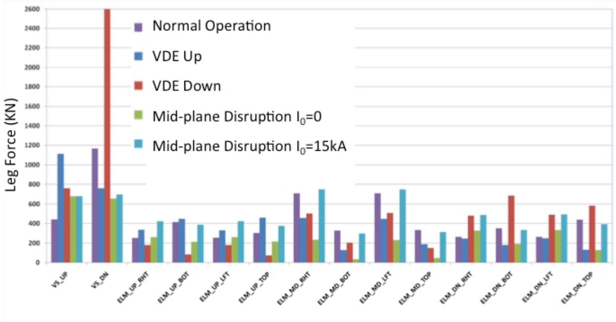

Fig. 3. EM Force Summary for VS and ELM

For VS the design-driver is the plasma disruption condition (2.6KN) whereas for ELM the operating and disruption forces are similar (~ 0.8KN). Since the ELM operating load can have a frequency up to 5Hz it drives the design due to fatigue considerations and dictates the use of the CuCrZr copper alloy.

In addition to the EM forces the disruption events have the potential to create circuit over-currents in case the power supplies cannot limit the current (e.g. they are faulted or the induced voltage exceeds the power supply voltage. Worst case currents are 20kA in ELM (15kA normal) and 105kA in VS (60kA normal).

VI.B. Nuclear and Ohmic Heat Loads & Cooling

Considering the structure, conductors, and entrained water the average nuclear heating rate is of order 0.5 watt/cc in both the ELM and VS coils (Ref. 7). Thermal loads and temperatures are summarized in Table III. Ohmic heating is accounted for in both the feeders and coils. The head loads are removed by de-ionized cooling water flowing in the central passages of the SSMICs.

TABLE II. Thermal Performance

	ELM	VS
Ohmic Heating per Coil + Feeder	563 KW	587 KW
Nuclear Heating Coil + Feeder	106 KW	414 KW
Total Heat Load Coil + Feeder	669 KW	1001 KW
Water ΔT across coil @ 3m/s	47 deg C	21 deg C

The coil temperature rise is critical since it generates thermal stresses. The present design assumes 3 m/s cooling water flow velocity which avoids erosion concerns. However an increase to 5 m/s is being considered to mitigate the thermal stress. Flow corrosion/ erosion studies are planned to qualify the flow velocity

VII. STRUCTURAL RESPONSE AND ANALYSIS

VII.A. ELM Structure and Response

As depicted in Figure 4 the ELM structural design employs clamps on the limbs of the coils. The thermal growth tends to generate stress in the corners. On top of this the sinusoidal (5Hz) current produces in-plane forces which tend to deform the rectangle to a circular shape, along with forces due to interaction with the background toroidal and poloidal fields which are normal to plane of coil and reacted by the VV. The large number of cycles (30,000 pulses for durations up to 1000s and frequencies as high as 5Hz) results in fatigue-driven design.

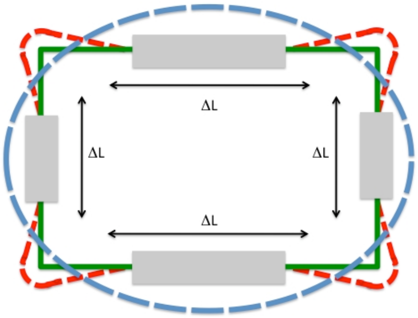

Fig. 4. ELM Structural Response

The ELM structural design aims to balance stiffness to react cyclic Lorentz loads which are normal to the coil vs. flexibility to allow thermal expansion in the plane of the coil. Typical ANSYS results are shown in Figure 5.

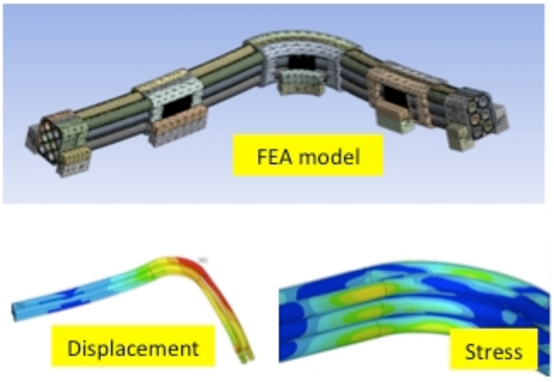

Fig. 5. ELM FE Model and Analysis

VII.B. VS Structure and Response

As depicted in Figure 6 the VS structural design concept places the conductor in a structural spine which is attached to VV using clamps. As a result the thermal strain places the conductor in hoop compression. These stresses are mild since the temperature rise of the VS coils is only ~21C (vs. ~47 C for the ELM coils). The main design drivers are the spine and clamp features. Stresses due to disruption as well as cyclic stresses due to normal operation are the design-drivers.

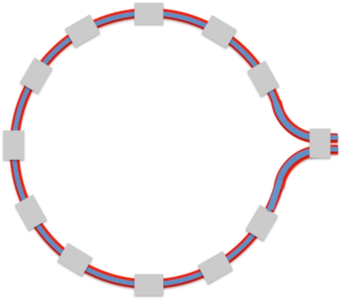

Fig. 6. VS Structural Response

The VS structural design optimizes spine and clamp attachment features including the bolt preloads. Typical ANSYS results are shown in Figure 7.

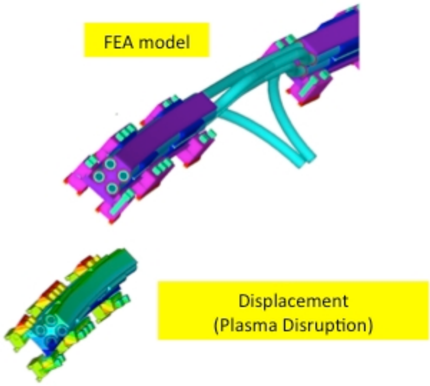

Fig. 7. VS FE Model and Analysis

VIII. ELECTRICAL DESIGN FEATURES

VIII.A. Power Supplies

The ELM power supply can be realized using a standard 12-pulse 4-quadrant thyristor AC/DC converter. The net load on the AC system will be steady during plasma operations due to the phase shifted sinusoidal currents in the 9 toroidal sectors.

The VS power supply will require a high power chopper with 1 ms time response to meet the 60kA VDE requirement as well as the ability to respond to smaller feedback control signals with an RMS current of 9kA. A conceptual sketch of such a power supply is given in Figure 8. Note that with the energy storage feature the large transient VDE pulses will not impose a transient on the AC distribution system. To limit voltage to ground, two such supplies will be interleaved in series with the upper and lower VS coils.

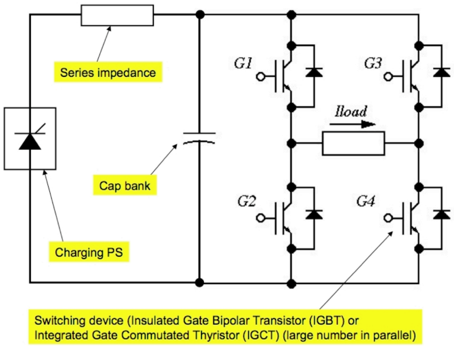

Fig. 8. VS Power Supply Concept

VIII.B. Grounding

The SSMIC-based circuit will exhibit relatively low and variable resistance to ground due to the RIC and temperature dependent resistivity of the MIC. The stray capacitance will also be relatively high. As shown in Figure 9 with the typical grounding method the asymmetries in the stray parameters will have the same effect as a ground fault so the grounding design must anticipate this effect. The use of a common mode AC voltage in the ground connection with filtering of the ground current is a possible solution to avoid this issue.

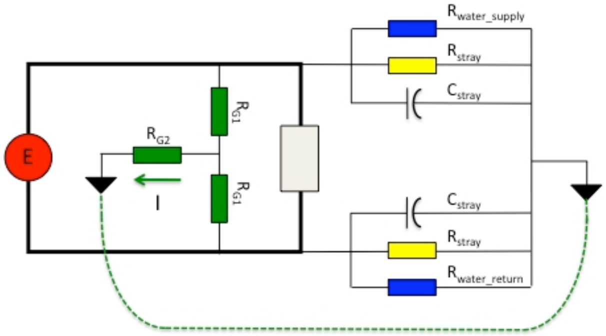

Fig. 9. Typical Circuit Grounding

IX. R&D

As shown in Figure 10 the ITER conductor represents a significant scale-up from prior experience. To demonstrate the ability to produce the large ITER SSMIC, two parallel prototype development activities were launched, one by Tyco Thermal Controls (Canada) and the other by the Institute for Plasma Physics Academy of Sciences (ASIPP, China). Both have successfully produced prototypes. Additional R&D activities are underway to determine the electrical and mechanical properties of the prototypes and to develop joining techniques. Cross sections are shown in Figure 11.

Fig. 10. Comparison of Conductors (to scale)

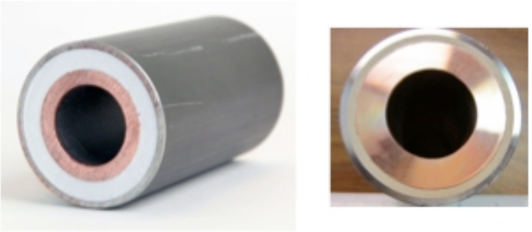

Fig. 11. Prototypes (Tyco VS, left, ASIPP ELM, right)

X. CONCLUSIONS

The ITER in-vessel coils are challenging but necessary for the ITER mission. The Mineral Insulated Conductor is the key enabling technology. R&D is underway to develop the large SSMIC along with the required joining processes. The preliminary design has been completed and a credible approach has been demonstrated.

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