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P.J. Heitzenroeder, A.W. Brooks
J.H. Chrzanowski, F. Dahlgren, R. J. Hawryluk,
G.D. Loesser, C. Neumeyer, C. Mansfield
Princeton Plasma Physics Laboratory*
PO Box 451, Princeton, NJ USA 08543
pheitzen@pppl.gov

J.J. Cordier, D. Campbell, G.A. Johnson, A. Martin,
P.H Rebut, J.O.Tao
ITER Organization , CS 90-046
13067 St. Paul Lez Durance Cedex France

J.P. Smith, M. Schaffer, D. Humphreys
General Atomics, PO Box 85608, San Diego, CA
92186-5608, USA

P.J. Fogarty, B.E. Nelson
Oak Ridge National Laboratory,
PO Box 2008, Oak Ridge, TN
37831-6483 USA

R.P. Reed
Cryogenic Material, Inc
2625 Iliff
Boulder, Co 80305

Abstract — ELM mitigation is of particular importance in ITER in order to prevent rapid erosion or melting of the divertor surface, with the consequent risk of water leaks, increased plasma impurity content and disruptivity. Exploitable "natural" small or no ELM regimes might yet be found which extrapolate to ITER but this cannot be depended upon. Resonant Magnetic Perturbation has been added to pellet pacing as a tool for ITER to mitigate ELMs. Both are required, since neither method is fully developed and much work remains to be done. In addition, in-vessel coils enable vertical stabilization and RWM control. For these reasons, in-vessel coils (IVCs) are being designed for ITER to provide control of Edge Localized Modes (ELMs) in addition to providing control of moderately unstable resistive wall modes (RWMs) and the vertical stability (VS) of the plasma.

Consequently, design option studies have recently been undertaken for the IVC's to address these concerns. In addition, an alternative vacuum vessel (VV) study recently began whose goal is to simplify its manufacture and reduce costs. In the alternate VV design, the outer vessel wall is moved outwards by 150 mm and the blanket/shield modules are supported by a separate structure inside of the vacuum vessel. The IVC options study includes development of options for both the reference and alternative vacuum vessels. The IVC options being studied include "dry" coil insulation designs, and separation of the IVC system into (27) individual ELM/RWM coil assemblies and 2 to 4 individual VS coils. This paper provides an overview of the reference IVC design and the IVC design options being considered for both the reference and alternative vacuum vessels.

I. INTRODUCTION

The reference IVC system is highlighted in the Figure 1. It consists of (27) 3-turn picture frame type coils which serve the dual function of ELM and RWM control, and (2) 3-turn toroidal ring coils which provide vertical stabilization. These coils are fabricated from ceramic coated copper conductors enclosed in welded stainless steel coil cases as shown in Figure 2. They are bath-cooled by water circulating in channels in the copper. This arrangement provides a convenient way of removing both the nuclear heat deposited in the coil and case and Ohmic heat generated in the copper. Although these coils meet their functional requirements, risk analyses identified a number of serious concerns which mostly center around the use of water as a dielectric, the high number of in-vessel high current joints located behind the blanket/shield where routine maintenance is impossible, and the use of ceramic which is prone to cracking due to thermal and mechanical stresses and which has several manufacturing issues which appear to be difficult and costly to overcome.

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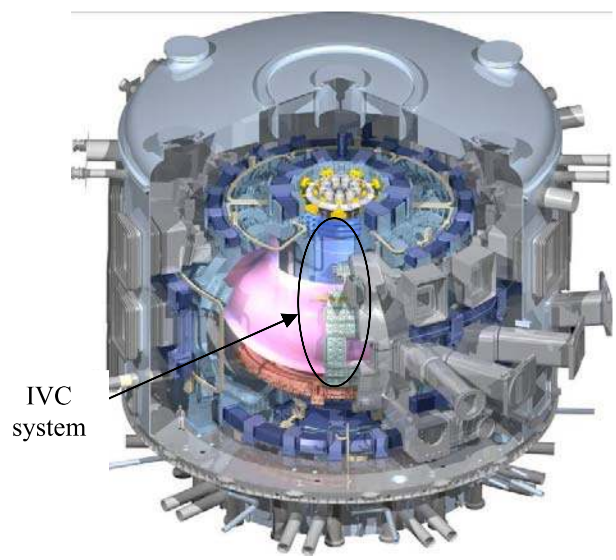

Figure 1. A sectional view of ITER showing the location of the IVC coils.

feeders and the VS coil segments are then connected by jumpers as shown in Figure 5. Finally, the mid-coils are completed by installing their poloidal sections and jumpers.

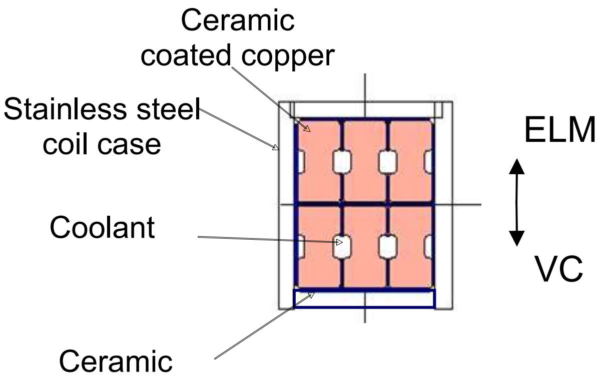

Figure 2. A cross-secction of an IVC

II. THE REFERENCE IVC DESIGN [1]

Figure 3 is an interior view of a vacuum vessel segment showing the integration of the IVC's. Blanket/shield modules which cover the IVC's are supported from the vacuum vessel via flexible mounts which appear as an array of circular elements in this figure.

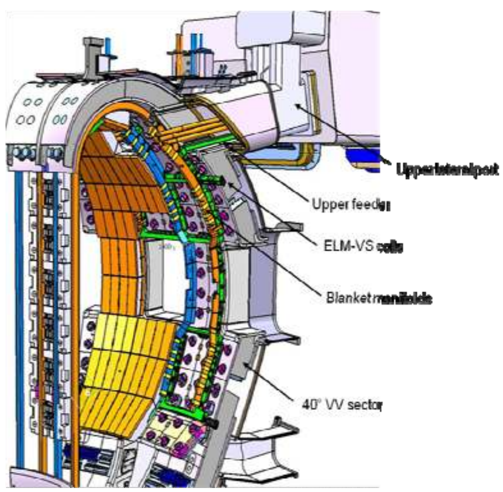

Figure 3. Integration of the IVCs in ITER

Figure 4 is in electrical schematic of one sector of the IVC coils. It is important to note that all toroidal winding segments contain multiple windings. The uppermost and lowermost segments contain both ELM/RWM windings and VS windings; the mid horizontal segments contain windings of both the upper or lower ELM/RWM windings and the mid-coil windings. A concern of this design is the increased risk of turn-to-turn electrical failures due to turns of different systems being adjacent to each other with deionized water as the dielectric.

The upper feeders for current and water are routed out of the vessel through the upper shield ports; the lower feeders are routed out of the vessel through 9 feed throughs. The IVC assembly sequence begins by mounting the upper & lower ELM/VS coil sub-assemblies on the vessel wall. The

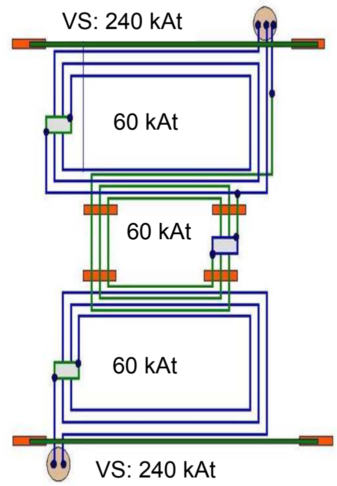

Figure 4. IVC Electrical schematic

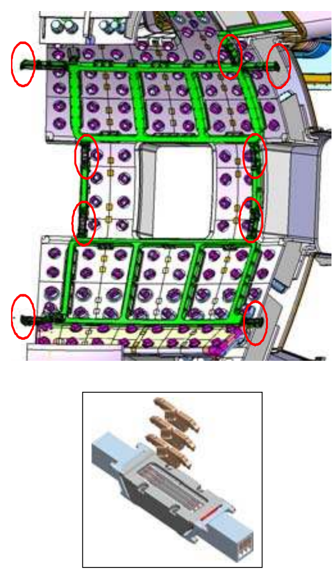

Figure 5. Locations of jumpers (upper figure) and jumper details (lower figure).

A. Power Supplies

Each of the ELM/RWM coils are powered by an individual power supply- i.e., a total of 27 power supplies is required. The upper and lower VS coils are arranged in an anti-series arrangement with two power supplies interleaved between them to halve the coil voltage to ground. A recent study suggested that the coil voltage to ground could be halved again by employing a virtual ground at the center point of the two supplies.

The power supply requirements for the ELM/ RWM and VS coils are given in Tables 1 and 2, respectively [2]. Each ELM/RWM and VS coil has 3 turns. Studies were performed to determine power supply options for both the ELM/RWM and the VS coils [3, 4]. Thyristor, chopper, and hybrid thyrister / chopper supply options were considered. The study concluded that the chopper type supply is the preferred solution for the VS since it meets the time response and bi-polarity requirements and buffers the grid from the transient load. For the ELM/RWM coils both the thyristor and chopper solutions appear to be viable, and the final choice will be taken after further study. However, the high current levels required exceed the existing state of the art for chopper supplies, and will require R&D. A study is being undertaken by the University of Wisconsin personnel, who have experience in chopper type supplies which are used on their PEGASUS device.

Table 1. ELM/RWM Coil Power Requirements

Mode	Current (kA, rms)	Voltage, (V)
For ELM control	20	130
For moderately unstable RWM control	2	100
For ELM control + moderately unstable RWM control	20	130

Table 2. VS Coil Power Requirements

Mode	Current (kA)	Voltage, (V)	Pulse Details
For a single large disturbence	80 (peak)	900	Max. of (10) 0.3 s pulses; min. 10 s between two disturbances.
For repetitive disturbances	20 (peak)	900	Max. of 100 1-s pulses; min. 2 s between disturbances.
For noise in dZ/dt diagnostics	10 (rms)	900	Continuous

B. Physics Design Basis [5]

Experiments on C-Mod, DIII-D, JET, NSTX, and TCV have provided a criterion for evaluating the vertical stability control: D_z/a >0.05 for reliable vertical stability and D_z/a >0.1 for robust vertical stability. The proposed reference VS coil design is capable of D_z/a ~0.1

Of the ~300 MJ stored thermal energy in ITER H-mode plasma, about 100 MJ will be in the pedestal. Therefore, unmitigated Type 1 ELMs in ITER with energy up to 20MJ are predicted. Characteristic time for thermal pulse to target is set by parallel transport ≈ 250µs (arrival time). This is many times the energy, for this timescale, that is needed to evaporate any target material (wetted area ~4m^2 and peak/mean ~2). A pellet pacing system would have to reduce the ELM energy loss per event by a factor of 20 and be highly reliable. The alternative approach, which has been used on DIII-D, is to suppress ELMs by the application of non-axisymmetric magnetic fields to create resonant magnetic perturbations (RMP) in the edge region. The ELM coil current requirements are based on DIII-D results. In DIII-D RMP experiments at low collisionality and ITER Shape (ISS) plasmas, ELM suppression is correlated with achieving the Chirikov overlap parameter of 1 at ψN = 0.835. This corresponds to 50kAT, for each of the ITER ELM coils. A 20% margin to account for uncertainties in the extrapolation from DIII-D to ITER has been incorporated, resulting in the present 60kAT requirement. Further analysis and benchmarking of codes is in progress.

"Steady state" operation in ITER entails β_N>3, which can result in a RWM. Active feedback control on DIII-D and NSTX have shown that it is possible to stabilize RWM even at low rotation. The ITER in-vessel coils are predicted to stabilize RWM to β_N>3.8.

C. Risk Analysis

Several of the most serious risk concerns are associated with the use of water as a dielectric in the bath-cooled coil design. Although the turns are coated with ceramic, pinholes in the coating and cracks formed due to thermal expansion and contraction and electromagnetic stress make it necessary to consider water as the dielectric. This requires careful control of water chemistry and would require extensive R&D to quantify and study the effects of bubble formation due to water flow, electrolysis, and radiolysis and build-up of contaminants to ensure that none of these factors result in electrical breakdown. Having ELM/RWM and VS coils in a common housing with bath cooling was also identified as a reliability risk due to the possibility of system-to-system electrical faults. Another serious concern is due to the fact that the entire IVC system is hydraulically connected together, with no means to isolate regions to detect and isolate a leak, if one occurred.

There are also several issues associated with the use of ceramic. Besides long-term reliability concerns of ceramic coating on conductors with high thermal and electromagnetic stresses, achieving uniform coating thickness is extremely difficult, making shimming in the case to assure that adequate load paths are provided from the winding to the case and to the vacuum vessel. Lastly, the many bolted jumpers presented both reliability risks and remote handling challenges which would be extremely difficult to overcome.

III. ALTERNATIVE STUDIES

Alternative concepts of the IVC system consisting of 27 discrete ELM/RWM coils and 2 (or more) discrete VS coils which could be fabricated with several variants of "dry" insulated conductors capable of withstanding ITER's 200 C bakeout temperature and fast neutron fluence of 10^{23} n/cm^2 are under study to improve the reliability and simplify the manufacture of the IVCs. These concepts are applicable to both the reference and alternate VV designs.

Currently, three internally cooled copper conductor options are being considered. The first is based on the use of ceramic polymer and fiberglass insulated conductors. Left in the "green" state (i.e., cured at temperatures below ~400 C) ceramic polymers would not be fully converted to a crystalline ceramic structure. They would have some ductility, are expected to have good compressive and dielectric strength, be capable of operation at temperatures up to ~350C, and have radiation resistance superior to polyimide. However, ceramic polymers are presently developmental. R&D is now underway to characterize them and determine the effects of irradiation. Irradiation is likely to cause the evolution of gases (primarily CO) which is not expected to be a problem for this application, may result in further pyrolysis (i.e., conversion to a crystalline ceramic) which would increase brittleness, and may result in the formation of carbonaceous compounds which may degrade its dielectric strength. If the ceramic polymers prove to be suitable, they would permit the coils to be fabricated in a conventional manner: fiberglass cloth insulated hollow copper conductors would be wound and enclosed in a welded stainless steel coil case. The coil would then be vacuum pressure impregnated with ceramic polymer resin and cured.

The second option would use stainless steel jacketed, magnesium oxide insulated hollow copper conductors. These conductors have been used in some high energy physics application where high radiation exposure limits the use of materials, but the size required by the IVCs is considerably larger and will require a scale-up of the manufacturing process. In this concept, conductors would be wound, welded inside a stainless steel coil case, and then potted in ceramic slurry to provide a load path between the windings and the case.

The third option would use stainless steel jacketed, dry fiberglass insulated hollow copper conductor. The coil manufacture would be similar to that of the MgO option.

In the alternative VV, shown in Figure 6, the outer wall is moved outwards by 150 mm and the blanket/shield modules are supported by a separate back plate shell structure located within the vessel. These changes impact the IVCs in several ways: the A-t of the coils will increase because of their increased distance from the plasma and field penetration through the partially insulated back plate may degrade RWM and VS performance. Studies of the RWM and VS performance are currently under study to provide information for a scheduled upcoming review.

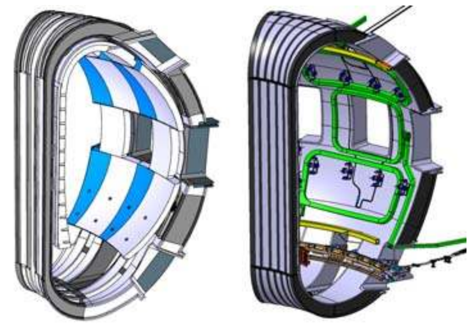

Figure 6. The alternative vcuum vessel. The blanket/shield modules will be supported by the separate back plate shown with in the figure on the left. The IVCs will be mounted on the vacuum vessel behind the back plate, as shown in the figure on the right.

IV. SUMMARY

Tremendous progress has been made in the development of the in-vessel coil system. Several promising design options are being developed and supporting R&D is underway to provide ELM mitigation, vertical stabilization, and the RWM stabilization required for ITER.

ACKNOWLEDGEMENT

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

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov