Overview of the Design Development, Prototype Manufacturing and Procurement of the ITER In-Vessel Coils

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Outline

- Overview of ITER In-vessel coils role
- Design and integration of ITER In-vessel Coils
- Overview of the Reference design
- Outcome of IVC Prototype manufacturing
- Alternative designs
- Installation strategy
- Procurement and schedule

Overview of the ITER In-Vessel Coils



27 ELM (Edge Localized Mode) water-cooled "picture frame" coils fabricated of Mineral insulated conductor

- 9 lower, 9 equatorial, and 9 upper coil
- 6 turns/1 coil
- 1 flow path/coil

A. Encheva, 25th IAEA Fusion Energy Conference, 13-18 October 2014, St. Petersburg, Russia

Coils → Aimed at suppression of Type I ELMs (90 kA per coil)

ELM Control

2 VS (Vertical Stability) "ring coils" fabricated of MIC common power supply connected to produce a radial magnetic field (60 kA per turn, 2.3 kV)

- 4 turns connected separately to cooling water and power supply

Integration Challenges

- In-Vessel Coils (IVCs) are attached to the inner vacuum vessel wall
- Limited space for support rails
- Tight fit behind Blanket Shield Modules
- Manufacturing constraints
- Integration with Diagnostics
- Integration with Manifold Rails
- Integration with Blankets
- Complex and iterative integration process



Challenging loading conditions

- Cyclic and fatigue requirements : design to last for the lifetime of ITER, 30 000 pulses, pulse duration up to 3000s;
- Pressure loads
- Electromagnetic (EM) loads: these loads are a strong design driver during transient events (e.g. plasma disruptions: MDs and VDEs), max. load 400 kN/m;
- Thermal loads: these loads are a strong design driver and they are caused by temperature gradients induced by:
 - The neutron heat load: 1.4 W/cc for the VS coils and 1.2 W/cc for ELM coils
 - Operating Thermal Loads :

Joule heating of the coils

Thermal expansion of the coils and the vacuum vessel (temperature of 100 C)



Reference Design of a VS Coil



A. Encheva, 25th IAEA Fusion Energy Conference, 13-18 October 2014, St. Petersburg, Russia

Prototype Coil Manufacturing at ASIPP

Two prototypes of ELM and VS coils have been completed by ASIPP in April 2014 and the work concluded with a Final Prototype Review, 28-30 April 2014, Hefei, China

Goals :

- Development of suitable manufacturing procedures and techniques based on R&D results
- Manufacture 1 Equatorial ELM coil and 1 VS segment of 120°
- Electrical and mechanical tests of the prototypes to meet the acceptance criteria



Conductor Manufacture

- Mineral insulated conductor (MIC) is made by centering a copper pipe in a stainless steel pipe, filling the annulus with magnesium oxide (MgO), and then drawing the assembly in dies or pressing the assembly between rollers to compress the MgO.
- Problem with high hydroscopic feature of MgO which requires special protection against humidity



Compaction machine

- 10 pairs for compaction

14 pairs rollers



- **4 pairs for straightening** Well controlled outer diameter and good electrical properties MgO evenly distributed around the conductor
- Billet size limited, max. length of conductor 10.7m.

Conductor brazed joints – ELM coil

- All conductor joints for the ELM coils have been completed and inspected by X ray in a vertical direction only
- However, there are uncertainties on the X-ray detection sensitivity and additional tests are needed to qualify this sensitivity
- 324 joints in total: can introduce a large risk for ITER operation, since the IVC are not repairable or replaceable inside the ITER Vacuum Vessel
- An advanced ultra-sonic (UT) techniques as an additional and potentially more sensitive inspection method will be investigated



Cleaning the ends for joints developing



Putting and Compressing the Brazing Foil



Preparation for Copper Brazing



Jacket Butt joint assembly



Conductor brazed joints – VS coil



A key issue for the VS coils is the joining of the 120° sectors of 4 conductors inside the vacuum vessel ASIPP has completed the 4 brazed joints simultaneously between 40 and 80 degree segments of the VS coil The quality of these joints shall be assessed by destructive tests

The simultaneous brazing of the four conductors entails significant risk due to possible difficulties in achieving precise conductor positioning and alignment in the ITER VV and in controlling key brazing parameters

ELM / VS Coil bending, forming, final assembly





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- Complex shape of the coil, 3D bends, stringent tolerance requirements: ± 4mm; ± 2mm
- The bends are the main contributor to the winding profile tolerance
- The accuracy required for good quality brazed joints between conductor and brackets (in the order of 0.1-0.2 mm) was not achieved with the present forming and winding techniques used by ASIPP
- The initial big gaps (up to 8-9mm) between conductors and brackets in the ELM coil have been reduced by optimizing the sequence of assembly and by brazing copper shims

The final tolerance of the complete assembled coil after brazing and welding of the brackets of +/-9mm



Summary and conclusions from R&D work

- The IVC prototype development has been concluded, but IVC design is not mature enough for series production;
- The main outstanding open issue of the reference design is the brazing between conductors and brackets. The performance and integrity of the coils is not guaranteed . There is a large risk for ITER operation since the IVC are not repairable or replaceable inside the ITER Vacuum Vessel;
- 37 Cracks occurred on the Inconel 625 jacket of the ELM Coil conductor. The cracks originate from the coupling of mechanically stressed Inconel jacket with the Ag-containing brazing alloy used to join the brackets to the conductor;
- Simultaneous in-situ brazing of the four VS coil conductors entails significant risk
- Although the brazed joints appear to be of good quality from the NDE done so far, final conclusions on quality and reliability cannot be drawn at this stage post mortem tests are foreseen;
- Difficulty in achieving the required installation tolerances for the finished assembly due to the thermal deformation during brazing process.

Improved Reference Design

- Conductor made of OFHC copper will be used for the core and SS316 L for the jacket;
- Dimensions will remain the same;
- Limited brazed area;
- Bolts could be added to increase the stiffness;
- Brazing to be carried out in a vacuum oven;
- Match machining of the bracket;
- Fatigue requirements are not fulfilled due to high thermal stresses – outcome from preliminary analysis;
- High stress concentration occurs on the edges of brazing joint parts: This is due to partial brazing, not full circles. In real case, it could be worse due to irregular brazing joint quality.



Design of alternative ELM conductor/coil



- Integrity and robustness of the coil by stiffeners and longitudinal welding of the conductor.

R&D on Alternative ELM control coil design

A call for tender has been launched in September 2014

The main challenges of the alternative design to be investigated as part of this tender are:

- Fabricating long composite conductors with a square stainless steel jacket, mineral insulation and a copper core;
- 3D forming of a coil mock-up by bending at small radii square shaped conductors while maintaining tight tolerances to allow the welding of the turns to each other;
- Assess welding distortion.

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Proposal for Installation of Alternative VS coil



<u>Reference design:</u>The simultaneous brazing of the four conductors entails significant risk due to possible difficulties in achieving precise conductor positioning and alignment in the ITER VV and in controlling key brazing parameters

Main design driver of Alternative VS design: to facilitate in-situ installation and meet the stringent tolerance requirements



- The alternative VS coil conductor will be supplied to the assembly hall wound on a large reel (~ 4 m diameter);
- To be introduced into the VV through the equatorial ports;
- A set of assembly tools will be used inside the VV: straightening unit, horizontal and vertical bending rollers, and hydraulic forming tools;
- The four conductor turns will be welded together, to ensure structural robustness.

Alternative VS coil design



- 1) Full survey of IVC rails
- 2) Finish-machining of the large inner IVC brackets to match the individual rail to the bracket
- 3) Small inner IVC bracket will be assembled next
- 4) Winding of conductor turns
- 5) The fully formed coil turns will then be lowered or lifted to its position
- 6) The conductor will be pressed inward and downwards into the bracket datum corner
- 7) TIG welding of the upper and lower edges of the outer brackets to the conductors
- 8) Unscrew VS coil from the VV rails and lift it
- 9) Welding of the lower part

Present Installation Strategy for ELM control coils



Installation through the equatorial ports after full completion of the VV sectors

In-Vessel Coils handling equipment



IO Strategy for IVC Development



Since there is a limitation on the existing IO resources, available budget and the time necessary to complete either of the two possible solutions, the present strategy is to include the design finalization, full scale prototype production and qualification activities in the first stage of the supply contract for the manufacture of the 27 ELM and 2 VS coils

- Procurement will be done via a direct Call for Tender
- Activities running in parallel:
 - market survey;
 - development of procurement strategy
- ITER envisages to place 2 calls for tender or 1 call for tender with two lots: one for conductor manufacturing and one for coil manufacturing/assembly
- Schedule

Design Review Launch of Call for Tender Contract awarded March-June 2015 September 2015 June 2016

Summary

- The reference design and prototype work provided a good basis for the development of radiation resistant conductor capable of operating within the harsh conditions in ITER vacuum chamber;
- This effort identified shortcomings in achieving satisfactory manufacturing solution, and most significantly, difficulties with making four simultaneous brazed joints for VS coils sections and difficulties in brazing the brackets onto the ELM coil conductor;
- The ITER IVC team is focused on :
- 1) Detailed thermal and structural analysis for both alternative ELM and VS coil designs, including the impact on the VV rails;
- 2) Small prototype of the alternative ELM control coil with square conductor which will give an answer to the most critical technical issue, that is fabrication of a long conductor with a square stainless steel jacket, bending at small radii while maintaining the tight tolerances and assess the welding distortion;
- 3) Development of a reliable NDT for Cu and CuCrZr joints;
- 4) Brazing and welding trials with Cu and CuCrZr conductors.

ITER IVC team is confident that a reliable, feasible, and manufacturable design for the IVC coils will be available in the near future.

Thank you for your attention !