Examination and Characterization of Physical and Mechanical Properties of the ITER Central Solenoid Module Coils

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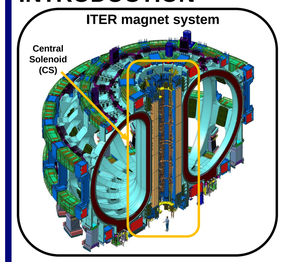
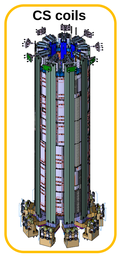
Abstract: The ITER Central Solenoid (CS) consists of a stack of six independent coil packs called modules. It features a total height of 18 m and a diameter of over 4 m. The modules are in an advanced stage of fabrication and testing by the US ITER Project Office (USIPO) and its subcontractor General Atomics (GA). A qualification module mockup at one-to-one scale but of reduced height was wound and Vacuum Pressure Impregnated (VPI) by GA to validate final manufacturing, using tooling and processes fully representative of a series module. The module was submitted to a thermal cycle down to the temperature of 4.5 K at which the coils will be cooled by supercritical helium. During plasma operation, the CS modules are subjected to a complex combination of static and dynamic forces. The understanding of the mechanical behaviour of the CS module coils is of paramount importance to analyse and predict the overall response of the CS stack. To this purpose, an extensive programme of investigation of the module mockup has been defined and applied. This allowed assessing, through examination and testing of a large number of VPI conductor array samples extracted from the mockup, the soundness of the coil through advanced non-destructive examination techniques including X-ray microtomography, dimensional metrology measurements and micro-optical observations. Moreover, additional testing of physical and mechanical properties carried out at room and cryogenic temperature allowed the behaviour of the conductor stacks to be assessed. The paper summarises the results of these investigations and their interpretation through mechanical analyses based on the individual properties of the coil constituents.

INTRODUCTION

ITER magnet system



CS coils



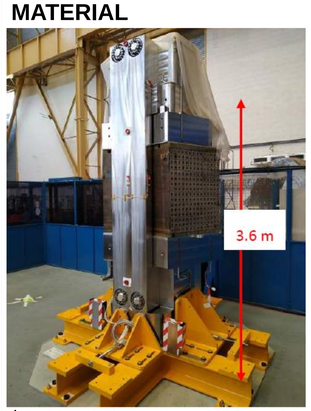
CS Module 2 following VPI (height 2120 mm)

⇑ **The ITER Central Solenoid, consisting of six electrically independent stacked coil packs called modules, will be installed in the centre of the ITER machine, and will drive up to 45 kA of current in each module during plasma operation. It features a total height of 18 m and a diameter of 4.13 m. A peak field of 13 T will be reached in its centre. A vertical pre-compression structure provides the required preload while allowing contact between the modules during all stages of plasma operation to be maintained.**

- General Atomics (GA) is in charge of the fabrication and testing of the six modules of a height of 2120 mm each (a seventh module will serve as a spare).
- Moreover, **a qualification module mockup** coil using dummy conductor **at one-to-one scale** but of reduced height of 840 mm **was produced** to validate the final manufacturing steps, namely winding and Vacuum Pressure Impregnation (VPI). This mockup, based on copper and not superconductor strand, has 16 layers in height, as opposed to 40 in a full series module.

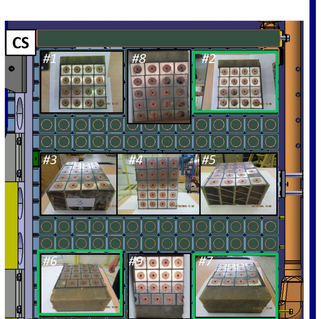
⇐ **Full azimuthal cross-sectional slice (original thickness: 110 mm) of the module mockup coil after dissection (inner windings on the left side).**

MATERIAL



- **A full cross-section annulus** sector of the mockup was extracted and **submitted to an axial compression test at CEA up to** a load of 23 MN corresponding to a stress of **26 MPa**.
- A full azimuthal cross section slice was also dissectioned and VPI conductor array samples were extracted from it.

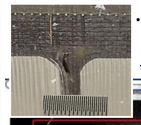
Identification of the different array samples (hereafter called CS MMU-1 to -9) and their position in the azimuthal cross-section ⇒



⇑ **Annulus winding pack sector of the module mockup featuring an area of 0.883 m², 948 mm height (including a bottom and top G10 plate and ground insulation) and 720 mm width, axially tested in the CS Pre-compression test setup. A full laser survey of the winding pack sector equipped with 18 fiducials was carried out by the company Metromecanica /SP at CEA before, during and after loading on the two sides of the winding pack.**

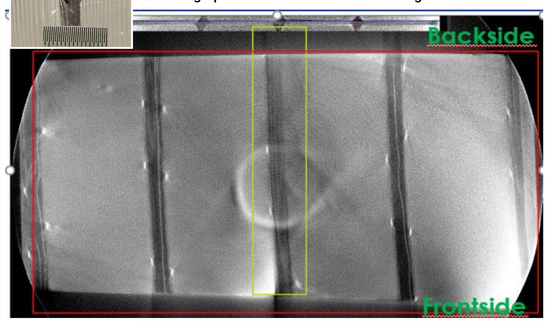
TESTS AND RESULTS

A. Macro and microscopic inspections, X-ray microtomography (μCT)

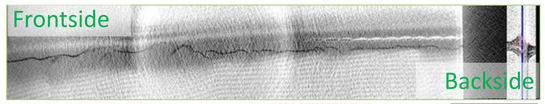


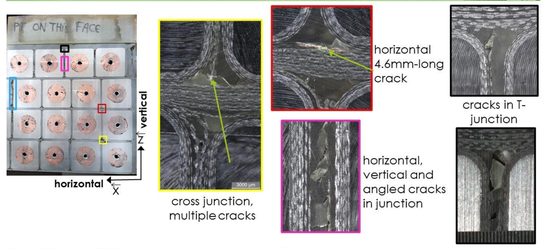
- **μCT was performed at CERN** on CS MMU-2 with the help of a ZEISS METROTOM 1500 tomograph. **Resolution** was in the order of **10 μm**.

⇐ **Macrographic examination reveals shrinkage cavities and cracks in the resin junctions**



⇐ **Results of μCT showing that channelling cracks go through the whole 110 mm thickness of the slice from the front to the back side in the azimuthal direction**

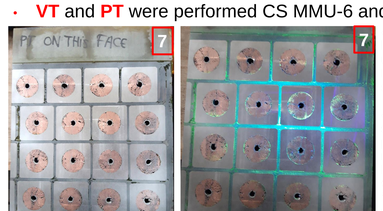




⇐ **Microoptical observations confirm that the volumes filled with a high density of fibres do not show imperfections such as cracks, while in resin rich areas multiple cracks are observed, particularly in cross and T junctions.**

B. VT and PT inspection, glass fibre content

- **VT** and **PT** were performed CS MMU-6 and -7.



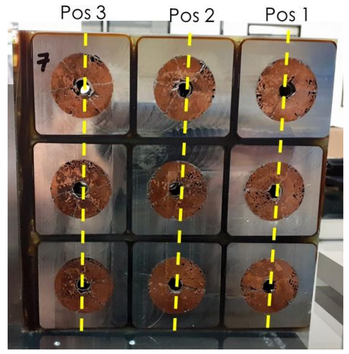
⇐⇐ **VT was performed on backside faces prior to PT, using a white light torch. Indications were found in both samples.**

⇐ **PT was performed on the same backside face with the penetrant liquid and the revelator as per the table below. Indications (darker spots at visible light exposure) were found in both samples (slightly more indications for CS MMU-6 than for -7). Line indications are mainly vertical.**

Cleaner	Alcohol
Penetrant liquid	Ardrox fluorescent penetrant 9703
Revelator	Ardrox developer 9D1B

A content of fibre of 63.50 wt% for the horizontal and of 58.20 wt% for the vertical positions was measured through an ATD/ATG Setaram Labsys EVO analysis platform.

C. Thermal contraction measurements

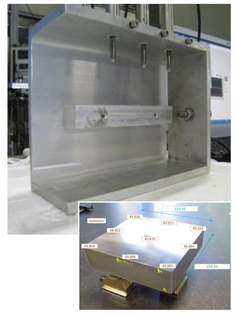


	Pos 1	Pos 2	Pos 3
Steel thickness [mm]	48.625	48.461	48.431
Insulation thickness [mm]	13.277	13.381	13.603
Rel. insulation thickness [%]	21.45	21.64	21.92

- The measurements were performed on a cross sections of CS MMU-7.

⇐ **Prior dimensional metrology measurements were performed along three parallel lines (Pos 1, Pos 2 and Pos 3) in 13 locations with the help of a ZEISS O-INSPECT 863 Multisensor Coordinate Measuring Machine (CMM).**

Integral thermal contraction between RT and 77 K was measured at the Laboratoire de cryogénie et des stations d'essais (LCSE) of CEA (Saclay). The equipment was calibrated with a stainless steel block (316LN) of comparable dimensions (previously controlled by dimensional metrology at CERN). The test bench is made of bolted aluminium plates, with 3 'locators', which guarantee the right positioning of the sample after successive tests. The calibrated displacement sensors (SGD-25 mm) operate thanks to the deformation of strain gages glued to membranes ⇒

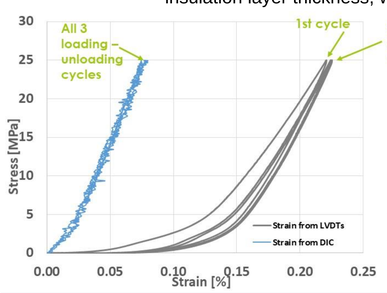


	Position 1	Position 2	Position 3
Absolute integral thermal contraction /mm	0.337±0.034	0.400±0.023	0.430±0.035
Rel. integral thermal contraction /ppm	2100	2490	2670
Relative thickness of insulation /%	21.45	21.63	21.92

⇑ **The different measured positions feature a different contraction, due to the heterogeneous repartition of the insulation and metallic phases in the sample. The average thermal contraction (2410 ppm) is consistent with previous results (between 2300 ppm and 2500 ppm) obtained by the National High Field Magnetic Laboratory (NHMFL) and the National Institute of Standards and Technology (NIST) on a prototype 4 x 4 conductor array. The calculated value is 2460 ppm, in good agreement with the experiments.**

D. Compression and push-out tests

- The **compression modulus** calculated from the response obtained **through LVDT sensors** between 20 MPa and 15 MPa (25 MPa and 20 MPa) **is 32.8±0.1 GPa (35.2±0.2 GPa)**. From the **DIC measurements** it is **33 GPa** and **35 GPa**, respectively, for the same stress ranges. These results are consistent with the ones obtained previously on a 3 x 3 test prototype array (34.7 GPa).
- Moreover, the DIC measurements allow to estimate the **Poisson ratio** which **is in the range 0.27±0.01**, as well the **local compression modulus** of the insulation through a virtual extensometer covering the insulation layer thickness, which **is 4.7±1.1 GPa** and **5.5 GPa±1.0 GPa** for the respective stress ranges.



⇐ **Stress-strain curves for the compression tests of CS MMU-2. A detail Finite Element Analysis (FEA) model has been created. The calculated smeared vertical compression modulus is 36 GPa in the 25 MPa – 20 MPa stress range, consistent with the experimental results.**

Push-out tests show a maximum pushout force of 95 kN, before the expulsion starts, which corresponds to a push out shear stress of 9.2 MPa. This value is relatively low when compared to the usual requirements of push out strength of similar VPI conductor arrays such as for the ITER Correction Coils, in the order of 20 MPa ⇒

DISCUSSION AND CONCLUSIONS

This extensive experimental campaign on a large module mockup sector sample produced during the qualification phase allows to understand the response of the CS winding, based on a detail dimensional, physical and mechanical assessment of its components which will be very helpful for the modelling of the behaviour of the full-scale modules.

Acknowledgments: The authors are thankful to the different laboratories and companies that performed glass fibre content measurements and metrological inspections of the module mockup sector.

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"The views and opinions expressed herein do not necessarily reflect those of the ITER Organization"