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The DTT device: Advances in conceptual design of vacuum vessel and cryostat structures

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ABSTRACT

In this work we present the latest progresses (September 2018) in the conceptual design of the main containment structures of DTT fusion reactor. The previous DTT baseline design is revised in terms of structural materials and overall reactor shape. The major change involves the vacuum vessel, which now foresees a welded double-wall stainless steel structure. The basic design includes eighteen sectors, with novel ports configuration for remote maintenance systems, diagnostics and heating equipment. New supports are designed for the first wall, which is conveniently segmented in view of assembly and remote replacement. The cryostat of the machine is conceived as a single-wall cylindrical vessel reinforced by ribs. The cryostat base is also in charge of supporting the vacuum vessel and the magnets system. A preliminary FEA analysis confirms that the main mechanical structure might withstand the design loads, in particular the ones resulting from possible plasma disruptions.

1. Introduction

The major goal of the *Divertor TOKAMAK Test facility* (DTT) is to bring alternative divertor solutions to a sufficient readiness level to be adopted by EU-DEMO [1]. To this end, the 2015 DTT baseline design [2] is deeply revised to take into account new possible plasma configurations (i.e. Double Null -DN) involving two divertors (upper and lower) and a symmetric configuration of the ex-vessel magnet system (Toroidal Field Coils and Poloidal Field Coils). In this work, the latest progresses related to the conceptual design of the main containment structures of DTT device are presented. The design of Vacuum Vessel (VV) and Cryostat Vessel (CV) is mainly constrained by the space reserved for the magnetic coils and a new ports configuration (see, e.g. Fig. 1); therefore, it is subjected to major changes. Concerning the VV, a double-wall structure made of AISI 316L(N) stainless steel is preferred over the previous single-shell Inconel structure. On the other hand, the shape of the Cryostat has to be compatible with the new ports configuration, which is now better detailed to consider remote maintenance systems, diagnostics and heating equipment.

Supports are also designed for the first wall, which is conveniently segmented in view of its remote installation/replacement.

Given the continuous progresses in the design activity, the CAD model of the VV is parametrized to allow for fast assessments [3], according to a systems engineering approach [4].

Finite element analyses (FEA) confirms that the mechanical structures are compatible with the load cases here analyzed, in particular the ones resulting from possible plasma disruptions.

2. Vacuum vessel

The Vacuum Vessel (VV) is located inside the magnet system. It provides an enclosed, vacuum environment for the plasma and also acts as a first confinement barrier. VV is a stainless-steel torus vessel with a "D" shaped cross-section, delivered in several modules to be field welded. Its main components are: the main vessel, the port structures and the supporting system.

The main functional requirements of the VV are listed as follows:

- it shall provide a boundary consistent with the generation and maintenance of a high-quality vacuum;
- it shall provide the first confinement barrier and withstands postulated accidents without losing confinement;
- it shall withstand the nuclear heating within the allowable temperature and stress limits;
- it shall support the in-vessel components and their loads under normal and off-normal operations;
- it shall maintain, together with the in-vessel components, a specified toroidal electrical resistance;
- it shall provide access ports or feedthroughs for in-vessel component, diagnostic, heating system, services and maintenance.

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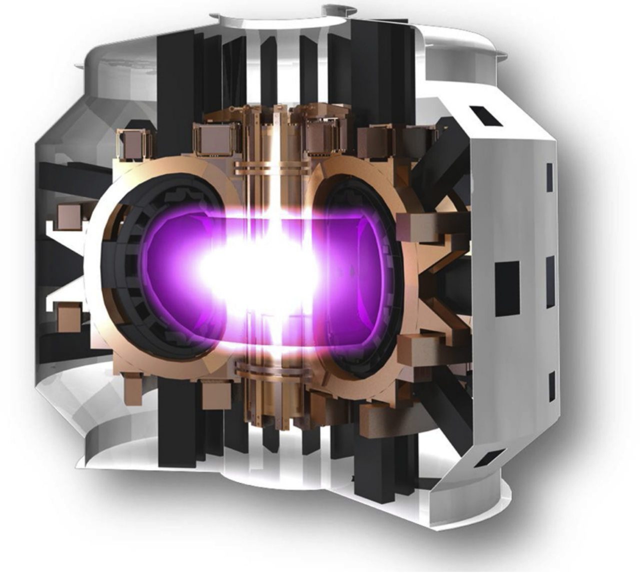

Fig. 1. VV, cryostat and magnets system (pictorial view).

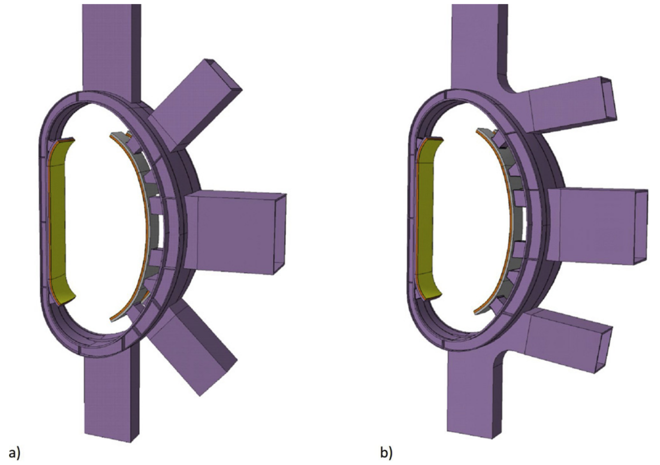

Fig. 2. Standard (a) and RH (b) sectors of the Vacuum Vessel with first wall modules and their supports.

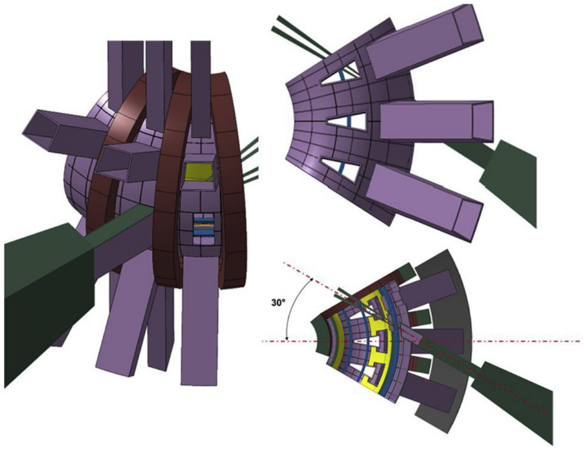

Fig. 3. NBI VV sector (60°).

The ports position and geometry are defined considering the interfaces with Poloidal Field (PF) coils, Toroidal Field (TF) coils and the inter-coil structures. At the current stage (September 2018), the

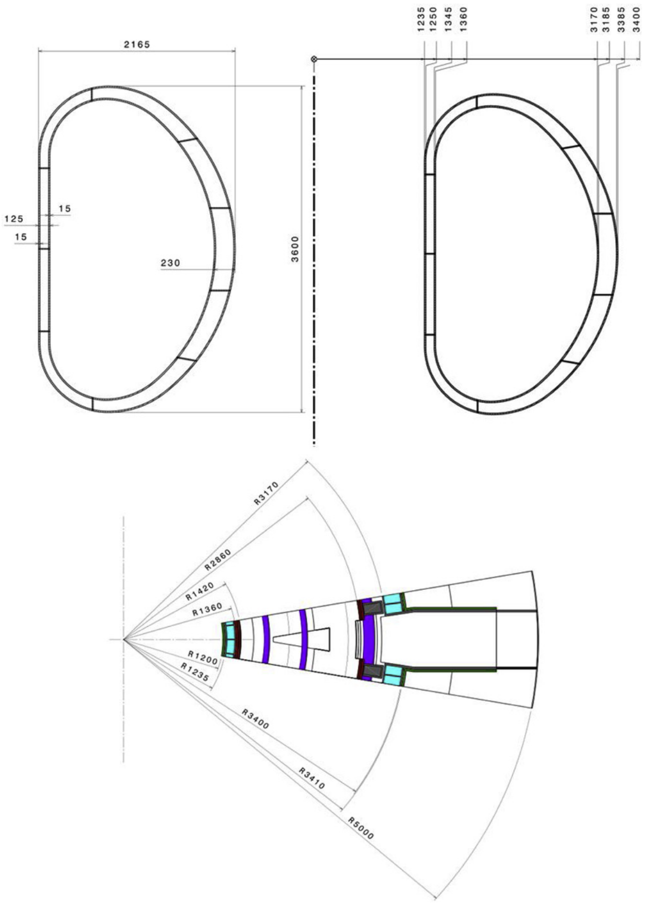

Fig. 4. Overall dimensions (in mm) of main vessel section and radial build.

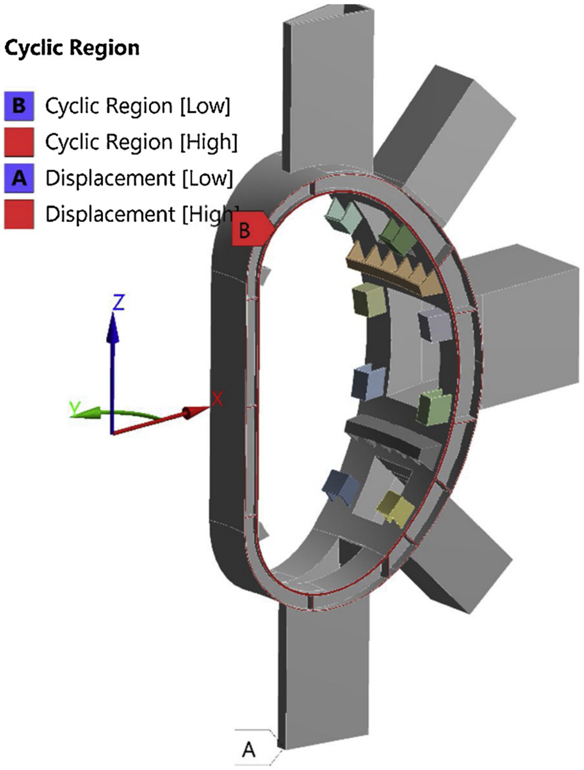

Fig. 5. FE reference system and boundary conditions.

Table 1
VV Main Parameters.

Shell Thickness (inboard)	15 mm
Shell Thickness (outboard)	15 mm
Ports Thickness	25 mm
Material	AISI 316-L(N)
Ribs thickness	10 mm

following modules are preliminary designed (see Figs. 2 and 3):

- **No.6** Standard modules (of 20°), having two ports aligned with plasma center (Fig. 2a).
- **No.6** Remote handling modules (of 20°), allowing for the remote handling of the upper and lower divertor (Fig. 2b).
- **No.2** NBI modules (of 60°), which allow for the installation of a tangential neutral beam injection (NBI) at the equatorial port (Fig. 3).

The main vessel is an all-welded double wall structure. Since between the two shells is possible to use water/borated water as coolant, the shielding performances of the vessel might be enhanced with respect to a single shell configuration. In the current configuration, the thickness of the inner and the outer shells is set equal to 15 mm. The shell will be manufactured by hot forming/bending and then field welded.

The overall external dimensions of the VV are reported in Fig. 4. The maximum height is equal to 3600 mm, with a diameter of 2470 mm at the inboard side and of 6800 mm at the outboard side.

The material to be used for vacuum vessel has a significant influence on performance, fabrication characteristics, mechanical strength at operating temperature, chemistry properties, and cost.

Initially, two material candidates are evaluated: AISI 316 L(N) and Inconel 625. The DTT device has low dose rate (i.e. about 10 mSv/h) in vacuum vessel at one month after shutdown at the end of DTT operations [2]. Hence the main drivers for material selection are costs and technology manufacturability. Since AISI 316 L(N) has lower costs and more companies can actually work with this material, this is selected as the main structural material for the vessel.

A set of internal ribs (Fig. 5) has been conceptual designed. The design has been driven by thermohydraulic and structural requirements.

Table 1 summarizes the main design parameter of vacuum vessel.

2.1. Design for RH issues

VV is designed also considering needs for remote installation/replacement of divertor cassettes and first wall modules. In particular:

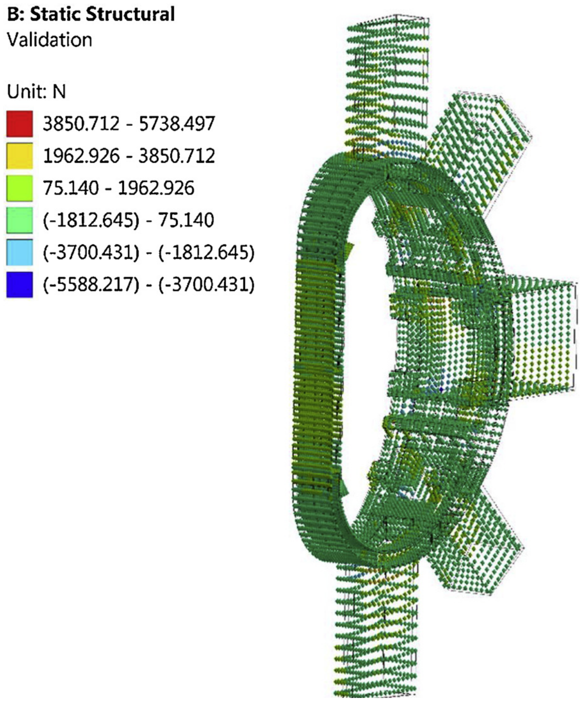

Fig. 7. EM force mapping on VV mesh.

- The external dimensions of the lower and upper RH ports (see Fig. 2b) allow the insertion/replacement of the divertor and its RH equipment.
- The external dimensions of the equatorial ports of two RH sectors (see Fig. 2b) allow the insertion/replacement of the first wall and its RH equipment.
- Supporting rails are foreseen inside the lower and upper RH ports and inside the main vessel to maneuver the equipment for divertor cassette positioning.
- Further studies will be done on how the (eventual) vibrations and flexibility induced by the remote transportation of the in-vessel components [5] might affect the design of the ports.

2.2. Structural analysis

The standard module in Fig. 2a is used as reference for FEM analyses. The simulation model includes the main vessel, the port structures and the FW support system. The coordinate system is cylindrical, with its origin in the center of the tokamak, on the equatorial plane.

A cyclic symmetry boundary condition was set on the left and right

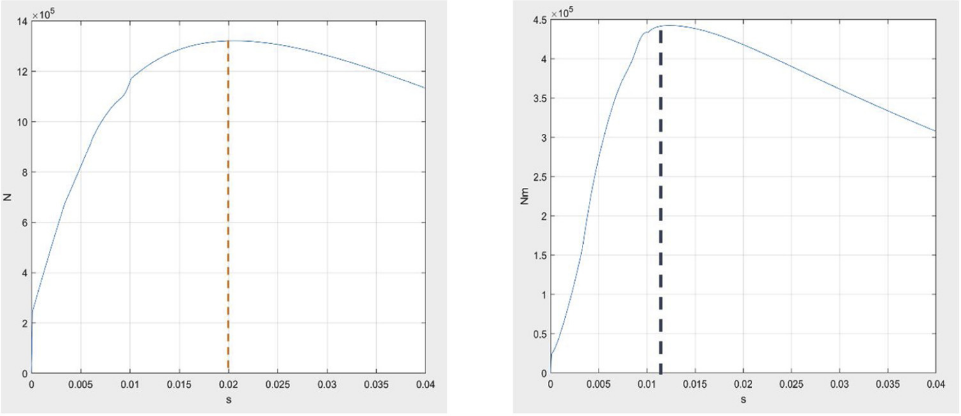

Fig. 6. Time history of the total EM forces and moments.

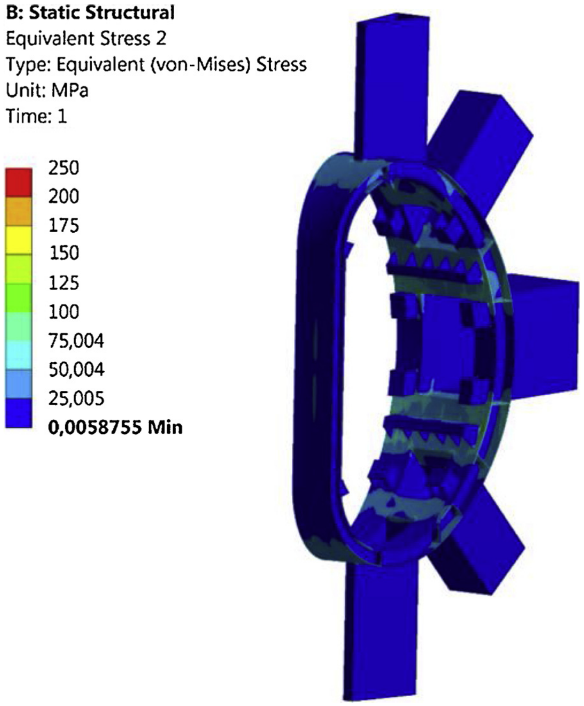

Fig. 8. VV Equivalent stress (von-Mises).

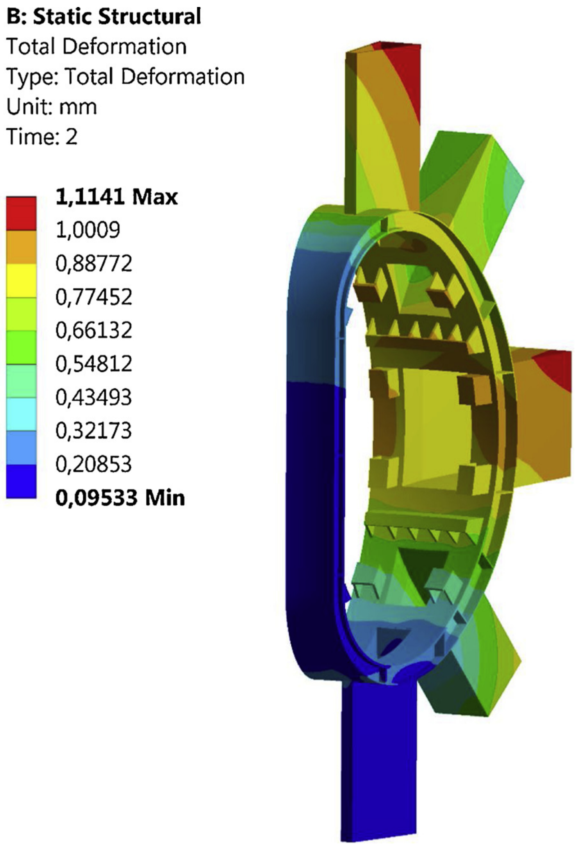

Fig. 9. VV - Overall displacement.

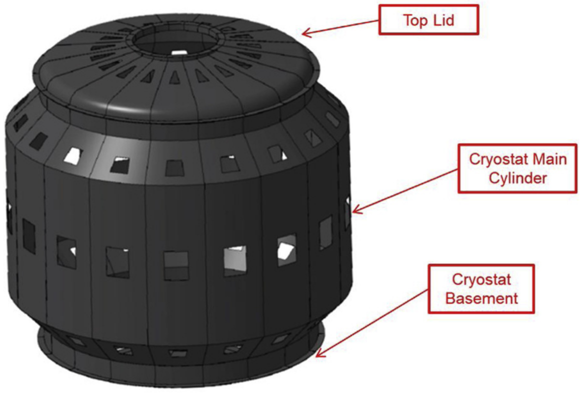

Fig. 10. Cryostat vessel model.

Table 2
CV Main Parameters.

Maximum Radius	5000 mm
Structural Material	AISI 304 L (Co < 0.05 wt%)
Thickness	30 mm (*Single walled structure with ribs increasing its bending stiffness*)
External pressure	0.1 MPa (Normal operations under vacuum)
Maximum internal pressure	0.12 MPa (in case of ICE)
Operational pressure	Vacuum, 10^{-3} Pa
Design temperature of cryostat wall	293 K

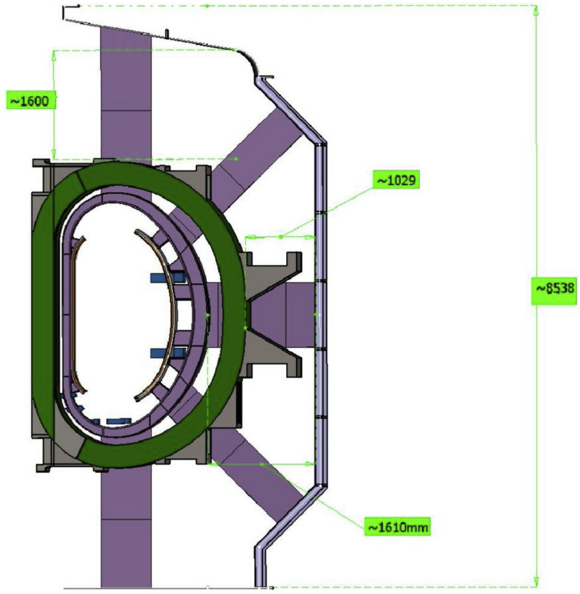

Fig. 11. Cryostat vessel poloidal section.

surfaces of the vessel sector. Since none of the main vacuum vessel supports have been designed yet, a displacement type constraint that limits the rotations in the xz plane but allows for thermal deformation in radial and z directions has been applied to the lower port. Fig. 5 shows the cylindrical reference coordinate system and the applied boundary conditions. The FE mesh for the mechanical analysis is made up of 1422097 nodes and 805616 solid elements (solid 186 element in Ansys).

The loads from the EM analysis on the Vacuum Vessel during a major disruption [0.00 s – 0.04 s] are considered. From the time history of the total EM forces and moments, a critical window is identified between 0.01 s and 0.02 s, as high EM forces and moments occur (see, e.g. Fig. 6).

Nodal forces are mapped from the EM mesh to the structural mesh (Fig. 7). The own weight of the Vacuum Vessel is considered as well.

The material proprieties of the AISI-316 L(N) were extracted from ITER SDC-IC code for Structural Analysis of the ITER In-vessel components [6]. Considering a conservative reference temperature of

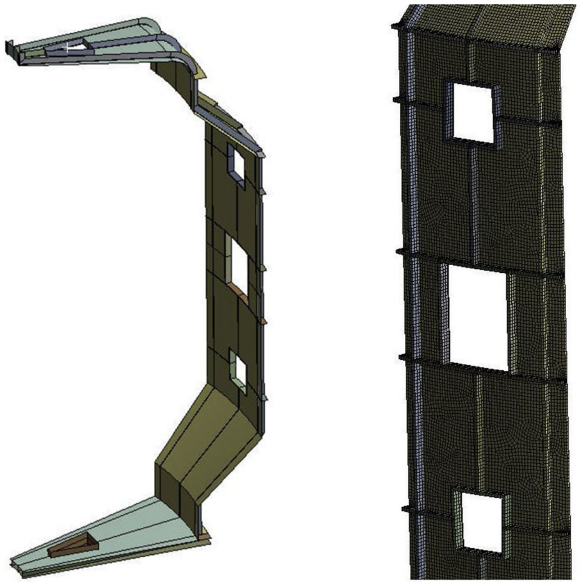

Fig. 12. External ribs.

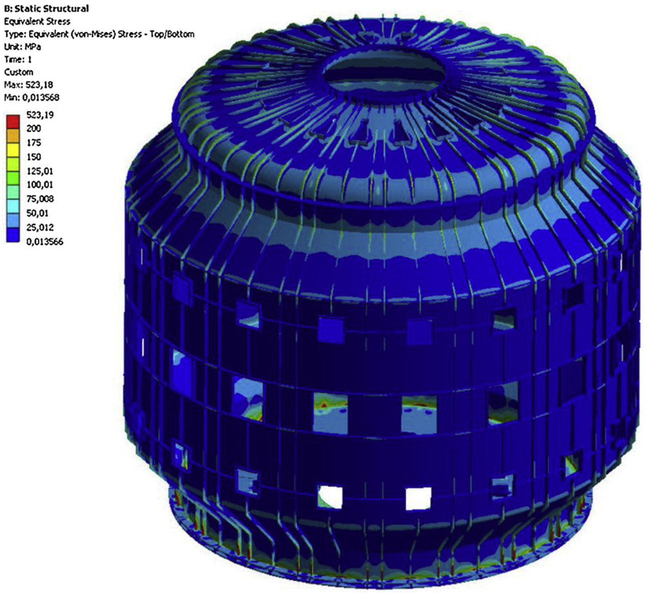

Fig. 13. Equivalent von-Mises stress on the Cryostat vessel model in normal operating conditions.

100 °C, the maximum allowable stress results as $\mathbf{S_m = 147\ MPa}$.

The equivalent Von Mises stress exceeds the maximum allowable stress S_m just in some boundary nodes (see Fig. 8); thus, this aspect can be neglected. Nevertheless, the juncture between ports and VV shall be evaluated with a dedicated model in future activities. Fig. 9 shows the displacements, which result to be higher for the upper and equatorial ports.

The preliminary result shows that the selected combination of material and thicknesses for the VV and ports could be enough to withstand the EM loads due to a Major Disruption Event. However, further detailed analysis in accordance with accredited pressure vessels codes are required.

3. Cryostat vessel

The Cryostat Vessel (CV) is a vacuum tight container, surrounding the entire Tokamak Basic Machine, which provides the vacuum for the superconducting magnets and constitutes part of the secondary confinement barrier. The vacuum environment is intended to avoid excessive thermal loads on the components operating at cryogenic temperatures.

At the current stage, the cryostat is designed as a single-wall vessel reinforced by ribs. It is made of three main parts: the main cylinder, a tori-spherical top lid and a support basement, as illustrated in Fig. 10.

The CV provides ports and penetrations to the vacuum vessel. Proper stainless-steel bellows allow for differential movements (simulated but still to be implemented).

CV must also provide openings for pipes connecting the equipment outside the Cryostat with the corresponding elements inside the Cryostat (e.g. magnet feeders, water cooling pipes, instrumentation feedthroughs, CV pumping systems) as well as manholes for providing shielded access ways for the technical personnel.

The maximum allowable leak rate shall be consistent with achieving the global leak rate requirements for the Cryostat Vacuum boundary. The main design parameters for CV are summarized in Table 2. Fig. 11 shows a poloidal section of the CV highlighting main dimensions and distances from magnet structures.

A first set of external ribs to increase bending stiffness has been conceptual designed as shown in Fig. 12.

3.1. Structural analysis

A shell model is adopted for the FE analyses. The material proprieties of the AISI-304 L are extracted from ITER SDC-IC code for Structural Analysis of the ITER In-vessel components. Considering a reference temperature of 20 °C (room temperature), the maximum allowable stress resulted as $\mathbf{S_m = 120\ MPa}$.

During normal operating condition, the pressure is supposed to be uniformly distributed on the external surface (0.1 MPa) and vacuum is supposed to be in the internal structure.

The preliminary results show that the rib-reinforced shell structure of the cryostat might withstand the loads due to normal operating conditions, since the equivalent Von Mises stress is always lower than the allowable limit, apart from some boundary areas which need to be reinforced in the novel CAD design (see, e.g. Fig. 13). In a next phase, we will perform a more detailed analysis in accordance with accredited rules for pressure vessels, evaluating also loads coming from accident conditions (i.e. in case of loss of fluid from the piping line).

4. Conclusions

The latest advancement (September 2018) in the conceptual design of the main containment structures of DTT fusion reactor was presented here. The work moved from the geometrical constraints imposed by the magnetic coils. Many other design constraints have been taken into account such as remote maintainability and space reservations for diagnostic and heating equipment.

The main vessel was designed as a double-wall structure. Custom supports were designed for the first wall, which was conveniently segmented in view of remote maintenance. The effects of the electromagnetic loads acting on the vacuum vessel, resulting from the current quench due to a plasma disruption, were evaluated.

The FE mechanical assessment showed that AISI 316L(N) stainless steel could be a suitable material to be used for DTT vacuum vessel, with the thicknesses hypothesized in this work

On the other side, the design drivers of the cryostat were mainly the minimization of cost and maximization of functionality. Therefore, the cryostat was conceived as a single-wall cylindrical vessel supported by a steel frame structure, which is currently still on development. The same structure will hold both the vacuum vessel and the magnets.

The results shown in this work are only preliminary: when detailed CAD models will be available, we will perform more detailed analysis in accordance with accredited rules for pressure vessels.

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