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Preliminary design and structural assessment of DTT in-vessel coil supports

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Abstract. The present work regards the design methodologies for a crucial component of the new thermonuclear fusion energy machine named "Divertor Tokamak Test facility" (DTT). The purpose of this experimental facility is the investigation of the thermal exhaust issue, a critical aspect in the view of DEMO construction, and future nuclear fusion reactors for commercial use. The construction of DTT machine is starting in the ENEA Site, Frascati, Italy. The poloidal magnet system in the proposed DTT includes a central solenoid divided into 6 independent modules, plus 6 external coils. The poloidal field system also includes six copper in-vessel coils, namely two in-vessel coils for radial and vertical plasma stabilization and control, and four out of six in-vessel divertor coils for magnetic control of scrape-off layer and strike point sweeping. This work aims to provide a preliminary design of the supports for the 6 in-vessel coils considering the Electromagnetic (EM) loads due to a plasma Downward (DW) Vertical Displacement Event (VDE) at the flat-top of plasma reference single null scenario. During a DW VDE a huge amount of current flows in the in-vessel coils (circumferential direction), whose interaction with the poloidal EM field generates strong EM forces. The electromagnetic loads have been calculated with MAXFEA, a two-dimensional finite elements code for the simulation of plasma equilibrium, and then applied to homogenized in-vessel coils in the structural analysis.

1. Introduction

Divertor Tokamak Test (DTT) facility is the ambitious Italian project aimed to investigate alternative power-exhaust solutions in the view of future nuclear fusion reactors [1]. DTT is proposed by the Italian Scientific Community, promoted and funded by the Italian Government and supported by EUROfusion and other International organizations. Nowadays, the construction is starting in the ENEA Site, Frascati, Italy. The requirements that DTT has to conserve to be relevant for DEMO realization, are both technological and physical, guaranteeing comparable performances despite the lower size [2]. The DTT poloidal magnet system, as discussed in [3], is composed of a superconducting Central Solenoid (CS), divided in six independent stacked modules, and six external Poloidal Field (PF) coils. The poloidal system also includes six copper in-vessel coils, namely two in-vessel coils for plasma radial and Vertical Stabilization (VS) and control (assumed IVS=50kA x 4 turns each), and four out of six In-vessel divertor Coil (IC) for magnetic control of Scrape-off Layer (SOL) and strike point sweeping (assumed ICs=60kA x 1 turn each).

One of the major concerns for the design of tokamak components is represented by plasma Vertical Displacement Events (VDE), caused by the loss of the plasma vertical position control [4]. As specified in next section, during a VDE a strong poloidal flux variation (PFV) occurs [5] resulting in huge eddy currents generated in metallic passive structures and of course in the in-vessel coils. The interaction of the induced currents with the poloidal **B** field produces huge forces on the structures, that can generate dynamic phenomena on most of the elements of the tokamak. Some of the authors of this work have analyzed this circumstance on DEMO Vacuum Vessel during different VDE [6].

The first part of this work is focused on the identification of Electro-Magnetic (EM) loads acting on VV and in-vessel coils, during the worst possible scenario: a plasma DownWard (DW) VDE at the End Of Flat-top (EOF) instant of plasma reference Single Null (SN) scenario, modeled with MAXFEA code [7]. Once evaluated, the EM forces were used in the second part of the work, whose purpose is to determine the best configuration for the in-vessel coils supports, among a set of alternatives defined according to the main geometrical characteristics of DTT VV. The selected configuration must be compliant with a set requirements. Being the study at a preliminary stage, an acceptance criteria related to the maximum deflection of the in-vessel coils obtained with a specific support configuration had not been defined yet. Thus, it was only checked that the displacement field, obtained through the FE analysis, did not present interference of other components.

Furthermore, in this stage of the design, the supports are modeled considering a preliminary geometry; thus, the outcomes of the FE analyses regarding the stress state of the supports are indicative. Nevertheless, they provide useful indications regarding the suitability of the supports numerosity and about their angular dimension. Consequently, the stress state of the supports is verified considering the stress linearization, according to ASME [8] procedures.

Additionally, another important aspect to be taken into account is the numerosity of the supports, that must be limited as much as possible to contain both raw materials and manufacturing costs.

Moreover, the comparative analysis of the in-vessel coil supports is performed considering five different configurations. After the determination of the best arrangement for the supports, this configuration is going to be further investigated and developed towards a definitive design.

2. Electromagnetic loads derivation

Making use of MAXFEA 2D axisymmetric code, it is possible to simulate the plasma equilibrium and evolution during a VDE. Induced currents and EM forces are the output of this simulation, subsequently introduced in the structural model in order to design the in-vessel coil supports. The SN equilibrium of full performance scenario, featuring a plasma current of $I_p = 5.5$ MA, at the End Of Flat-top (EOF), is observable in Fig. 1, and was chosen as the worst scenario and the starting point of the DW VDE simulation. The magnet configuration with their nomenclature is instead depicted in Fig. 2.

The procedure adopted to simulate the DW VDE inside MAXFEA environment relies on the assumptions reported below:

(i) A small step in voltage is imposed on the VS coils system after 10 ms to simulate the loss of position control and trigger the plasma movement.

(ii) Thermal Quench (TQ) at a given critical safety factor ($q_{95} \sim 2$) as $\Delta\beta \sim 90\%$ in 1 ms is assumed.

(iii) Current Quench (CQ) duration of 4ms was considered.

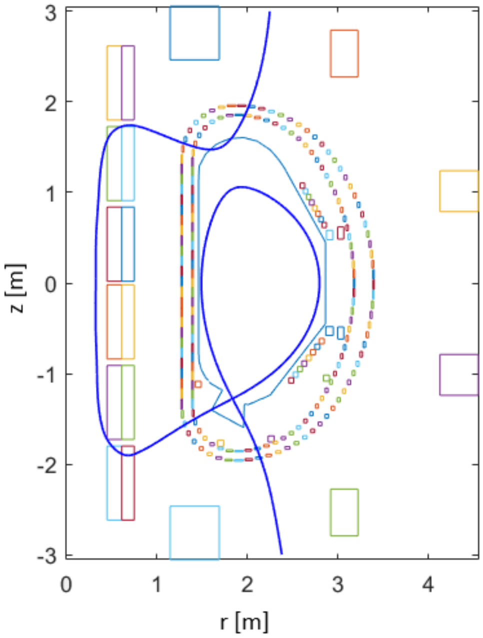

Figure 1. SN equilibrium configuration @EOF plasma reference scenario, in r and z coordinates.

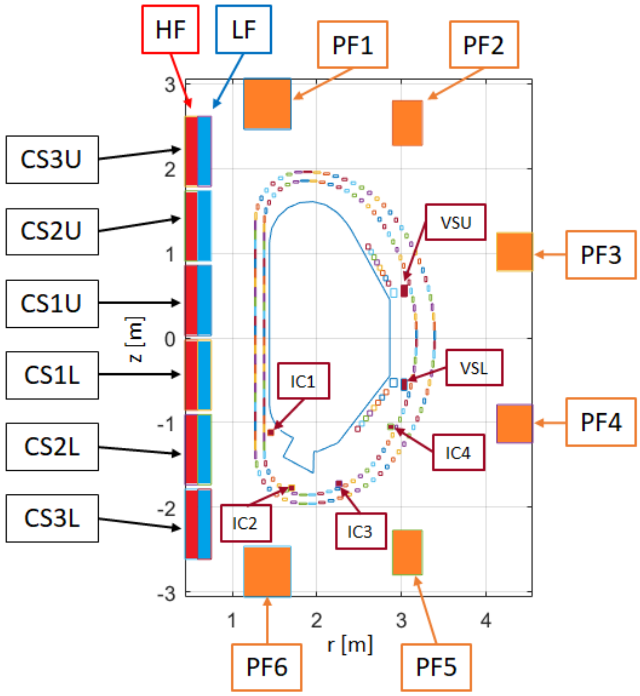

Figure 2. DTT poloidal magnet system and nomenclature.

In practice, starting from the equilibrium configuration (i.e. EOF of SN scenario) the plasma starts to move downward as a consequence of imposed voltage on the VS coils. The downward movement goes ahead until the critical safety factor q_{95} reaches a value of 2. At this point, the TQ in 1 ms is imposed as $\Delta\beta$ drop. After the TQ the plasma touches the divertor triggering the CQ, thus generating huge localized Halo currents (not evaluated in this model), and then shuts down in few ms ($\sim 4ms$).

With regard to the geometry, the VV shells and the stabilizing plates were discretized with rectangles and squares, equivalent from an electrical point of view to a continuous axisymmetric profile. As far as the material is concerned, for metallic components the AISI 316L(N) stainless steel was adopted, whilst copper was used for the conductors. The main electrical properties of these materials are reported in Table 1. The in-vessel coils section was considered, in a conservative way, entirely made of copper.

Table 1. Electrical properties of 316L(N) steel and copper.

	ρ [$\mu\Omega$m]	Relative Permeability [$-$]
AISI 316L(N) steel	0.760	1
Pure Copper	0.017	1

3. FE structural modeling and EM loads coupling

The structural analysis was performed taking into account the DTT VV with in-vessels coils and their supports. In particular, it was considered an assembly of 3 sectors since the support

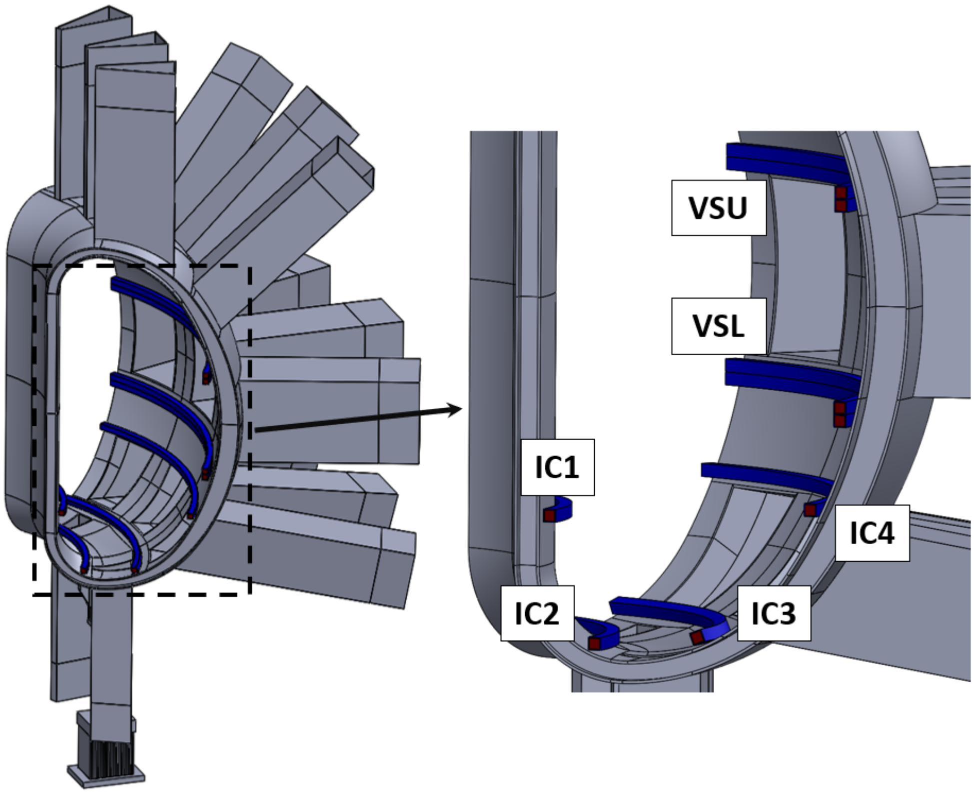

Figure 3. CAD model of VV, in-vessel coils and their supports.

leg is alternatively present in the VV sectors, as shown in Fig. 3; each sector features an angular extension of 20°. The main VV structural components such as inner and outer shells, ports, toroidal and poloidal ribs were considered for the analysis.

The FE model was realized in ANSYS Mechanical APDL with structural solid elements having 8 nodes and 3 DOFs per node, see Fig. 4. A cyclic symmetry model could be carried out by employing this geometry and due to the symmetry of the loads. A mapped mesh is obtained with 1,423,046 brick solid elements and 1,144,556 nodes.

Considering that the analysis was performed on a very preliminary geometry configuration of the in-vessel coils and their supports, the interaction of these components was modeled exploiting a simplified technique. The elements at the interface between in-vessel coils and supports were connected with a set of spring elements. In particular, three different spring elements were employed to define the mutual relationship along each coordinate direction (Fig.5). Stiffness calibration of spring elements was diversified for the three directions. A sub-modeling and a specific FE analysis on a single support and an in-vessel coil segment was performed considering a contact pair with friction; the stiffness of the spring elements along the normal to the interface was set to obtain the value of penetration measured in the sub-model and, for the other two directions, parallel to the contact surface, the stiffness of spring elements was set to obtain comparable values of slip.

Furthermore, bonded contact regions were utilized to obtain the connection between the VV mesh and the in-vessel coil supports one, as shown in Fig. 5. This choice allows to reduce the effort required for the parameterization and thus to simplify the overall optimization procedure.

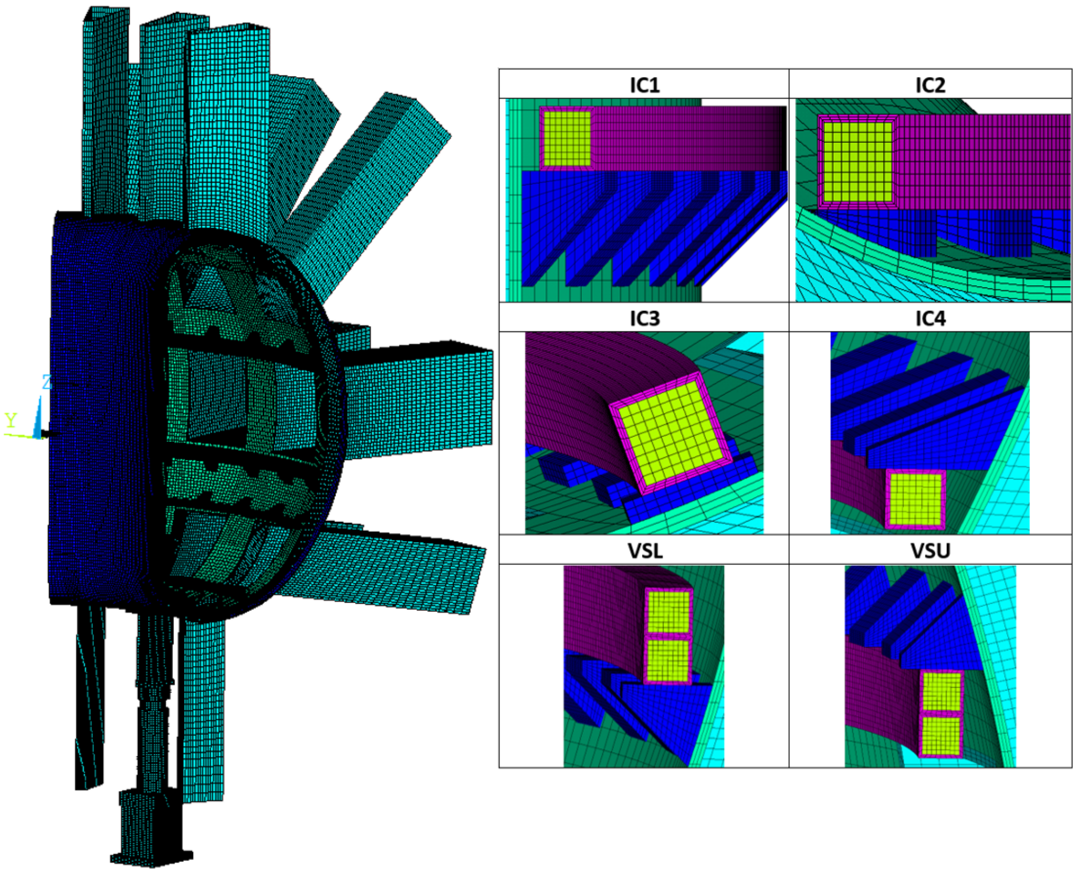

Figure 4. Structural FE model of the VV (left), particular of the in-vessel coils and their supports (right).

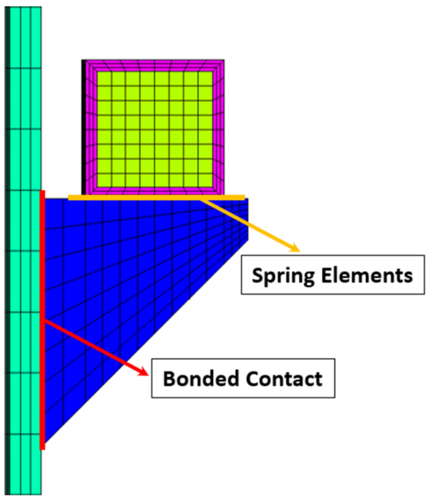

Figure 5. In-vessel coil and supports constraints.

As regards the constraint conditions of the structure, the support leg of the VV central sector was fully clamped. Additionally, constraint equations for the cyclic symmetry were applied at

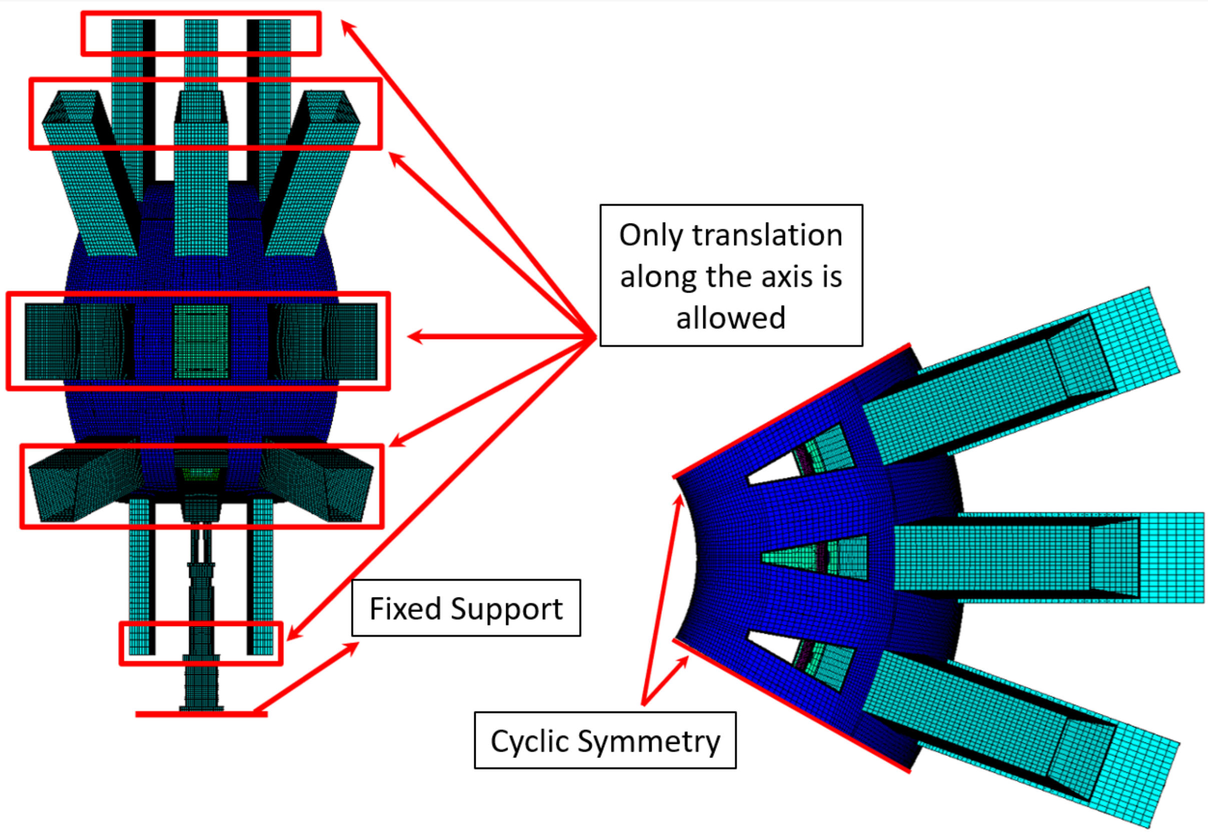

Figure 6. Kinematic boundary conditions of the FE model.

the boundary edges of the FE model. The free ends of the ports connected to the VV were further constrained; the translation along their axis was the only allowed movement, Fig. 6. In this way, the joining of ports with cryostat, realized by bellows components, has been simulated.

Then, the VDE loads previously obtained by means of EM analysis were mapped, as force densities, on the structural mesh. The 3D map of load densities can be easily obtained by revolving the 2D map extracted from MAXFEA. Force densities have been adequately mapped to ensure conservation of force resultants.

The material properties of the AISI 316L(N) steel, utilized for the in-vessel coils jacket and the supports, and of the pure copper present in the core of the in-vessel coils are derived at the temperature of 60°C. These properties are reported in Table 2.

Table 2. Elastic properties of the materials at design temperature $T_{DES} = 60°$C.

	E [GPa]	$\nu[-]$
AISI 316L(N) steel	196	0.3
Pure Copper	117	0.3

For the structural analyses the in-vessel coils were modeled with an equivalent cross-section. In terms of percentage area the steel jacket covers the 30% of the overall area, and pure copper core for the remaining 70%. The coils jacket and the pure copper core of the in-vessel coils are represented respectively in magenta and yellow in Fig. 5.

4. Comparative analysis of in-vessel coil supports configurations

The purpose of this work is to define a procedure for finding the optimal shape and positioning of the in-vessel coil supports, defining their circumferential extension and their numerosity. In-vessel coil supports must be able to bear electromagnetic loads. In particular, the worst load condition taken into account for this optimization is the Vertical Displacement Event (VDE), in addition to gravity loads. The configuration of the supports must ensure a controlled deflection of coils, too; in fact, excessive deformations and distortions could damage the jacket of the coils or compromise their electromagnetic function.

The arrangement of the supports must be symmetrical within the three sectors, thus ensuring cyclic symmetry for the entire tokamak. The electromagnetic loads present during the VDE are axisymmetric and have a different radial and axial resultant forces in each coil. For these reasons, it was decided to test configurations with identical and evenly spaced supports for each type of coil. These choices facilitate the full exploitation of the supports material and also help to contain construction costs.

The optimal configuration must keep the number and size of supports to a minimum, as well as meeting all the requirements described above, such as the restraint of both the in-vessel coils deformation and the supports stress. Such expedients make it possible to reduce costs and the overall footprint, in order to increase the design flexibility of other components

A specific design of the supports is needed for every in-vessel coil to ensure exact positioning and fastening to the VV. In the comparative numerical analyses, elementary geometries of supports have been adopted, to develop the best configuration for the supports. At this preliminary stage, the optimized design of supports would have been useless as the coils are still in the definition phase. In Fig. 7 are reported the six types of in-vessel coils and the related supports.

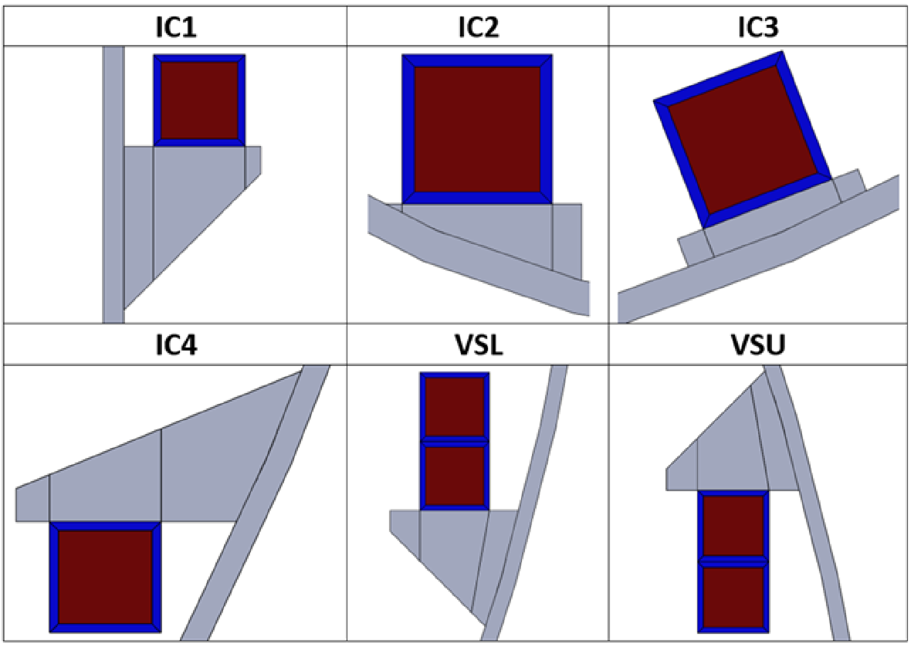

Figure 7. Six types of in-vessel coils and related supports.

The template of the supports was sketched in order to not occupy the openings of the ports, and to have a possible footprint usable for future optimization. Through the numerical simulations, it was ascertained that the change in the configuration of the supports of one coil

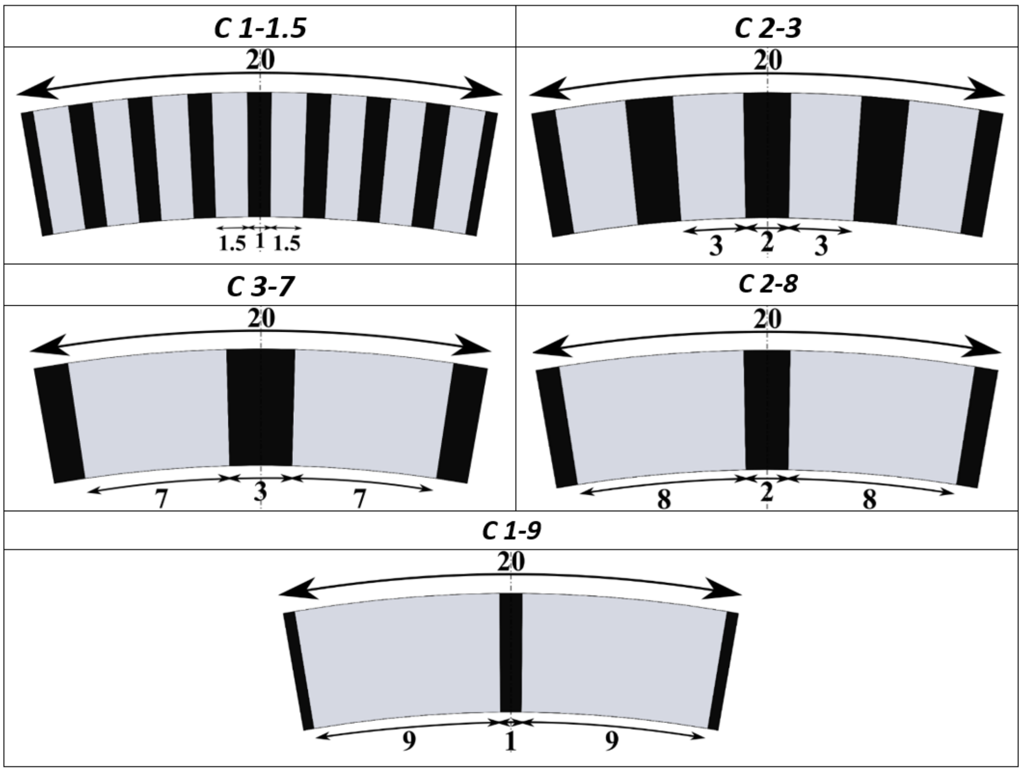

Figure 8. Supports configurations.

does not influence the mechanical behavior of other coils. In other words, optimization can be carried out on individual coils without analyzing the mutual influence between them. Five different configurations of in-vessel coil supports were defined and tested. The configurations were obtained by optimizing the circumferential extension and spacing of supports. All the other supports dimensions were fixed. The five configurations of supports in a single sector of the VV with an angular extension of 20° are shown in Fig. 8. In every configuration, it is reported the angular extension of the supports, represented in black, and their angular spacing, represented in gray. All the angles are expressed in degrees. The total number of supports per in-vessel coil, for every configuration, is reported in Table 3.

Table 3. Total number of in-vessel coil supports for each configuration.

C1-1.5	C2-3	C3-7	C2-8	C1-9
144	72	36	36	36

5. Results

In this section the electromagnetic and mechanical results of the aforementioned simulations are reported. As previously stated, EM analysis provides the load data of the entire model simulated.

The electromagnetic loads impacting the most on the structural assessment of the supports are the vertical peak forces on in-vessel coils and, to a lower extent, the radial peak forces on the same elements. These forces are due to the interaction between the induced currents in the in-vessel coils and the **B** field during the plasma Downward Vertical Displacement Event.

In Fig. 9, with cyan color, the time evolution of plasma current centroid during DW VDE is represented, whilst the red, blue and black curves, considered in this order, reproduce the plasma Last Closed Flux Surface (LCFS) time evolution, from equilibrium to shut down.

The current carried by the plasma through the time is instead shown in Fig. 10. The fast current drop phase is related to CQ.

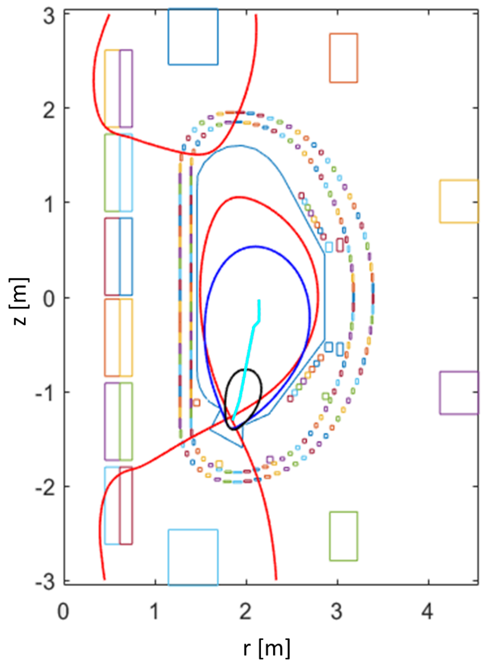

Figure 9. Time evolution of plasma current centroid (cyan curve) and plasma LCFS trhought time (red, blue and black curves in this order).

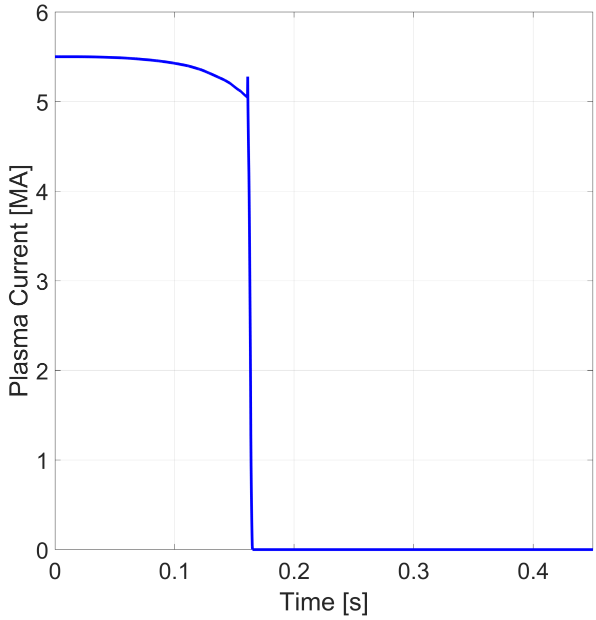

Figure 10. Plasma current vs. time.

Fig. 11 shows the graph of the induced currents of the six in-vessel coils during the DW VDE. The time occurrence of the current peaks and their relative values are shown in Table 4. As it can be noticed the greater peak value is obtained for IC1 (I_{IC1} = 441.4 kA). The total vertical peak forces and the radial ones are reported in Table 5. Also for vertical force, the most loaded coil is IC1, with a resultant downward force of 0.54 MN.

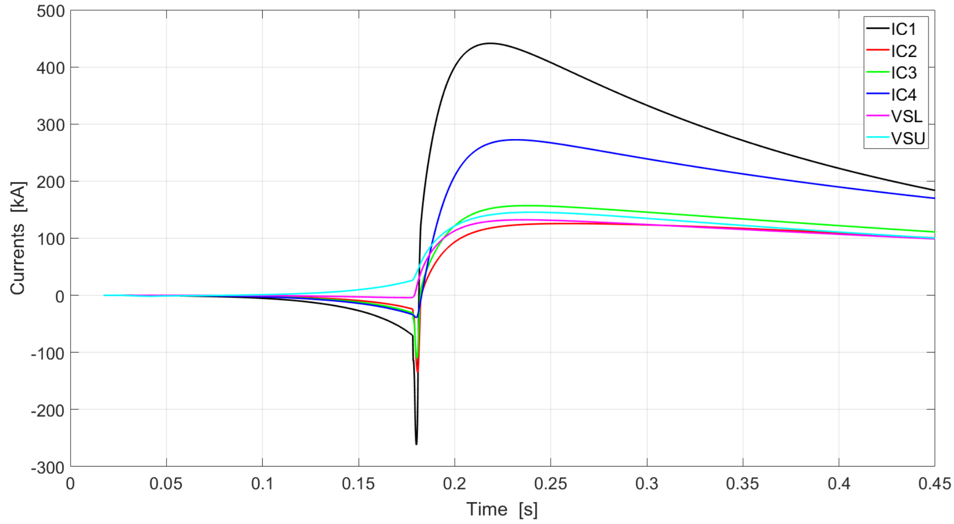

Figure 11. Induced currents in the in-vessel coils during the DWVDE.

Table 4. Induced currents on in-vessel coils.

	t_{peak} [ms]	I_{peak} [kA]
IC1	0.201	441.4
IC2	0.242	125.7
IC3	0.221	157.1
IC4	0.215	272.5
VSL	0.220	132.2
VSU	0.223	145.5

Table 5. Total Vertical and Radial Forces acting on in-vessel coil.

	Radial force [MN]	Vertical force [MN]
IC1	0.83	−0.54
IC2	0.10	−0.35
IC3	0.25	−0.13
IC4	0.55	0.18
VSL	1.35	−0.03
VSU	1.70	−0.14

The values reported in Table 5 were used as input of structural analysis, aimed to preliminary design the in-vessel coil supports.

In order to choose the best supports configuration for every coil, five different structural analyses were performed. In every simulation, the same support configuration is tested and adopted for all the coils. This is possible thanks to the absence of mutual influence among the different coils. In this preliminary structural study of the supports configurations, a useful

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procedure to study the stress state is the stress linearization method. This method is reported in ASME BPV Code, Section VIII, Division 2 [8] and also recalled in the Magnet Structural Design Criteria of ITER [9]. The stress linearization allows to obtain the membrane and bending stresses from the total stress in the component thickness.

The ASME code also provides the limit of equivalent stresses of membrane (P_L) and membrane plus bending ($P_L + P_B$) components at design temperature:

$$P_L < S_{PL} \tag{1}$$

$$P_L + P_B < S_{PL} \tag{2}$$

where S_{PL} is the allowable limit on the local primary membrane and local primary membrane plus bending stress. In Table 6 are reported the strength properties of AISI 316L(N) at design temperature. The supports have the same design temperature of the VV, i.e. $T_{DES} = 60°\text{C}$.

The stress linearization was applied for all the in-vessel coil supports. The membrane and membrane plus bending results of the most loaded support of every coil in each configuration are reported in Table 7 and 8. In these tables, the results reported in green meet the allowable limits, while the results in red are above the S_{PL} value of stress. A summary of the configurations respecting both the allowable limits is shown in Table 9. The definitive, in-vessel coil supports configurations are selected to minimize mass and technological operations among those agreeing with the allowable stress limit. Selected supports configuration for each in-vessels coil is reported in Table 10.

The IC4, VSL and VSU coils require the highest number of support configurations, mainly because they have the highest radial dimension and are therefore circumferentially more extended than the other coils.

In this preliminary phase, as the limits of deformation or displacement of the coils were not defined yet, the absence of any possible component penetration was checked and guaranteed with the chosen configurations.

Table 6. Strength Properties of AISI 316L(N) at design temperature $T_{DES} = 60°\text{C}$.

S_y [MPa]	$S_m = \frac{2}{3}\ S_y$ [MPa]	$S_{PL=1.5\ S_m}$ [MPa]
190	127	190

Table 7. Membrane Stress [MPa] of the most loaded support for each configuration.

	Membrane Stress [MPa]				
	C1-1.5	C2-3	C3-7	C2-8	C1-9
IC1	93.29	44.42	60.01	152.10	154.20
IC2	42.57	44.72	23.62	21.44	27.21
IC3	45.17	45.31	63.92	91.84	146.60
IC4	65.70	64.88	91.44	111.70	169.80
VSL	83.84	69.68	78.24	108.80	173.30
VSU	124.50	117.20	141.80	194.40	275.10

Table 8. Membrane + Bending Stress [MPa] of the most loaded support for each configuration.

	Membrane + Bending Stress [MPa]				
	C1-1.5	C2-3	C3-7	C2-8	C1-9
IC1	137.80	125.00	151.00	175.40	254.20
IC2	52.70	65.14	41.92	48.85	65.93
IC3	58.56	99.67	69.60	103.90	164.20
IC4	116.60	133.70	200.70	275.20	406.70
VSL	143.00	134.30	185.00	254.50	235.00
VSU	203.40	157.60	238.10	328.70	422.40

Table 9. Summary of the configurations respecting both the membrane and membrane + bending allowable stress limits.

	C1-1.5	C2-3	C3-7	C2-8	C1-9
IC1	OK	OK	OK	OK	NO
IC2	OK	OK	OK	OK	OK
IC3	OK	OK	OK	OK	OK
IC4	OK	OK	NO	NO	NO
VSL	OK	OK	OK	NO	NO
VSU	NO	OK	NO	NO	NO

Table 10. Selected supports configuration for each in-vessels coils.

IC1	IC2	IC3	IC4	VSL	VSU
C2-8	C1-9	C1-9	C2-3	C3-7	C2-3

6. Conclusions

The main goal of the presented work is the definition of a workflow for the design of the in-vessel coils support system. The design approach combines the EM FE analysis for the definition of the Down Ward Vertical Displacement Event, i.e. the most severe working condition, and the structural FE analysis for the assessment of the supports.

Different configurations of the supports were investigated; first, a selection according to structural criteria was executed to determine the admissible ones. Then, for each in-vessel coil, the configuration characterized by the lower mass and manufacturing processes was selected. The ASME Codes were considered for structural verification.

With regard to future developments, the geometry of the supports is going to be refined towards a definitive configuration. The structural FE model is going to be improved including fillet radii of the supports and contact pairs between the in-vessel coils and their supports.

7. Acknowledgments

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