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Vertical displacement events analysis using MAXFEA code in combination with ANSYS APDL in the final design stage of the DTT vacuum vessel

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A R T I C L E I N F O

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A B S T R A C T

In the context of the Divertor Tokamak Test facility (DTT) project, a recently developed procedure based on the use of MAXFEA code in combination with ANSYS APDL already presented in [1] has been applied to study the EM and structural response of the DTT vacuum vessel (VV) during plasma Vertical Displacement Events (VDEs). From this study, it has emerged that the vacuum vessel mechanical response is acceptable in all of the scenarios but, during a particular event, namely the down-ward VDE slow scenario, a localized stress concentration in the lower side of the vacuum vessel has emerged. Downstream this analysis, mechanical reinforcements in this zone have been introduced in order to optimize the design. The aim of the paper is to show the successful application of this procedure in this context and its reliability as supporting tool in the final stage optimization design of these kind of components. The abovementioned down-ward VDE slow scenario is reported, showing a vertical force peak of around -10MN as the result of the combination of eddy and halo currents during the Current Quench (CQ). The structural analysis highlights that the EM loads occurring at this time instant produce a stress concentration localized in correspondence of the connection of the pedestal with the VV outer shell. This stress concentration has suggested to reinforce this zone in order to optimize the vacuum vessel design.

1. Introduction

Divertor Tokamak Test Facility (DTT) is an experimental device whose construction is already underway in the ENEA site of Frascati. The DTT main aim is to bridge the gap between ITER and the future fusion reactors, such as DEMO, from power exhaust point of view. In order to be relevant for DEMO exploitation, DTT have to feature similar power density values [2]. The main machine parameters are resumed in the next table (Table 1), whilst the complete list can be found in [3]:

In the design phase of the Vacuum Vessel (VV) and in-vessel components one of the major concerns is represented by plasma disruptions (Major Disruptions (MDs) and Vertical Displacement Events (VDEs)), often occurring during tokamaks operations as consequences of transient plasma perturbations [4]. In such events, Eddy currents, due to both Poloidal and Toroidal Field Variations (PFV and TFV), and halo current (HC) are the main sources of electromagnetic loads on the passive structures. The effects of such loads on VV and in-vessel components were studied in depth through years on several existing machines.

In [5], the authors analyze the structural response of the Vacuum Vessel and Plasma Facing Components (PFCs) to the eddy currents and related electro-magnetic forces due to plasma disruptions on EAST tokamak, highlighting how eddy currents distribution, and then the mechanical response, vary through the PFCs. Subsequent studies in EAST [6] were carried out in order to verify VV and PFCs stresses and displacements during VDEs and possible enhancement of the PFCs supports have been proposed. Similar analysis was also performed in the contest of the China Fusion Engineering Test Reactor (CFETR) [7]. Here, a simplified but practical model of CFETR developed in ANSYS is used to analyze the electro-magnetic and structural behavior of the VV with respect to plasma MDs that were considered as reference scenarios for

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Table 1
Main DTT parameters for Single Null magnetic configuration.

R [m]	a [m]	q_{95}	I_p [MA]	B_t [T]	H_{98}	Pulse length [s]
2.19	0.70	3	5.5	6.0	1.0	100

the design. Analogous studies were conducted both in ITER and DEMO devices. *Giorgetti* et al. [8] have calculated the DEMO VV peak displacements and accelerations during 4 different VDEs. Transient analyses have been performed on a 360° FE model of the vessel. In this study the interaction between the vessel and the TF coils was also included in terms of stiffness and damping, whose values were obtained from previous Electromagnetic (EM) analyses. Instead, in [9] a recent overview of the EM methodology applied to support the pre-conceptual design phase of the Breeding Blanket is provided, with particular emphasis to the EM loads generated during plasma VDEs and MDs.

The requirement of withstanding the loads from disruptions and VDEs has a huge impact on the design of the fusion devices. In [10], different configurations of the supports for DEMO VV have been analyzed during VDEs, showing how the safest solution is reached considering a support acting on the lower ports. The study of influence of the disruptions in the fusion machine design is important even in the early stage of the design process. Nowadays, the availability of a fast simulation tool for evaluating different design options and also able to perform parametric analysis is very attractive to verify different concepts and drive the design. In response to this, the authors in [11] proposed a methodology based on multi-physics modeling capability offered by the Comsol software. This tool consists in coupled simulations based on the data sharing between 2D axisymmetric and 3D models.

So far, preliminary multiphysical analyses were carried out on the DTT machine too, in order to develop the conceptual design of the VV [12]. In particular, structural analyses have been conducted considering the EM loads from a fast upper and lower VDEs obtained from the MAXFEA software [13].

Since then, the design of the DTT VV has moved on and it is currently in the final design stage. Therefore, the necessity to analyze in detail the behavior of this component under the EM loads coming from plasma disruptions has emerged in order to verify the design or drive further modifications in the iterative design process. In this context, a study to analyze the mechanical and electro-magnetic behavior of the DTT VV has been carried out considering different types of plasma up-ward and down-ward VDEs, exploring different duration of the Current Quench (CQ) (fast events CQ 4 ms, slow events CQ 40 ms). To perform this analysis, the recently developed procedure based on the use of MAXFEA code in combination with ANSYS APDL [1] has been successfully applied. From this study, it has emerged that the VV mechanical response is acceptable in all of the scenarios but, during a particular event, namely the Downward VDE (DVDE) slow scenario, a stress concentration in correspondence of the connection of the pedestal with the VV outer shell has emerged. As a consequence, mechanical reinforcement in this region has been introduced in order to obtain an optimal design of the VV.

In this paper, the EM and mechanical response of the DTT VV during this DVDE slow event is presented. The aim of the paper is to show the successful application of this novel procedure in the context of the DTT project and its reliability as design supporting tool in the final design stage of these kind of components.

2. Methodology

In this paper, the procedure based on the use of MAXFEA code in combination with ANSYS APDL presented in [1] is applied to study the EM and structural behavior of the DTT VV during a plasma VDE. The

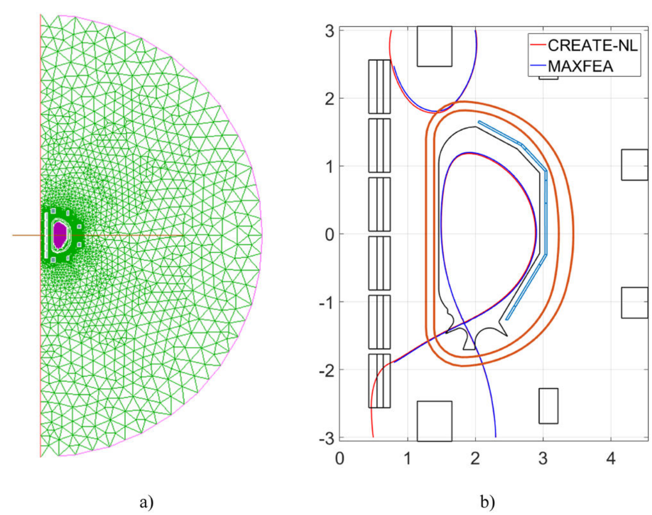

Fig. 2. MAXFEA model a) Overview of the whole FEM domain b) Zoom in the plasma region. The VV and the stabilizing plate are represented in dark red and dark blue, respectively. The reference SN reproduced by means of MAXFEA is reported in blue, red for the CREATE-NL.

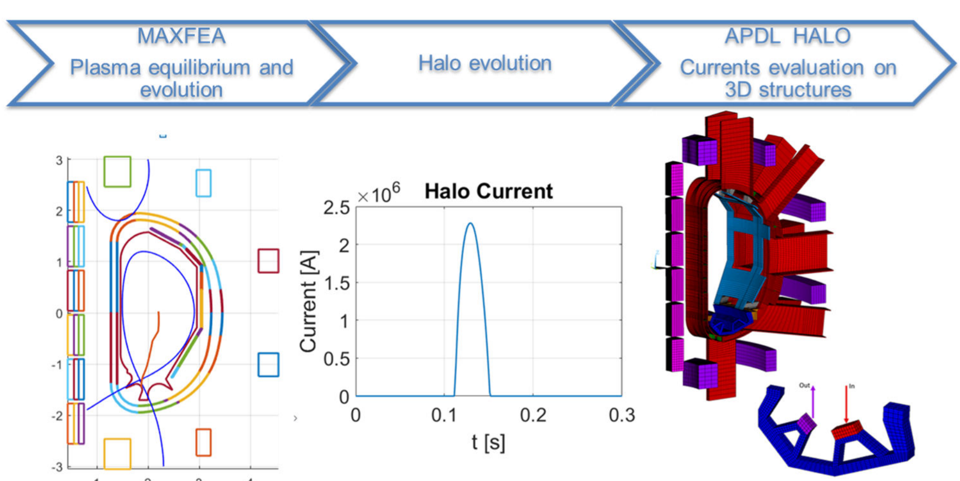

Fig. 1. Adopted workflow for the evaluation of currents and forces on 3D structures coming from HC: a) MAXFEA simulation of plasma equilibrium and evolution according to disruption scenario; b) The global HC expected is extracted from MAXFEA simulation; c) The HC is injected into the structures in the 3D APDL model assuming possible in and out locations.

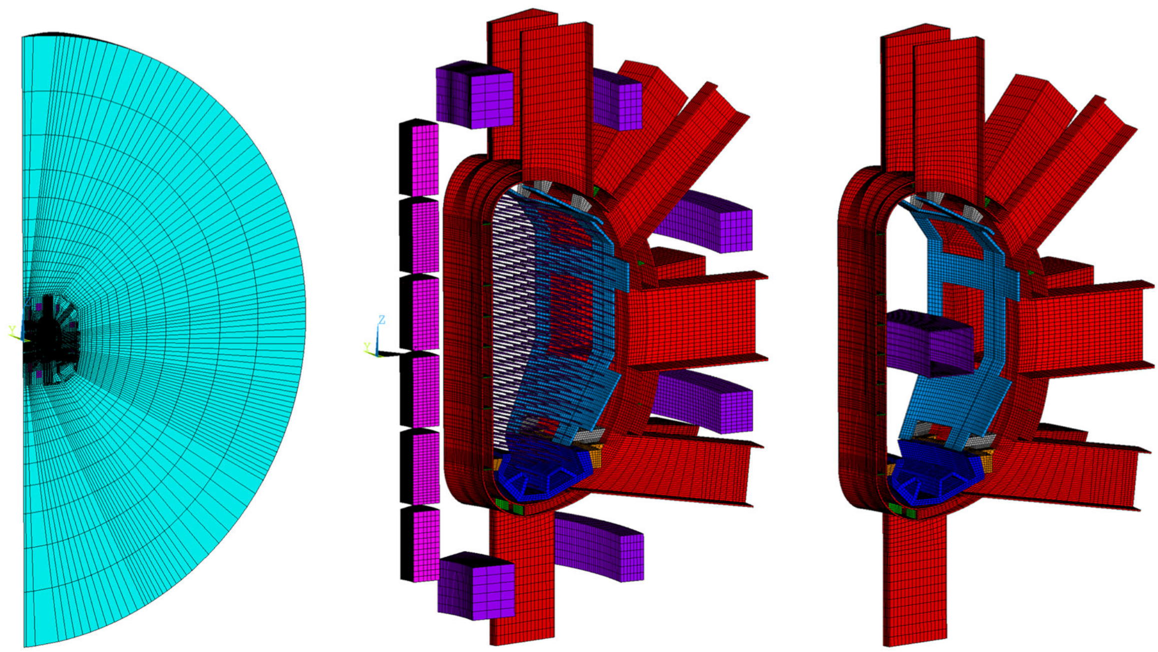

Fig. 3. 3D APDL EM model: overview of the whole model with region (left), mesh with filaments for PFV analysis (center) and mesh with torus for TFV analysis (right).

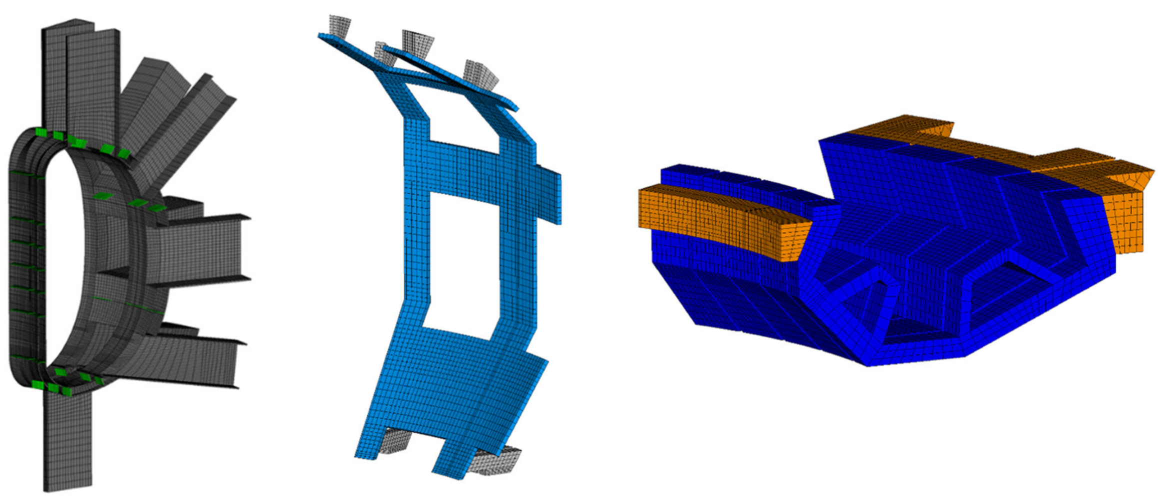

Fig. 4. 3D APDL EM model mesh details: toroidal ribs depicted in green (left), stabilizing plates and support, depicted in cyan and gray respectively (center), divertor cassettes and supports depicted in blu and orange respectively (right).

scope of the paper is to demonstrate the reliability of this tool in supporting the final stage design of the DTT VV. The work herein presented is divided in two main parts. The first one concerns the transient EM simulation of the plasma disruption event. From this analysis the induced currents and forces are extrapolated over time and then used as input for static structural simulations.

2.1. EM analysis

The three main sources of EM loads on passive structures during plasma disruptions are: poloidal and toroidal field variations (PFV and TFV), mainly occurring during the Thermal Quench (TQ) and the Current Quench (CQ), and the HC, taking place during CQ. Eddy currents coming from PFV are mainly in toroidal direction and mostly interact with poloidal EM field. On the other hand, the currents induced by TFV and HC are mainly poloidal and mostly interact with the toroidal EM field. These forces are in-plane forces. The misalignment between the poloidal components of the eddy and halo currents and the poloidal magnetic field could produce locally out of plane forces within the passive structures and also a net force. However, the latter is typically negligible with respect to the in-plane net forces [1].

Concerning the PFV and TFV analyses, the adopted methodology was already validated on DEMO single null configuration and fully described in [1]. In order to estimate plasma PFV and TFV on a 3D model the MAXFEA axisymmetric code is used in combination with ANSYS APDL. In particular, the plasma equilibrium and evolution, firstly simulated inside the MAXFEA, is then introduced inside the APDL 3D model. Plasma PFV is simulated by means of a set of filaments, whilst TFV is reproduced via a thin torus onto which an equivalent poloidal current is applied.

As discussed in [1], MAXFEA also provides information on the global halo current expected during the plasma evolution, but without tracking detailed HC paths into the structures. In order to evaluate 3D detailed HC distribution in the structures, the following approach is proposed

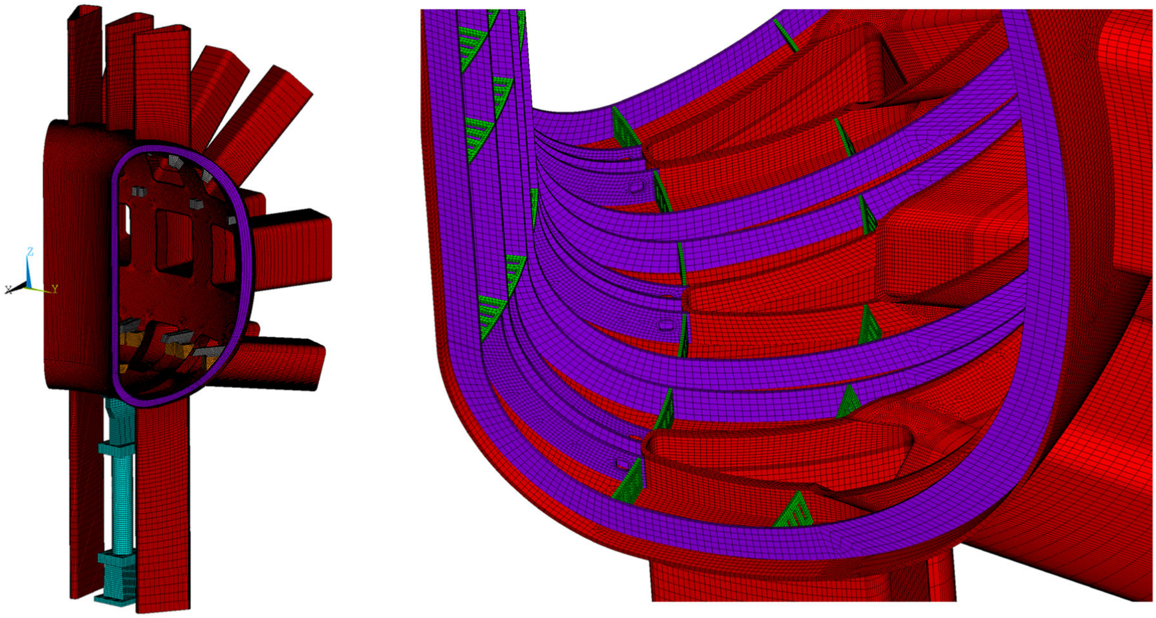

Fig. 5. 3D APDL 60° structural model: global mesh (left) and overview of the bottom part of the vessel in which the inner shell is hidden to show the toroidal and poloidal ribs, depicted in green and purple respectively (right).

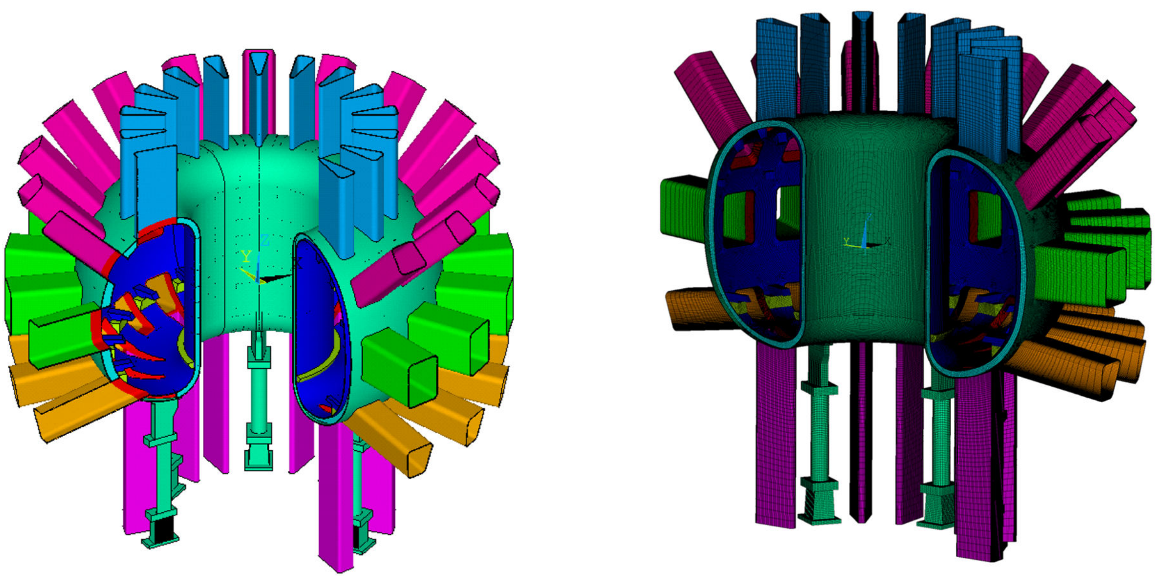

Fig. 6. APDL 360° mesh model overview (half model).

(the workflow is depicted in Fig. 1). Firstly, in analogy with what it was done for ITER [14], possible in and out locations for the HC are assumed according with MAXFEA simulation (Fig. 1c). These in and out locations represent the interface between the ex-plasma halo region and the PFCs. Then, starting from the information on the *global* HC expected from the previous MAXFEA simulation (Fig. 1b), the HC is injected through the considered in and out locations in the 3D ANSYS model.

Finally, all the EM contributions (PFV, TFV and HC) obtained with 3D simulations, are combined in the post-processing phase with a linear superposition. In particular, as shown in the next Section, the 3D model was developed with a feature that the same mesh can be used for PFV, TFV and HC analyses, merely changing the element type and the properties of specified set of elements. In this way, the various EM contributions can be easily added element by element, facilitating the post-processing operations.

One of the main advantages of the proposed approach is that the analyses are completely modular: each EM contribution on each component can be isolated and deeply analysed if needed. This circumstance permits to divide non-trivial evolutions of the currents, fields and forces in more elementary sub-contributions, facilitating a deeper understanding of the phenomenon. Clearly, this approach is possible until ferromagnetic materials are not present in the model, as for this case. Nevertheless, this procedure can be extended also to the case in which ferromagnetic non-linearities have to be considered in much similar fashion to what presented [9], being careful to use the appropriate problem formulation in ANSYS.

In this paper, the present methodology is applied to study a DVDE scenario with a CQ duration of 40 ms. All the EM contributions are computed and then applied to the structural model. As shown later in the next section, it was analyzed also a case in which a Toroidal Peaking Factor (TPF) is considered in the HC distribution. In particular, the TPF was introduced applying the following sinusoidal function:

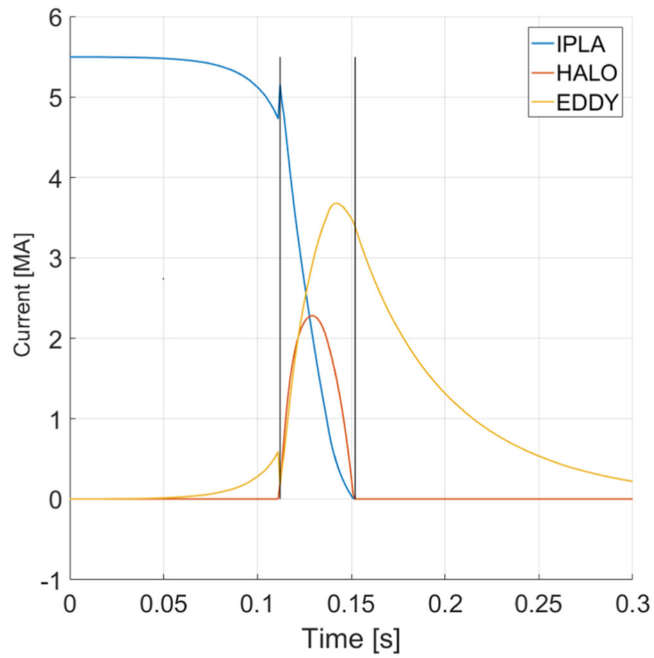

Fig. 7. MAXFEA plasma current (blue curve), eddy currents (yellow curve) and halo currents (red curve).

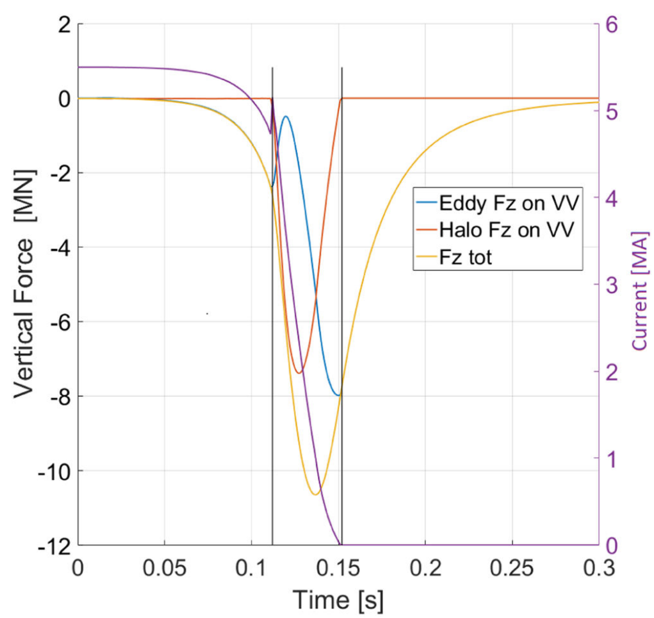

Fig. 8. MAXFEA Vertical Force on the VV due the eddy currents (blue curve, refers to left ordinate axis), due to the halo currents (red curve, refers to left ordinate axis), due to eddy+halo (yellow curve, refers to left ordinate axis) and Plasma current (purple curve, refers to the right ordinate axis).

$$F_{HC-TPF} = F_{HC}(1 + sin\theta)$$

where $0 \leq \theta \leq \pi$ is the toroidal angle. As consequence, in this case the EM halo forces are zero for $\theta = 0$ and assume twice the nominal value for $\theta = \pi$.

2.2. Mechanical analysis

The 3D structural model has to be realized with different features with respect to a 3D EM simulation, implying dissimilar mesh models.

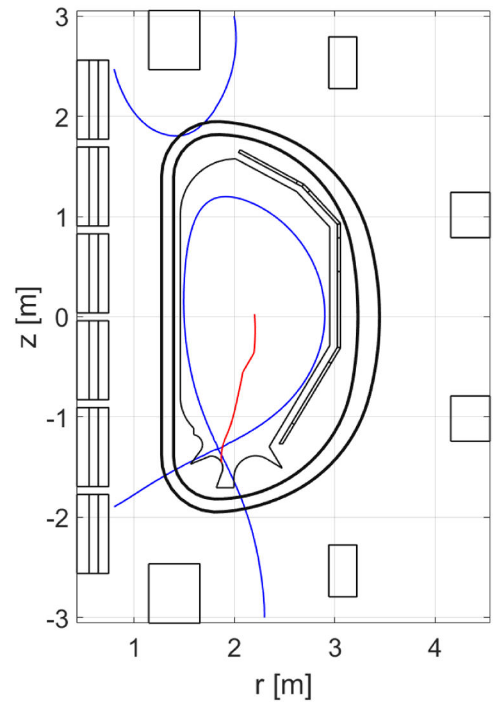

Fig. 9. Plasma initial equilibrium (SN @SOF) and plasma centroid (RJ-ZJ) movement during the DVDE slow.

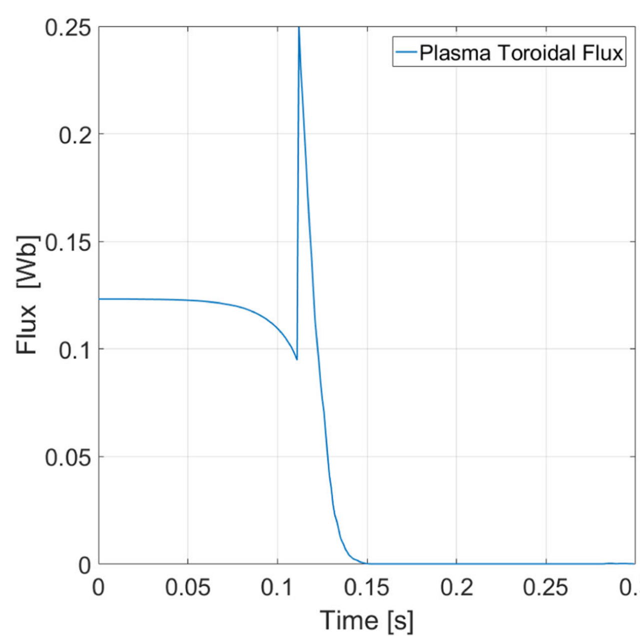

Fig. 10. Plasma TFV evolution during the DVDE.

Hence, the loads coming from EM simulations, in terms of force densities, have to be interpolated on the mechanical mesh model.

During the CQ phase of the DVDE slow scenario, a vertical force peak was observed as the result of a combination of both eddy and halo currents. The VV structural response is studied at this critical time instant.

3. FE models

The DTT VV consists of two stainless steel (SS) shells of 15 mm thick each, separated by several toroidal and poloidal ribs. Each VV sector is

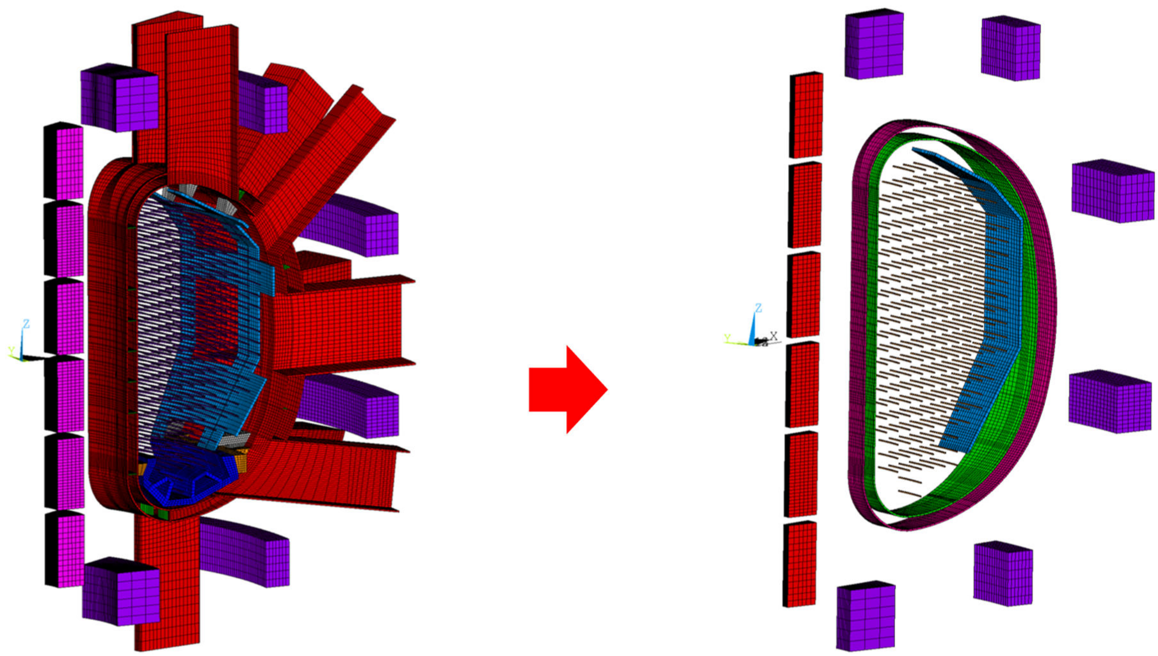

Fig. 11. 3D Model with filaments for PFV analysis (left) and Model Test (right), obtained from the 3D Model merely changing the material properties and the element degrees of freedom of specified set of elements.

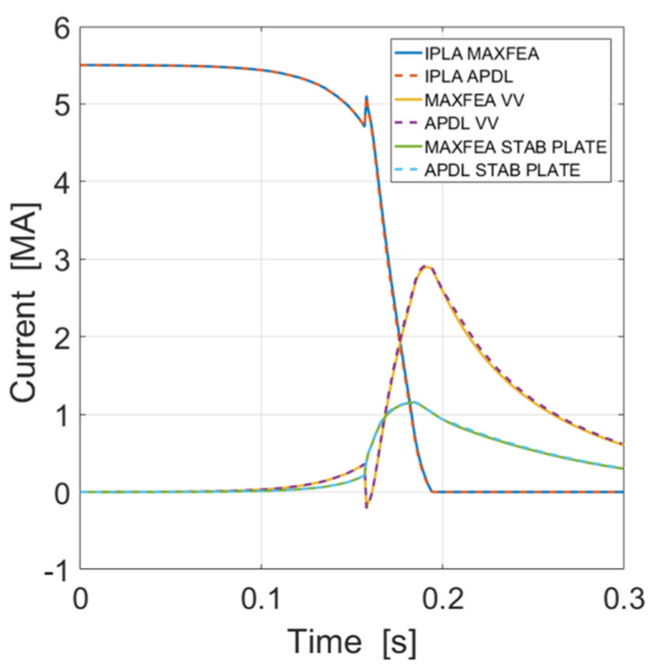

Fig. 12. Currents MAXFEA TESTCASE vs APDL Model TEST.

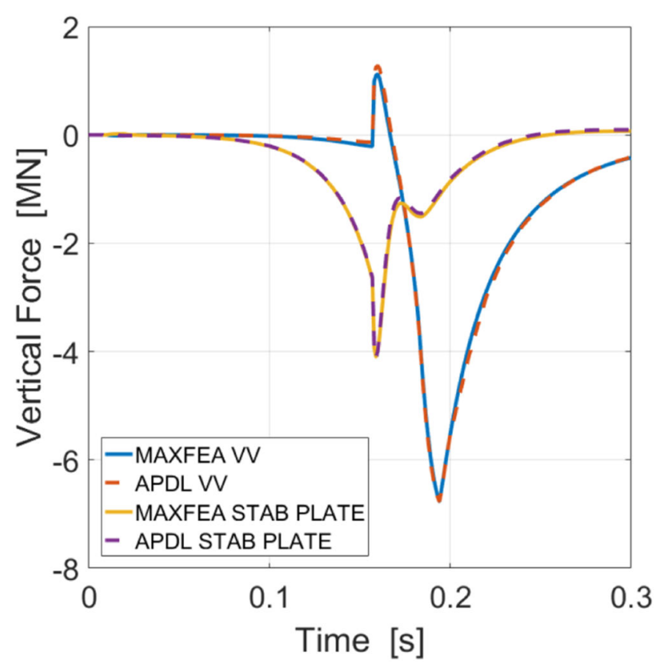

Fig. 13. Vertical Force due to eddy currents over 360°: MAXFEA TESTCASE vs APDL Model TEST.

20° wider in toroidal direction and feature 5 ports. In only 6 out of 18 sectors the lower port is replaced by the VV pedestal (located every 60°). The considered in-vessel components are: a preliminary design of the divertor cassette and its supports (i.e. inner and outer rails), and stabilizing plates with supports, that feature a toroidal continuity.

3.1. EM models

As mentioned before, the proposed approach relies on two EM models, namely MAXFEA 2D axisymmetric and 3D ANSYS APDL, and a 3D mechanical model, always developed inside ANSYS APDL environment.

3.1.1. MAXFEA 2D axisymmetric model

In this section the MAXFEA model is exposed. The developed model, whose overview is given in Fig. 2, includes:

- CS and PF coils
- The Vacuum Vessel (dark red areas in Fig. 2b)
- The stabilizing plates (dark blue areas in Fig. 2b)

In order to take into account the presence the VV ports, the resistivity of these components has been opportunely scaled with the ratio

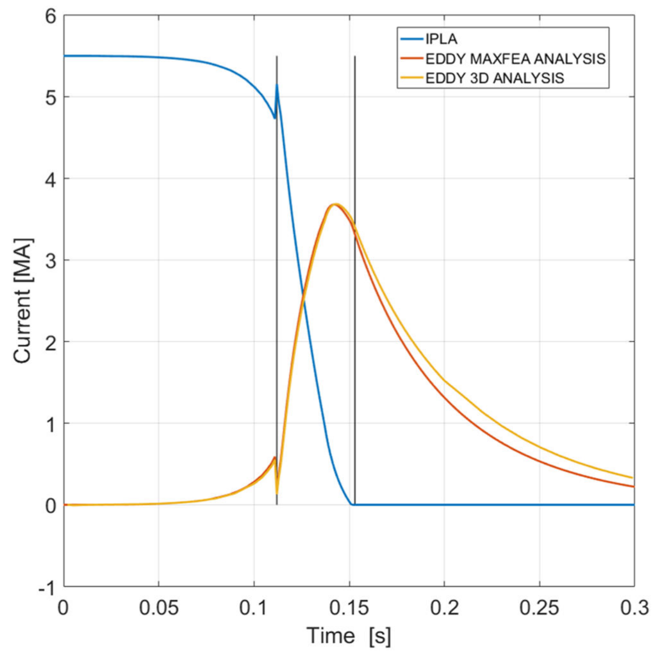

Fig. 14. Eddy Currents MAXFEA vs Full 3D.

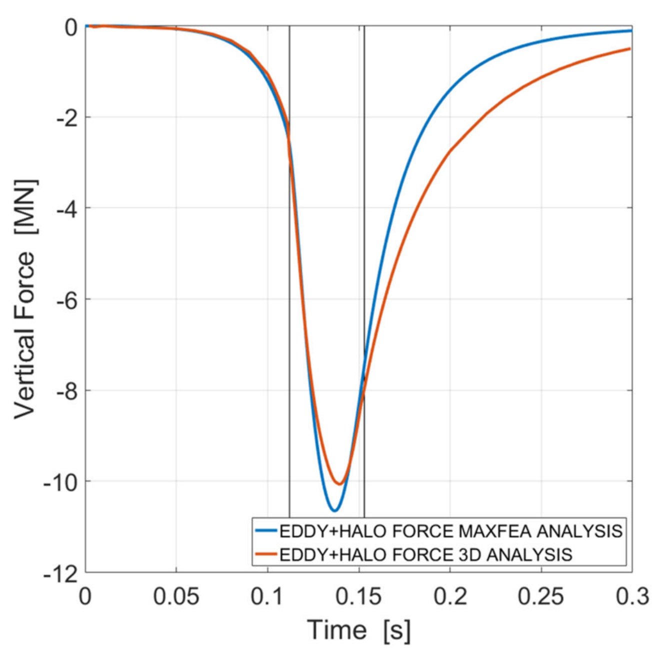

Fig. 15. Vertical Force due to both eddy and halo currents over 360°: MAXFEA vs Full 3D.

vacuum/filled in toroidal direction. Instead, the divertor system is not included in the model since its effect on the plasma evolution can be neglected. In fact, as shown in more in details later on, the divertor cassettes are segmented in the toroidal direction and insulated from each other so that no net toroidal current can arise.

The initial equilibrium considered is the reference Single Null (SN) at the Start Of Flattop (SOF) with plasma current at 5.5 MA and $R = 2.19$ m. The reference equilibrium reproduced with MAXFEA is shown in Fig. 2b, together with that computed by means of the CREATE-NL code [15], showing a very good agreement between the two codes.

The DVDE slow scenario has been modelled as follow:

- Destabilizing kick is imposed @10 ms after the start of the simulation to force plasma movement imposing a small voltage on a dummy coil for few time steps (time step = 1 ms);

- Consequently, the plasma starts to move vertically towards the wall, reducing the plasma area, typically with little change in the total plasma current since flux conservation is assumed.

- At a certain point, when the plasma reaches a given critical value of the safety factor (q95 = 2), TQ is imposed as betapol drop in 1 time step (TQ duration = 1 ms) and a plasma current spike is found, as regularly observed experimentally, due to the flux conservation and redistribution of the plasma current.

- CQ starts immediately after (40 ms), imposing a proper negative voltage on plasma. During the CQ phase, HC growth is considered.

3.1.2. APDL 3D EM model

The 3D EM model requires some preliminary simplification in order to reduce the complexity of the whole model. In fact, the differential formulation of the FE analysis needs to also model the vacuum. For this reason, to facilitate mesh operations, in the model development all the fillets were replaced with sharp edges. Another simplification is to neglect the presence of the poloidal ribs, since their presence does not affect the result significantly. Also the VV pedestal was neglected in the model, being insulated from VV outer shell. The divertor was represented in a simplified way and its cassette and the stabilizing plates considered connected to the VV inner shell through their relative supports (see Fig. 4). The periodicity of the system allows to consider only one sector and a half. In the post processing phase the current and force distributions were then extrapolated over three sectors, being this the minimum amplitude for mechanical cyclic symmetry (due to the presence of VV pedestal every 60°).

The EM model is composed of 983k nodes and 727k SOLID97 elements. This element type features up to 4 Degrees of Freedom (DoF), namely the three vector potential A components (for all conductive and non-conductive elements) and the VOLT (for current induction). The same mesh model is adopted for PFV, TFV and HC simulations. In the first case the plasma PFV is introduced through a set of filaments (see Fig. 3 center), whilst in the second a torus is adopted to apply the plasma TFV (see Fig. 3 right). Regarding the HC simulations, the total HC computed with the MAXFEA simulation is injected into the structures through chosen in and out locations. The assumption of the in and out locations will be presented in Section 4.1.3. Fig. 3 left shows the whole FEM domain. The adopted Boundary Conditions (BCs) depend on the simulation considered, but in any case, have the capability to reproduce the cyclicity of the system.

In Fig. 4, from left to the right, an overview of the toroidal ribs (depicted in green), of the stabilizing plates and support (depicted in cyan and gray respectively) and of divertor cassettes and supports (depicted in blue and orange respectively) is provided.

In the results shown in the following sections, the contribute of toroidal magnetic field is included in a simplified way, namely considering the analytic formulation $B_{tor} = A/r$, in which r is the radius from the center of the machine and $A = B_T{\cdot}R = 13.14\ T{\cdot}m$, where $R = 2.19\ m$ and $B_T = 6\ T$ [3].

3.2. Structural model

3.2.1. Sectors (60°)

As mentioned above, the structural model, used for all those analyzed cases in which the TPF is not considered, is composed by 3 sectors (i.e. 60°). In the central sector the port 5 is replaced by the gravity support. Compared to the EM model, in the structural one all the fillets have been included, as can be seen in Fig. 5 (left). Moreover, also the poloidal ribs have been modelled, in addition to the toroidal ones, as shown in Fig. 5 (right). However, in this case the divertor and the stabilizing plates have not been included in the model, but their contribution was considered only in terms of resultant forces and moments.

The mesh model consists of 1333k nodes and 1490k elements,

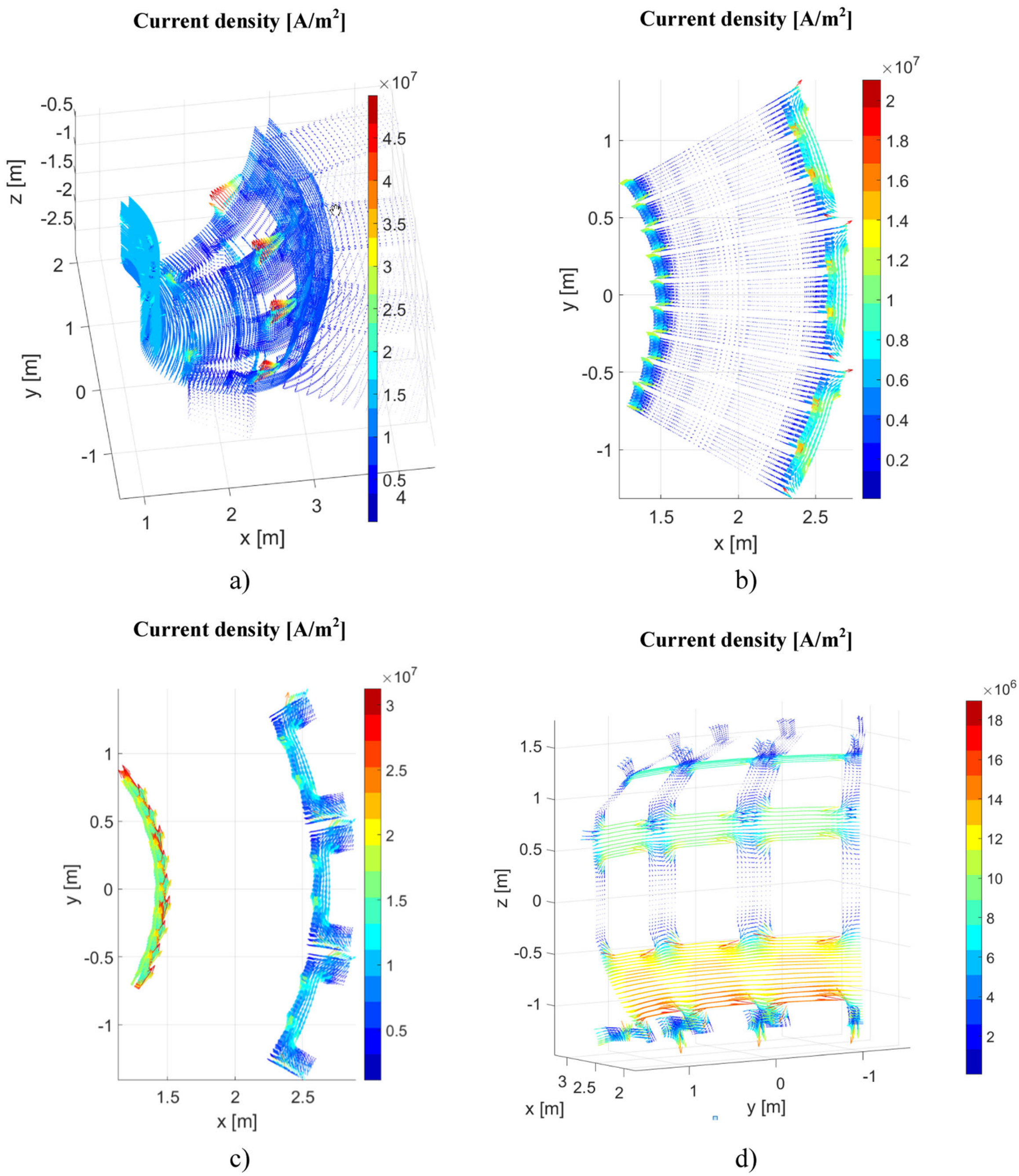

Fig. 16. Eddy current distribution at 0.143 s a) VV b) Divertor cassettes c) Divertor inboard and outboard supports d) Stabilizing plates + Supports.

composed of SOLID185 bricks and contact elements (CONTA174 and TARGE170). The cyclic symmetry was applied through a set of constraint equations. The VV gravity support is fixed at the bottom and connected to VV outer shell through contact elements. The port bellows are considered free to slide along their axis, whilst the movement in the other two directions is prevented. The EM loads acting on the structure are interpolated from the EM models and applied as body force densities on the VV. The resultant forces and moments on the divertor and the stabilizing plates were applied to a master node, located at the center of the tokamak, and linked to the support structures via RBE3 elements.

3.2.2. *Sectors (360°)*

If the TPF is introduced in the halo currents force distribution, the cyclic symmetry condition used in the 60° model shall no longer be valid. When the TPF is equal to 2 it is necessary to use a full 360° model.

In Fig. 6 the full model is shown together with a detail of the mesh, obtained from 60° model with 6 toroidal repetitions. The mesh consists of approximately 8000k nodes and 900k elements.

4. Results

The results of the EM and Structural analyses are exposed in Sections 4.1 and 4.2, respectively. Section 4.1.1 reports the results of the MAX-FEA analysis, while Section 4.1.3 presents the full 3D EM analysis (PFV+TFV+HC). In Section 4.1.2, the 3D EM model validation is discussed. From the mechanical point of view, the time instant in which a vertical force peak has been observed as the result of the combination of eddy and halo currents is considered (herein named eddy+halo instant) (Section 4.2.1). Moreover, also the impact of a TPF equal to 2 has been analyzed at the same time instant (Section 4.2.2).

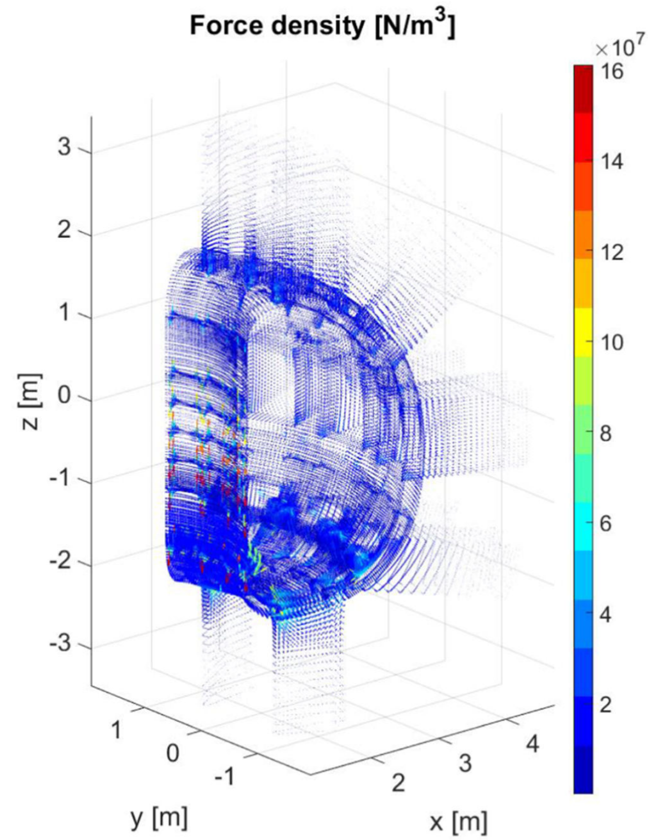

Fig. 17. Force distribution due to eddy currents (PFV+TFV) at 0.143 s in all the structures (VV + stabilizing plate and supports + divertor cassettes and supports).

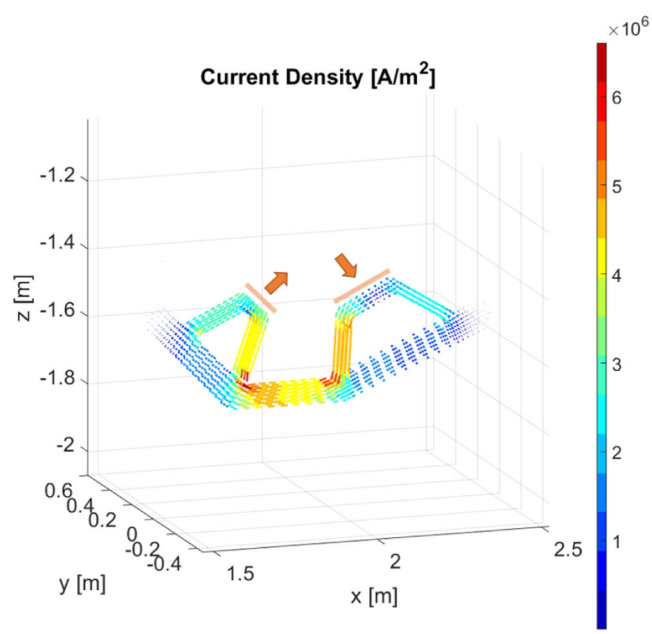

Fig. 18. Halo current distribution in a divertor cassette at 0.129 s together with the assumed in and out locations.

4.1. EM analysis

In the following sections, the results of the MAXFEA 2D analysis, of the comparison between MAXFEA and ANSYS APDL and of the full 3D

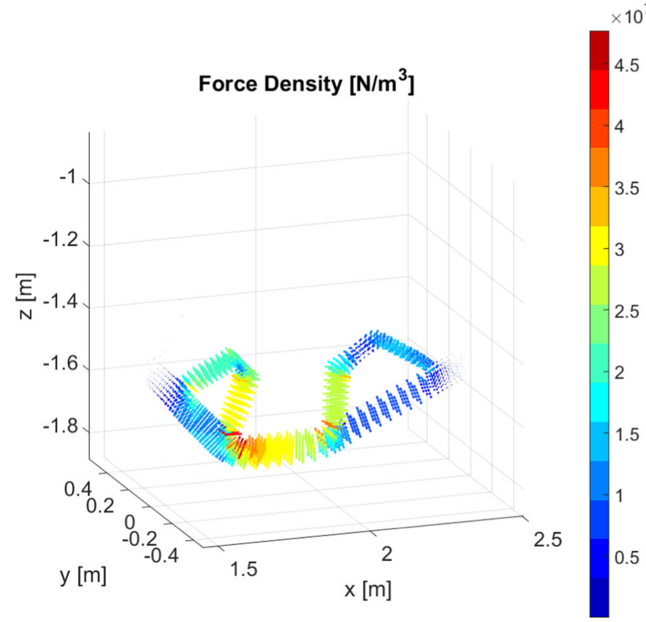

Fig. 19. HC force distribution in a divertor cassette at 0.129 s.

analyses are exposed.

4.1.1. MAXFEA analysis

The results of the MAXFEA DVDE slow simulation are reported from Fig. 7 to Fig. 10. Regarding the plasma current (named I_{pla} and depicted with blue curve in Fig. 7), in an initial phase, when plasma is moving downward until it reaches q95 = 2, a small reduction of current is observed because of flux conservation assumption. When the plasma reaches the given critical safety factor value, TQ is imposed (takes place at 0.112 s, identified with left black vertical line) and a plasma current spike is found, as regularly observed experimentally, due to the flux conservation and redistribution of the plasma current. Immediately after TQ, the CQ begins (CQ ends at 0.152 s, identified with right black vertical line). In the CQ phase, HC arises as shown with the red curve, reaching a peak of about 2.3MA. Nearly the end of this phase, at 0.143 s, eddy current reaches its maximum of about 3.7MA (yellow curve).

The vertical EM forces acting on the VV are instead reported in Fig. 8 (I_{pla} is also depicted with purple curve). In blue it is represented the global vertical force acting on the VV due to eddy currents, whose peak occurs at about the end of the CQ with a value of about −8 MN. Instead, in red it is reported the global vertical force due to the halo current, whose peak of about −7.4 MN occurs 0.127 s, when HC is at its maximum. Yellow curve shows the total eddy + halo force, highlighting a peak of about −10.6 MN at 0.137 s. Note that the forces connected with the eddy currents are those related to the interaction between toroidal induced currents and poloidal field, since the 3D effects are not evaluable inside MAXFEA code.

In Fig. 9 the evolution of the plasma current centroid (R_J - Z_J) during the DVDE together with the plasma initial equilibrium (blue curve) is reported, whilst the plasma TFV flux evolution against time is shown in Fig. 10.

4.1.2. model validation with simplified axisymmetric test-case: MAXFEA vs APDL

A preliminary test has been carried out with the aim to validate the APDL 3D Model against MAXFEA. To this end, a simplified 10° axisymmetric model (herein identified as Model TEST) has been obtained from the 3D Model (PFV, TFV and HC analyses share the same mesh) merely changing the material properties and the element degrees of freedom of appropriate set of elements in order to reproduce the same

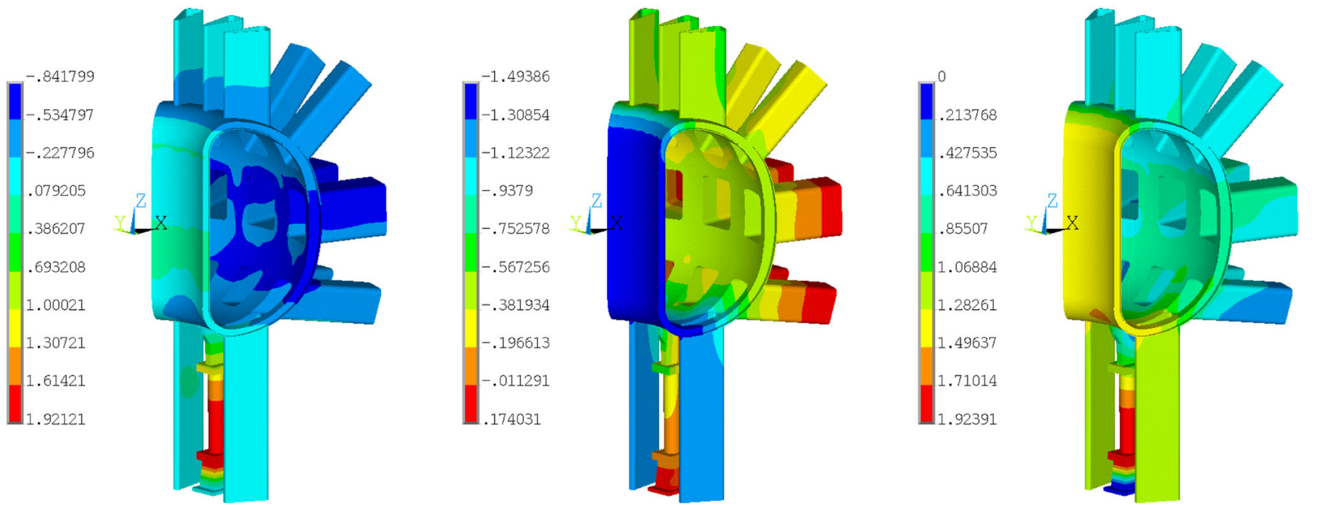

Fig. 20. DVDE slow (No TPF) @0.140 s: radial displacement (left), vertical displacement (center) and total displacement (right).

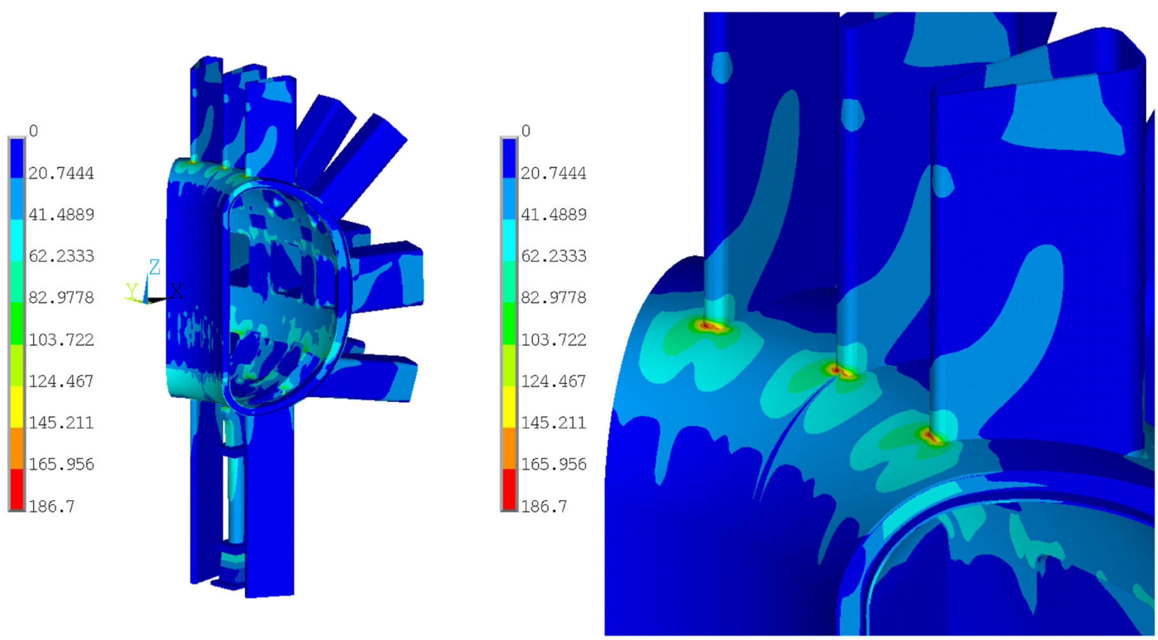

Fig. 21. DVDE slow (No TPF) @0.140 s: overview of von Mises stress contour of the three sectors (left) with a zoom of the upper ports (right).

geometry of the MAXFEA analysis (Fig. 11). Furthermore, a MAXFEA simplified simulation (herein identified as MAXFEA TESTCASE) has been performed simply considering the reference resistivity of the SS for the structures in order to obtain the same conditions between MAXFEA and APDL also in terms of material properties. The equivalent resistivities previously discussed to take into account the toroidal discontinuities of the components are not considered in this test case, thus a slightly different plasma evolution with respect of what reported in Section 4.1.1 is obtained.

The results are shown in Figs. 12 and 13. As it can be observed in Fig. 12, an almost perfect agreement was found between MAXFEA TESTCASE and APDL Model TEST, in terms of total eddy current in the VV and in the Stabilizing Plate, and also in terms of total vertical force (360°) on these components, as shown in Fig. 13. From Fig. 12 it is also possible to observe that the set of filaments conserves the plasma current evolution (MAXFEA plasma current and the equivalent current in the filaments are almost overlapped, represented with blue solid and red dashed lines, respectively). The results show that there is a very good agreement between the two codes, thus verifying the APDL 3D model.

4.1.3. Full 3D analysis: PFV+TFV+HC

Starting from the MAXFEA simulation shown in Section 4.1.1, a full 3D EM analysis has been performed introducing the plasma evolution in the 3D Model with the techniques exposed in Section 2. A comparison in terms of induced currents and vertical forces between MAXFEA 2D simulation and the full 3D analysis (PFV+TFV+HC) is shown in Figs. 14 and 15. The results highlight that the presence of 3D effects does not strongly affect the structures response in terms of global quantities (i.e. total currents and forces). A force peak of about −10MN is observed at 0.140 s (eddy+halo instant) looking at the red curve in Fig. 15. On the other hand, the presence of the ports, of local electrical connections and so on, produces non-trivial and non-negligible forces concentrations, with the appearance of local moments and torques on the components. Fig. 16 shows some eddy currents paths (PFV+TFV) on the components near the end of CQ, at 0.143 s, when the eddy current is at its maximum. Instead, Fig. 17 shows the force density distribution due to the eddy

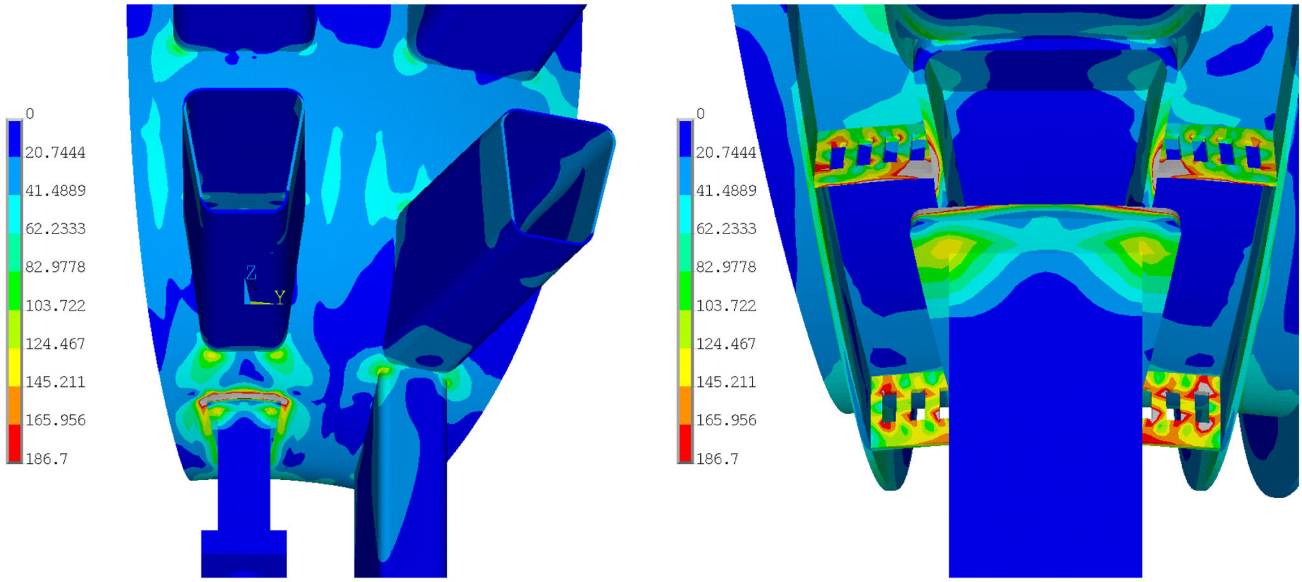

Fig. 22. DVDE slow (No TPF) @0.140 s: von Mises stress contour around the connection of the gravity support with the VV outer shell (left) and VV internal overview (right).

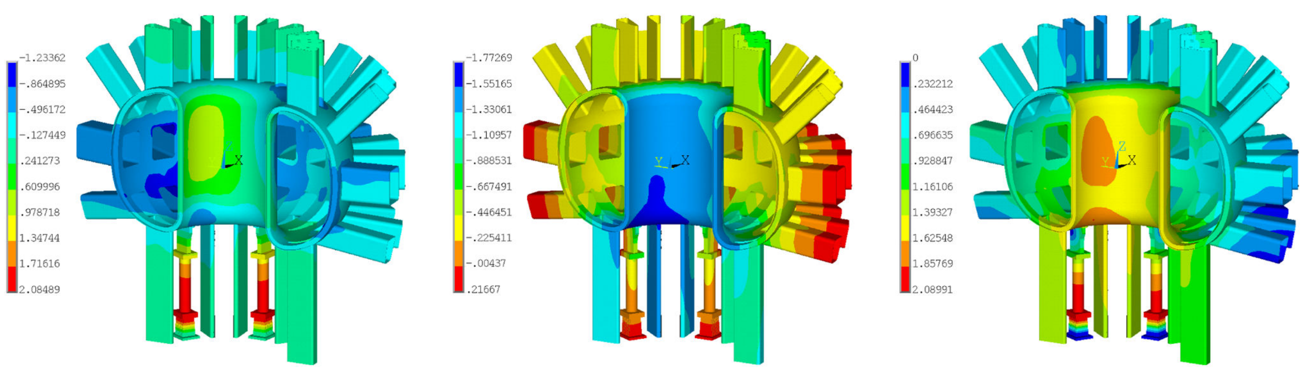

Fig. 23. DW + EM loads of DVDE slow (TPF = 2): radial displacement (left), vertical displacement (center) and total displacement (right).

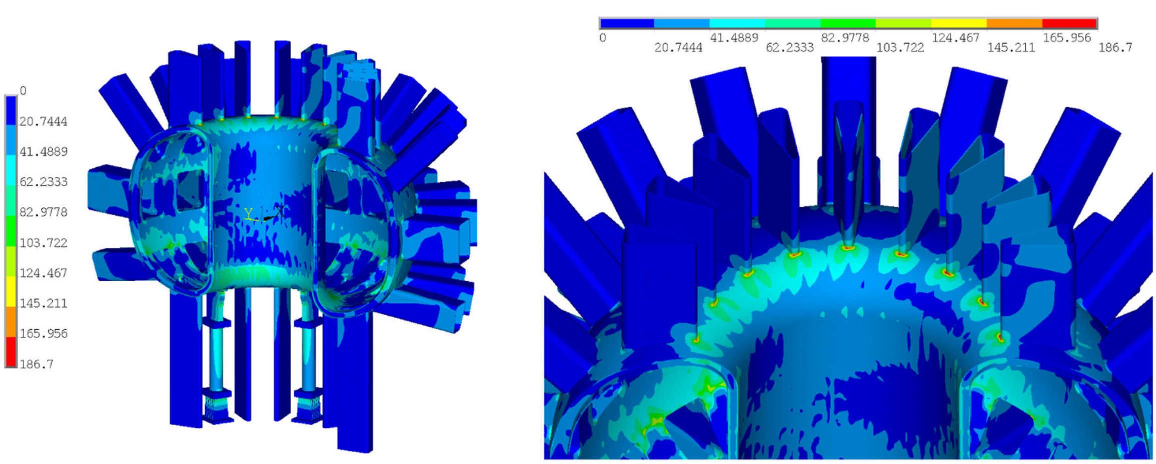

Fig. 24. DW + EM loads of DVDE slow (TPF = 2): overview of von Mises stress contour expressed in MPa of the half of the VV (left) with a zoom of the upper ports (right).

currents in all the components at the same time instant.

As far as the HC is concerning, Fig. 18 shows the current density in a divertor cassette at the peak of the HC, at 0.129 s, while Fig. 19 presents the force density at the same time instant. Fig. 18 shows also the assumed in and out HC locations.

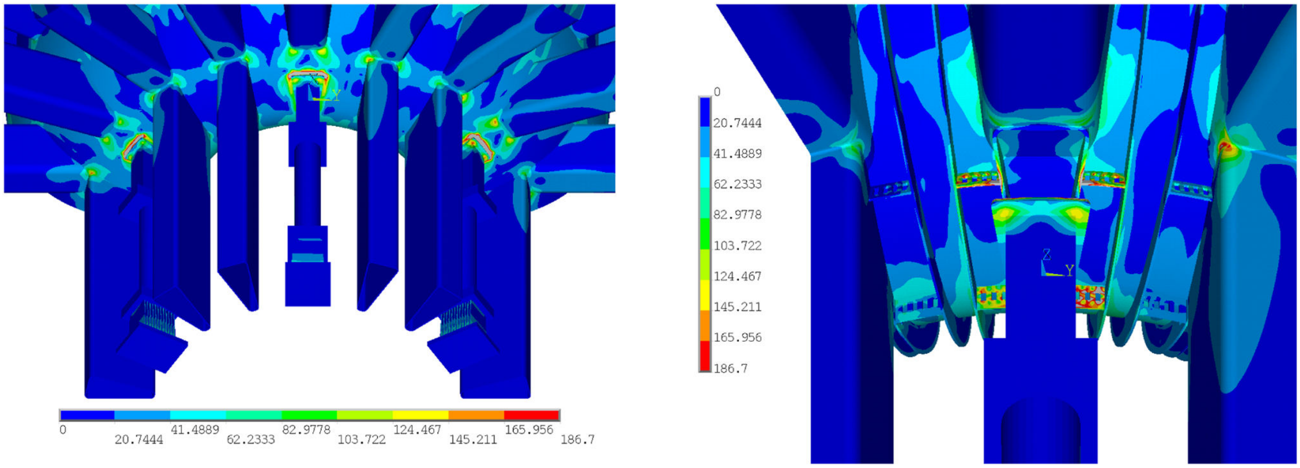

Fig. 25. DW + EM loads of DVDE slow (TPF = 2): von Mises stress contour around the connection of the gravity support with the VV outer shell (left) and VV internal overview (right).

4.2. *Structural analyses*

The structural results, in terms of total, radial and vertical displacements and von Mises stress, are shown in the following sections. In the stress contour maps the values lower than the prescribed stress limit (i.e. 186.7 MPa for 316LN steel @60 °C) are represented with colors, with the purpose to highlight only the portion of the model that violate the allowable limits. These values have been calculated as 2/3 of the yielding stress, as explained in the ITER structural design criteria [16].

4.2.1. *DVDE slow at eddy+halo f_z peak (0.140 s)*

In this section the results, in terms of displacements and stresses, are illustrated considering the eddy+halo instant (0.140 ms). This time instant corresponds to the maximum value of vertical force due to both eddy and halo currents. In Fig. 20 radial, vertical and total displacement are represented from left to right respectively. The maximum radial displacement, which occurs on the gravity support, is equal to 1.92 mm. The maximum values of the vertical (at bottom curved VV portion) and the total (at gravity support) displacements are instead −1.63 mm and 1.92 mm, respectively.

An overview of the von Mises stress contour on the whole 3 sectors is given in Fig. 21 left. It is possible to observe how the stress level is below the allowable value except that in limited zones of the structure. Fig. 21 right shows a zoom in the upper ports zone.

As observable from Fig. 22, the stress limit is violated on the VV outer shell all around the pedestal and also in different portions of the toroidal and poloidal nearby the support. However, it must be said that some parts of the ribs are modelled without any fillet, circumstance that leads to numerical peaks. It can be stated that the most critical zone is represented by the connection of the pedestal with the outer vessel.

4.2.2. *DVDE slow at EDDY+HALO with TPF = 2 f_z peak (0.140 s)*

In this simulation a TPF, equal to 2, for the halo currents has been taken into account. As consequence of the halo force TPF, the minimum amplitude of the structural model to be considered is 360°

In Fig. 23 DW + EM loads of DVDE slow (TPF = 2): radial displacement (left), vertical displacement (center) and total displacement (right). The radial, vertical and total displacements are represented from left to right respectively. The maximum radial displacement, which occurs on the gravity support, is equal to 2.08 mm. The maximum values of the vertical (inboard VV region around last three sectors) and the total displacements (gravity support) are instead −2.03 mm and 2.09 mm respectively.

An overview of the von Mises stress contour is given in Fig. 24 left. It is possible to observe how the stress level also in this case is below the allowable value except that in limited zones of the structure. Fig. 24 right shows a zoom in the upper ports zone.

As observable from Fig. 25 right the stress limit is violated in different portions of the toroidal and poloidal ribs in correspondence of the pedestal. The most critical zone is also in this case represented by the connection of the pedestal with the outer vessel. It is possible to state that this zone is the most stressed, especially in correspondence of the maximum halo TPF value.

5. Conclusions

In the context of DTT project, the MAXFEA code has been used in combination with ANSYS APDL following a methodology presented in [1] to study the EM and structural response of the DTT VV during plasma VDEs. From this study, it has emerged that the VV mechanical response is acceptable in all the scenarios but, during a particular event, namely the DVDE slow scenario, a stress concentration in correspondence of the connection of the pedestal with the VV outer shell has emerged. Downstream this analysis, mechanical reinforcements in this zone have been introduced in order to optimize the design. The aim of the paper is to show the successful application of this novel procedure in this context and its reliability as supporting tool in the final stage optimization design of these kind of components.

In this paper, the abovementioned DVDE slow scenario has been presented. The EM analysis has shown that a vertical force peak of around −10 MN is reached as the result of the combination of eddy and halo currents during the CQ phase. From the structural point of view, the EM loads occurring at this time instant produce a stress concentration localized in the connection of the pedestal with the outer vessel. This stress concentration has required the introduction of mechanical reinforcements in this zone in order to optimize the VV design.

CRediT authorship contribution statement

F. Giorgetti: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **R. Lombroni:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **V.G. Belardi:** Software, Validation, Data curation, Writing – review & editing. **G. Calabrò:** Resources, Supervision, Project administration, Funding acquisition. **M. Dalla Palma:** Conceptualization, Methodology, Resources, Supervision, Project administration, Funding acquisition. **P. Fanelli:** Methodology, Resources, Supervision, Project administration, Funding acquisition. **M. Fulici:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **G. Ramogida:** Conceptualization, Resources, Writing – review & editing, Supervision. **F. Vivio:** Resources, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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