# Abstract

The new designs of the Plasma Chamber (PC) and of the First Wall (FW) system are based on updated scenarios for vertical plasma disruption (VDE) as well as estimates for the maximum thermal wall loadings at ignition. The PC wall thickness has been optimized to reduce the deformation during the worst disruption event without sacrificing the dimensions of the plasma column. A non linear dynamic analysis of the PC has been performed on a 360$^\circ$ model of it, taking into account possible toroidal asymmetries of the halo current. Radial EM loads obtained by scaling JET measurements have been also considered. The low-cycle fatigue analysis confirms that the PC is able to meet a lifetime of few thousand cycles for the most extreme combinations of magnetic fields and plasma currents. The FW, made of Molybdenum (TZM) tiles covering the entire inner surface of the PC, has been designed to withstand thermal and EM loads, both under normal operating conditions and in case of disruption. Detailed elasto-plastic structural analyses of the most (EM) loaded tile-carriers show that these are compatible with the adopted fabrication requirements..

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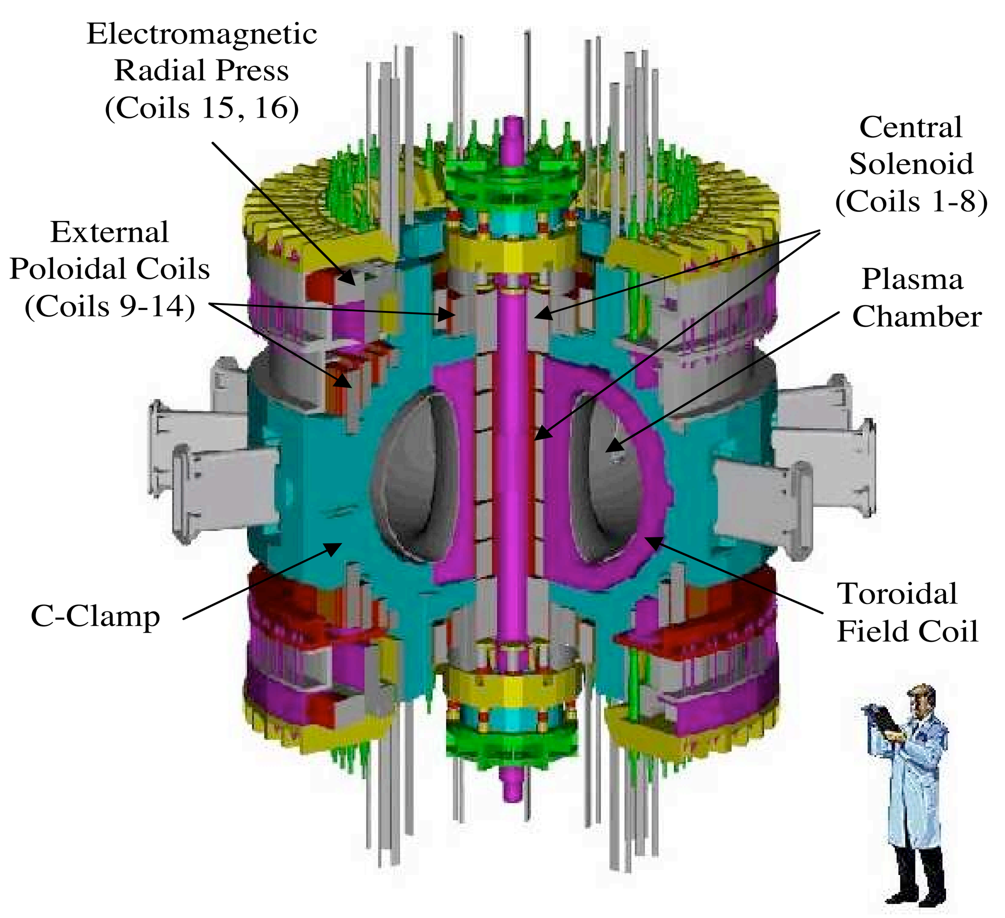


Figure 1. IGNITOR Machine view

# Introduction

IGNITOR (Fig. 1) Plasma Chamber is made up of 12 D-shaped toroidal sectors of Inconel 625 welded together to make up a torus by automatic remote equipment (Fig. 2). The whole inner surface of the PC is protected by TZM (Molybdenum) tiles to offer the maximum possible area for spreading the plasma heat load. The fast transient behavior and high values of the E.M. loads produce plastic strain in the PC structure. The first wall withstand the heat and the electromagnetic loads in normal operating conditions and plasma disruptions.
Complying with the new E.M. loads the wall thickness has been increased (from 26 mm to a 26/36/52 mm) in proper PC areas. The accuracy of the position of the tiles is required to be better than 2 mm all around the torus [2]. The FW mechanical design is remote maintenance compatible.
The first wall tiles are mounted on inconel 625 tile carriers. The thickness of the FW assembly has been kept within 23 mm (from the PC wall to the exposed tile surface) to satisfy the plasma design requirements.

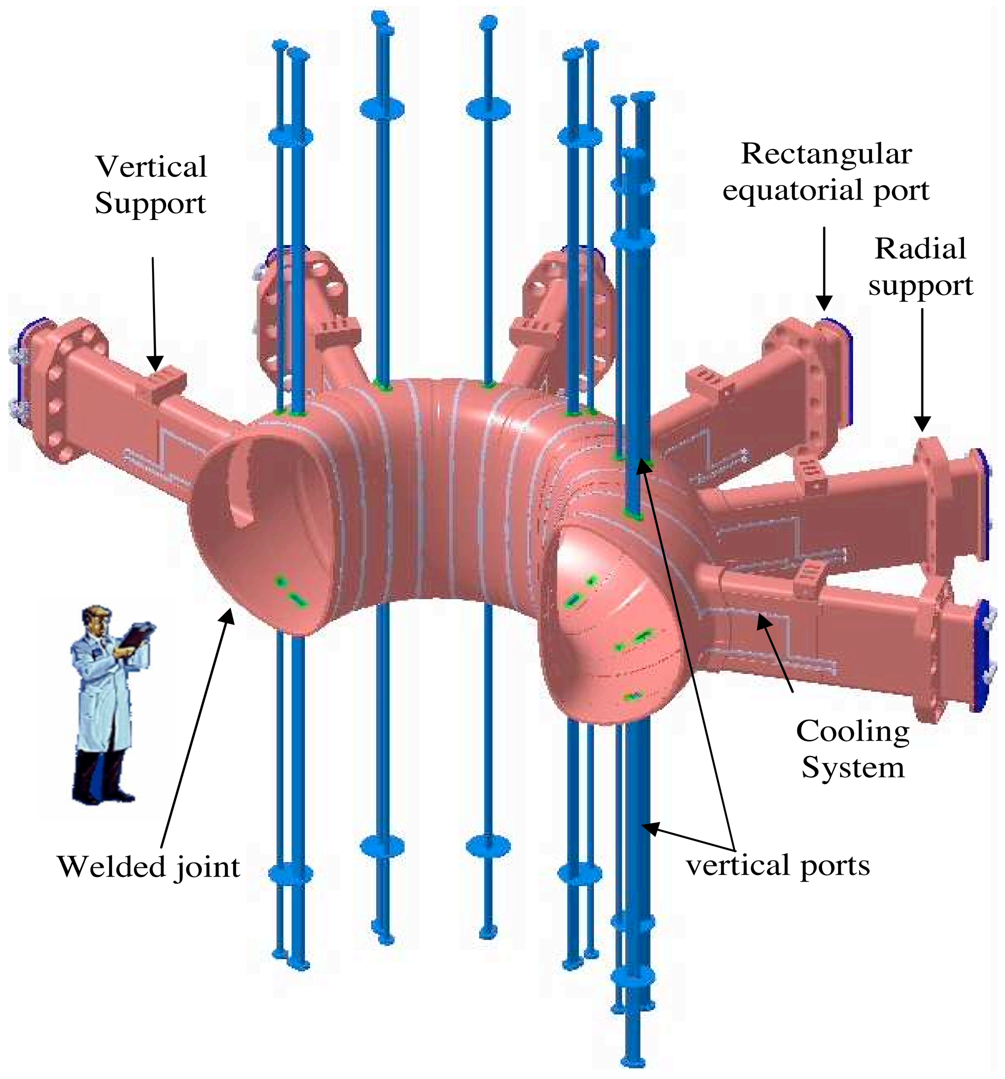


Figure 2. IGNITOR Plasma Chamber view.

# Electromagnetic Loads

The EM loads of the plasma disruptions have been obtained from the MAXFEA 2D code. The reference plasma disruption is a VDE of the plasma column with a slowly decreasing current, followed by the appearance of halo currents when the safety factor $q_{95}$ decreases below 2. The thermal quench and the fast current decay occur when $q_{95}$ falls below 1.5 (Fig. 3). A 3D Finite Element Model of 30° sector has been used to calculate the eddy current and the related E.M. forces during the VDE. The 360° model of EM loads due to eddy currents has been obtained by repeating in turn the acting force calculated for each sector.
The EM loads toroidal distribution due to halo currents is evaluated from MAXFEA output and distributed toroidally as the law (1+cos α), where α is the toroidal angle. A peaking factor equal to 2 has been assumed.
This asymmetry has important design implications, since lateral displacement of the JET vacuum vessel has been observed in JET disruption. Lateral loads has been measured for a 3.5 MA JET VDE to be in the order of 2 MN. An IpBtR scaling of this value to IGNITOR yields lateral loads of ~ 10 MN.
The asymmetry in the plasma toroidal current induces the source/sink of the vessel asymmetric current resulting in a net horizontal force.
The above total force is distributed in the toroidal direction as the law (sin α) and in the poloidal direction according to the picture below (Fig. 4).
A detailed 3D finite elements model has been developed in order to evaluate the electromagnetic loads on FW tile carriers during the reference VDE. Eddy currents and EM loads.
produced by the interaction of eddy currents with both the toroidal and poloidal (including plasma and coils) field have been evaluated using the EMAS finite elements code. The halo currents have been evaluated from the MAXFEA 2D code.

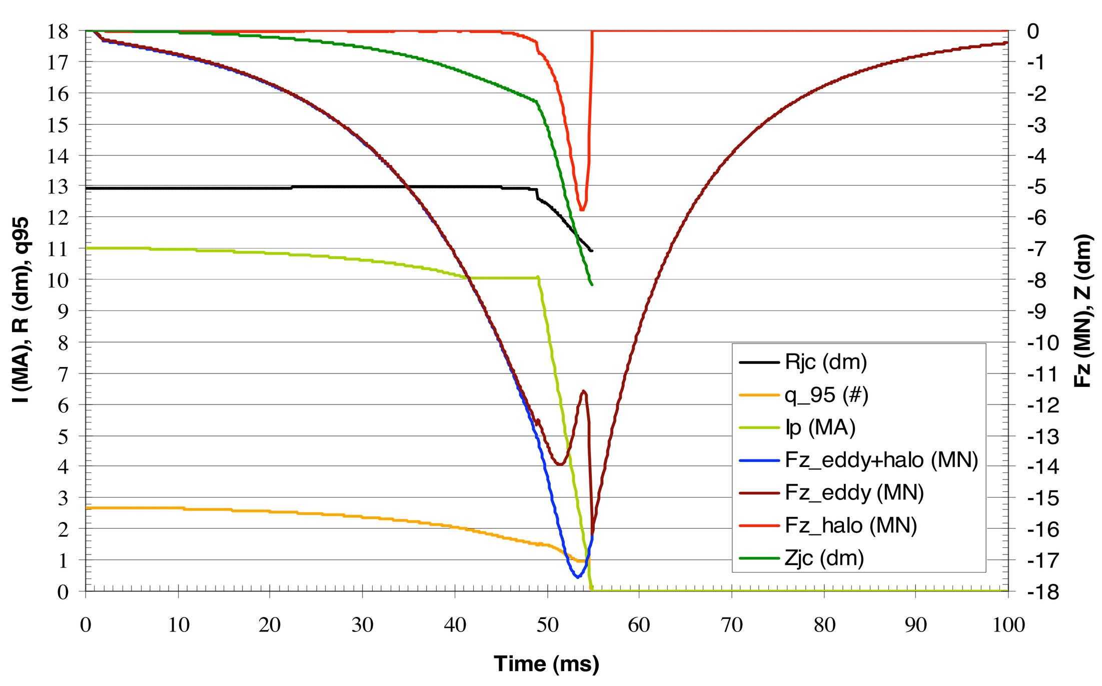


Figure 3. Main VDE parameters and vertical (Fz) and hoop (Fr) EM force.

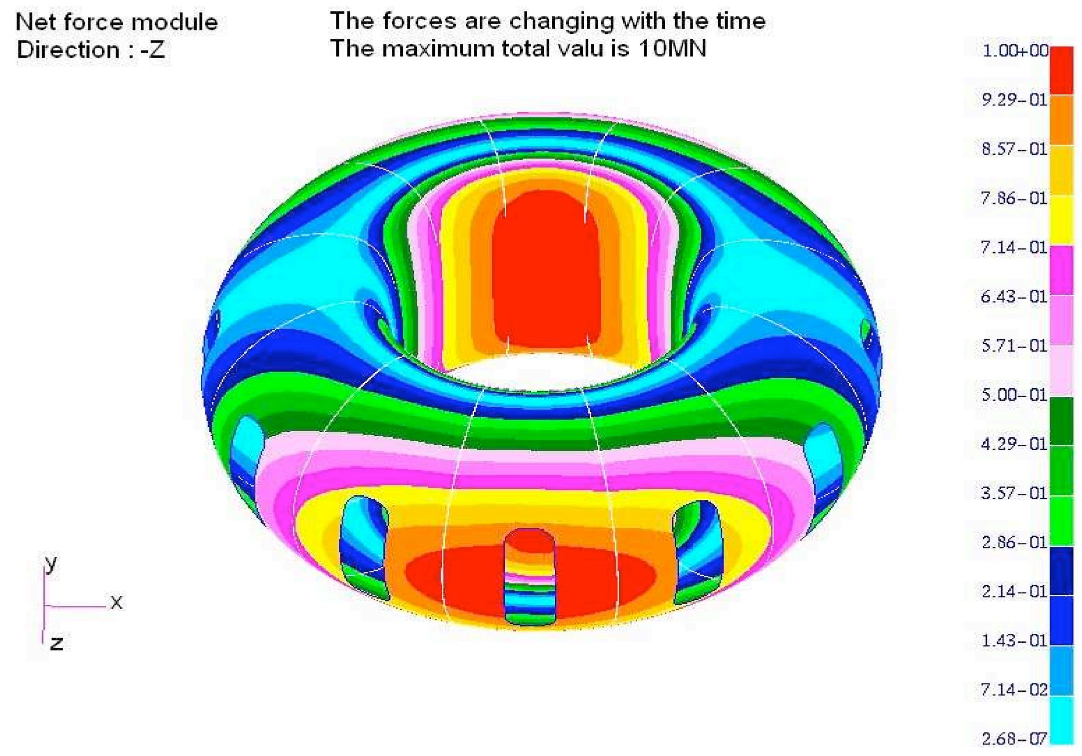


Figure 4. Net horizontal force module distribution on PC.

# Material

The PC material is Inconel 625. The PC reference design uses the following physical and mechanical properties at room temperature [3]:

$$\rho = 8400 \text{ Kg/m}^3; \quad E = 205 \cdot 10^9 \text{ N/m}^2; \quad \nu = 0.312;$$
$$S_y = 420 \text{ MPa}; \quad S_u = 820 \text{ MPa}; \quad \varepsilon_u = 50\ \%.$$

The PC final design is made of plates for minor thickness and forged material for large thickness regions.
The mass density of the Plasma Chamber wall has been increased from 8440 Kg/m$^3$ to 12900 Kg/m$^3$ to account the presence of the first wall.
The first wall is made up by TZM (Molybdenum) tiles mounted on Inconel 625 tile carriers. The tile is brazed to a square back plate (Densimet alloy D18 tougher than TZM) which is fastened directly to the carrier.

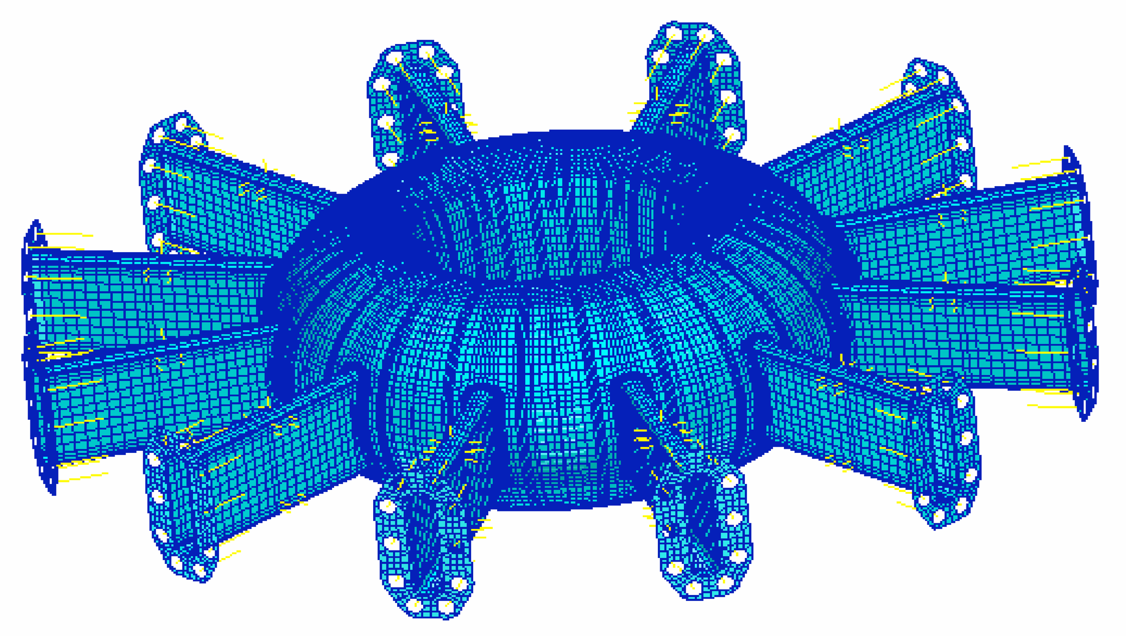

Figure 5. -360° Plasma Chamber Finite Element Model.

## Finite Element Model

The PC finite element model mesh (Fig. 5) consists of shell elements. Vertical and lateral supports are modeled with spring elements. Port is fixed in radial direction with truss elements reacting in all directions. The dynamic analysis with elasto-plastic material has been carried out by means of ABAQUS code.
On the 3D model (Fig.6) of the most EM loaded tile carrier, structural analysis, applying Eddy and Halo forces as well as thermal loads, has been performed.

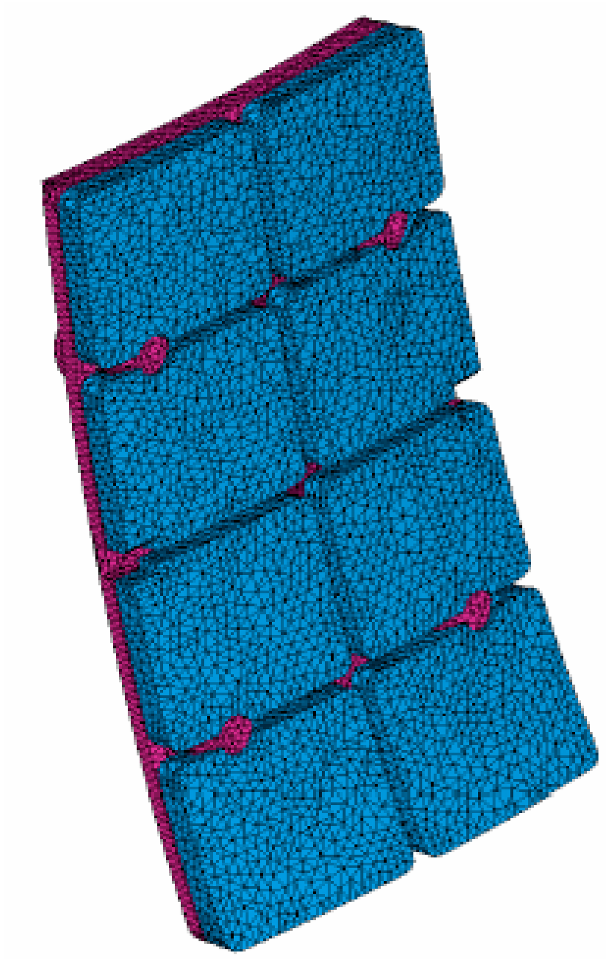

Figure 6. -Tile carrier Finite Element Model.

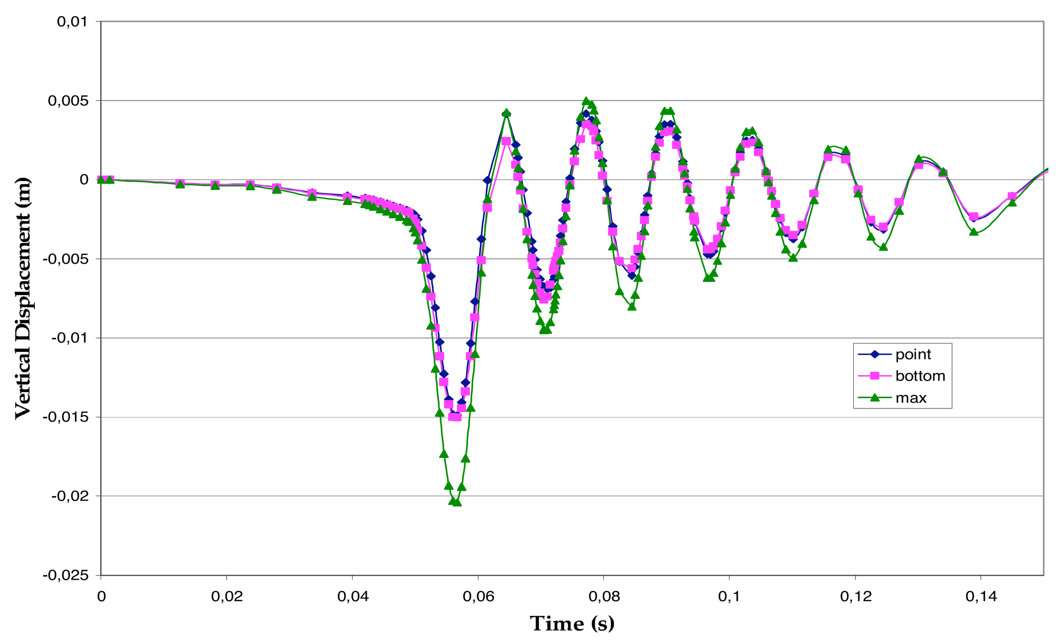


Figure 7. - Vertical displacement versus time.

## Plasma Chamber non linear transient analysis

Non linear transient analyses [3] [4] have been performed using Abaqus code on 26/36/52 mm PC configurations under Eddy, Halo and net horizontal loads condition (Fig. 7, Fig. 8).
The maximum Von Mises stresses result at 56.7 ms from VDE starting. These stresses raise a plastic deformation in the PC Top/Bottom area and on the port attachments (Fig. 9). The peak residual plastic deformation located in a discrete area of the welding zone is 0.83 %. The maximum residual plastic deformation located in the plate wall is 0.23 %.

Limits for inelastic strains, according to ASME – Boiler and Pressure Vessel Code [5], are:

• Strains averaged through the thickness, 1 %;
• Strains at the surface, due to an equivalent linear distribution of strain through the thickness, 2 %;
• Local strains at any point, 5 %.

All these limits are satisfied.

A complete load cycle has been analyzed, finding for each element the strain difference between a reference instant ("when conditions are at an extreme for the cycle") and any other time. To predict the low-cycle fatigue lifetime the cycle effective or equivalent strain is calculated using the ASME code equation.

Maximum plastic strain component values are achieved close to the weld regions at Top/Bottom zone, it results an equivalent maximum strain range of D emax = 0.00546. Entering this value on the design fatigue strain range curve [4] it turns out that the low-cycle fatigue lifetime close to the weld region is equal to a few thousand cycles.

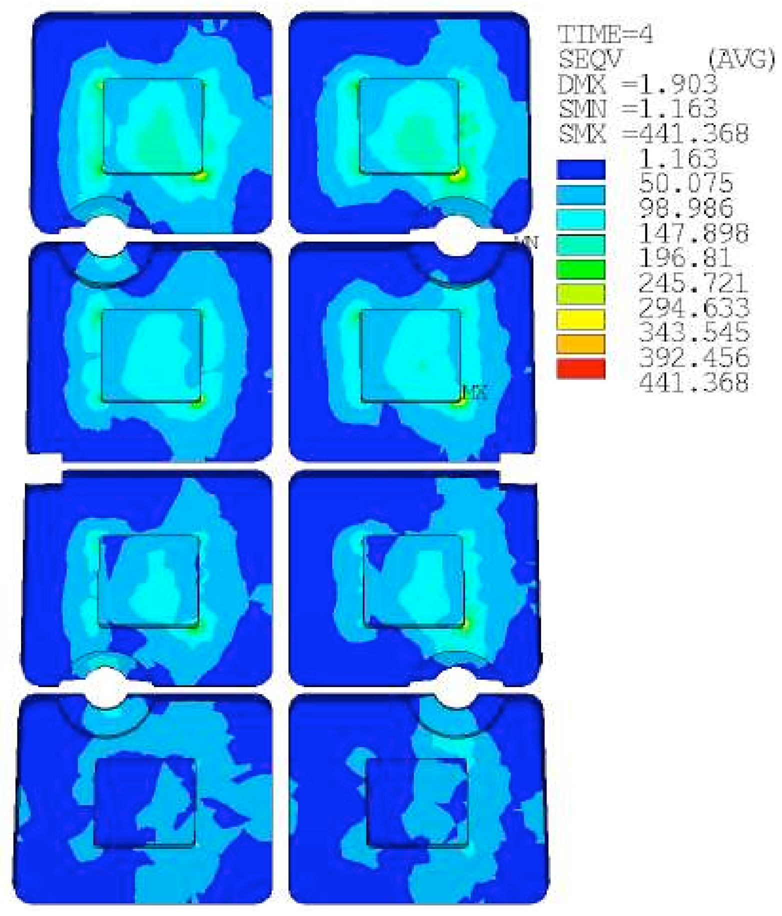


Figure 10. - Tiles stresses (MPa) due to Eddy, Halo and thermal load.

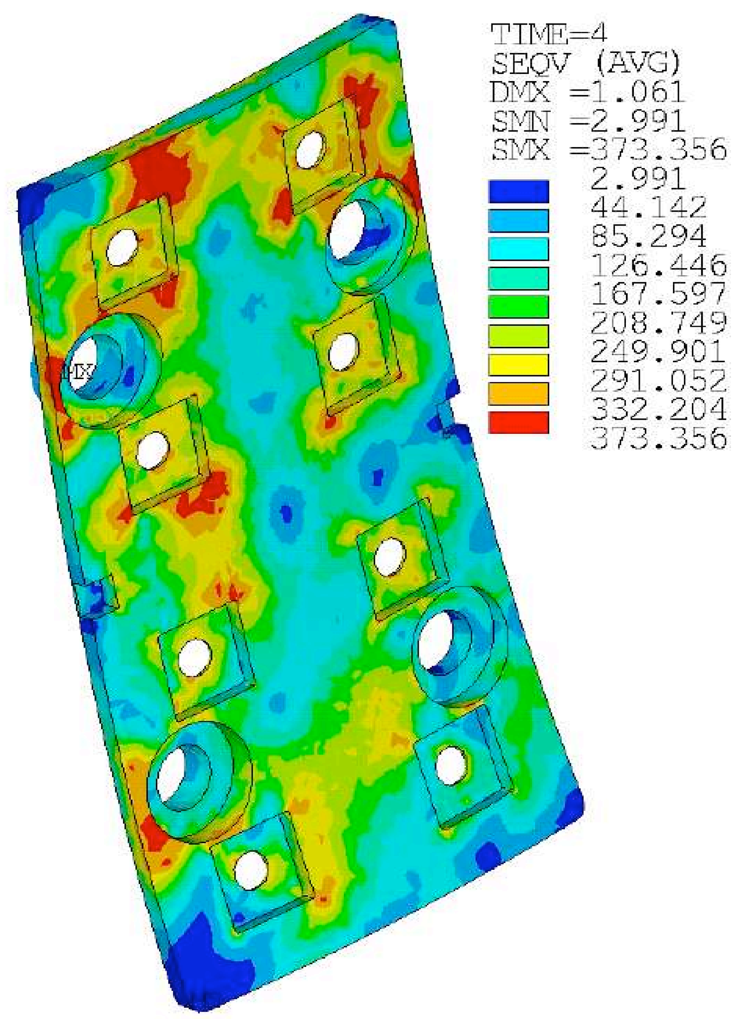


Figure 11. - Carrier stresses (MPa) due to Eddy, Halo and thermal load.

## First Wall Structural Analysis

A detailed structural analysis of the 3rd tile-carrier, the most loaded one, has been performed when the EM loads due to Eddy Current and halo current are maximum, that is at 53.5 ms from VDE starting (Fig. 10, Fig. 11) [6]. The thermal loads risen from plasma heat loads (peak value 1.8 MW/m2) have been also considered. In any case the maximum calculated stresses are within the allowable limits.

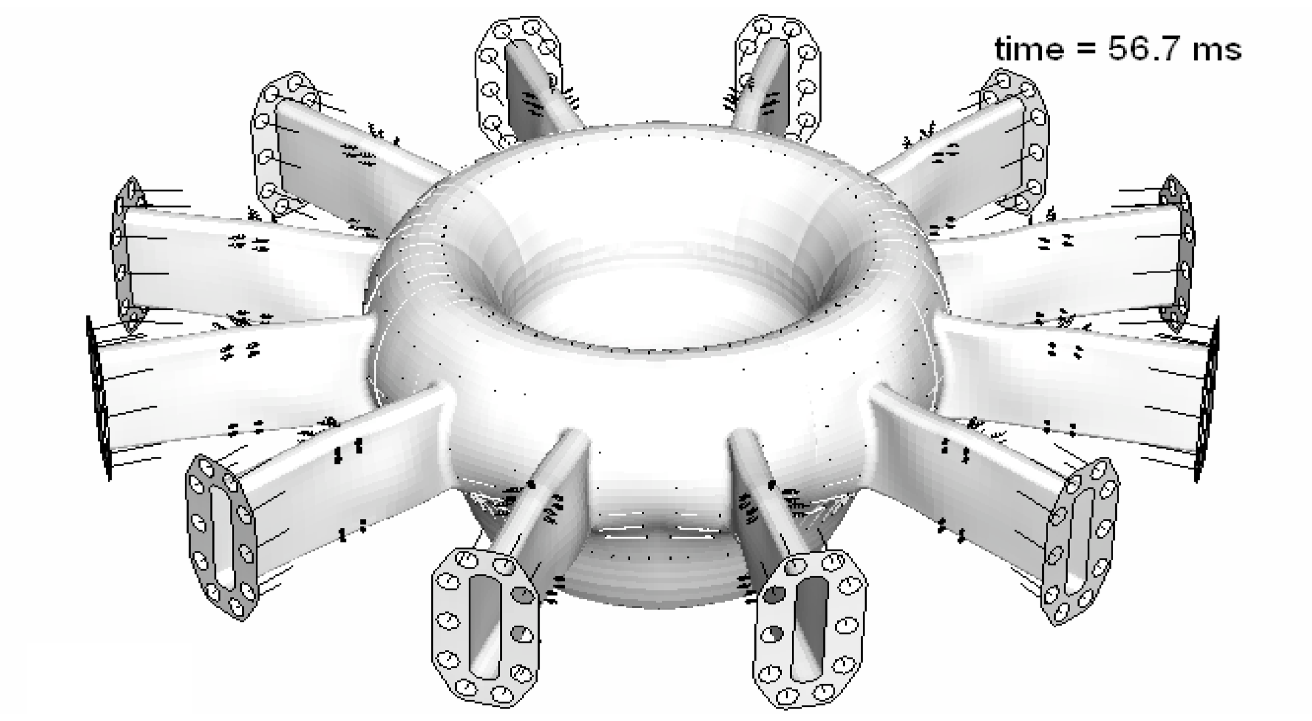


Figure 8. - Maximum vertical displacement at t=56.7 ms.

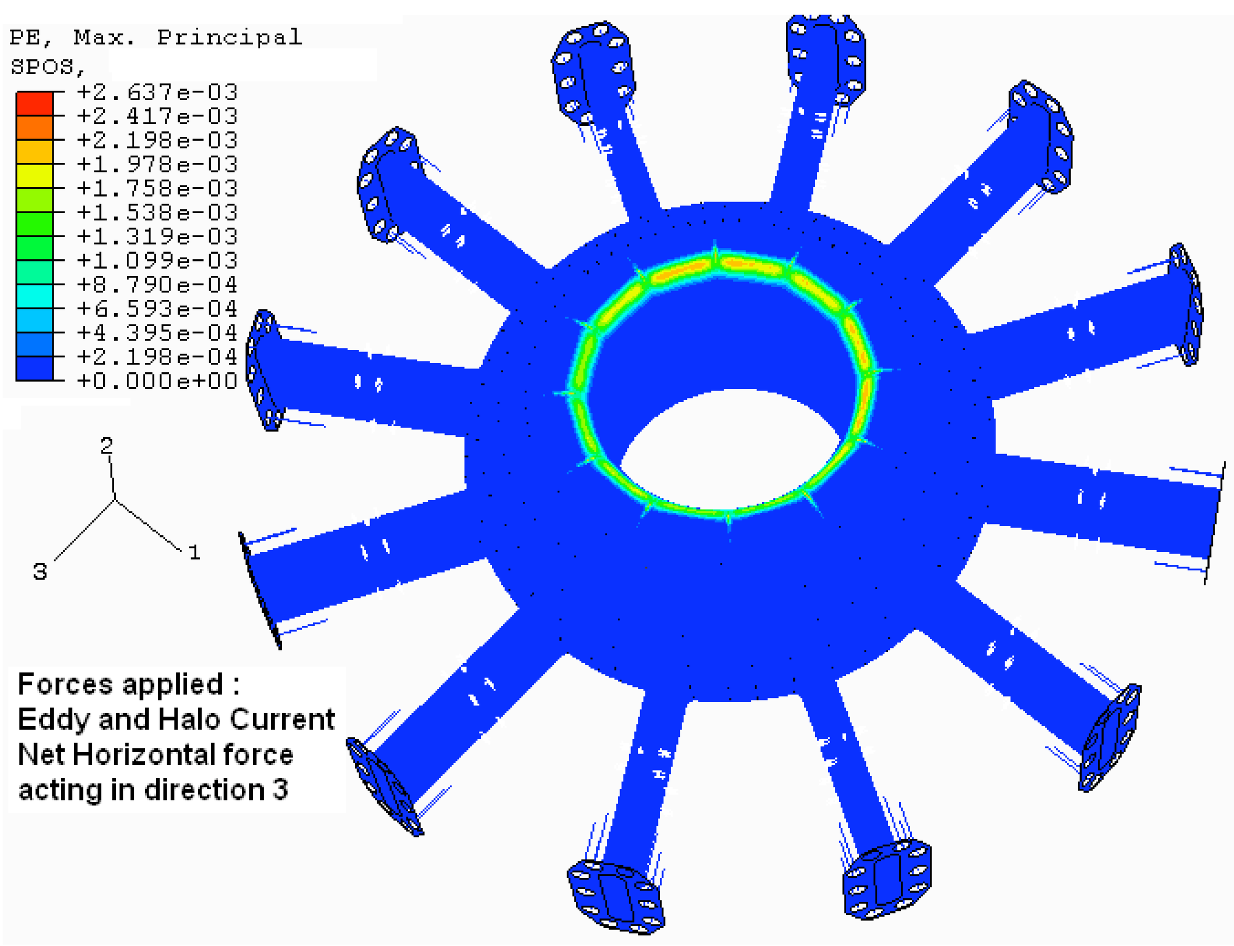


Figure 9. – Maximum residual plastic strain at the inner PC wall.

## Conclusions

More severe plasma disruptions induce higher EM loads in the IGNITOR PC. As consequence the stiffness has been increased to limit the displacements and mitigate stresses.

## References

[1] B. Coppi, IGNITOR project Group-Engineering Design Description- Ignitor Programm-RLE Reportn° PTP 96/03, December 96.
[2] A. Bianchi, B. Parodi "Camera a vuoto–PROGETTO IGNITOR" IGN.CAV.P.5101-Ansaldo Ricerche, Genoa (Italy), Aprile2003.;
[3] G. Mazzone, A. Pizzuto "Ignitor Plasma Chamber Structural Analysis" ERG-FUS-TECN-MEC IGNITOR 96/CV/002 & 96/CV/003;
[4] A. Cucchiaro, B. Coppi, A. Pizzuto et. al. "Ignitor Plasma Chamber Structural Design with dynamic loads due to Plasma Disruption Event" Soft, Venice (Italy), September 2004.
[5] ASME, Boiler and Pressure Vessels Code, Section III, Division 1, Code case N-47-29.
[6] A. Pizzuto, A. Cucchiaro, B. Coppi, "First Wall System and Plasma Chamber in Ignitor", *Bull. Am. Phys. Soc.* **49 (8),** 80 (2004) –DPP04 CP1 44