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Analyses and structural integrity estimation of the ITER divertor Thomson scattering system

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ABSTRACT

This article reports the results of the assessment performed on the ITER Divertor Thomson Scattering (DTS). It is designed to provide an instrument capable of measuring the electron temperature and the related density profiles in the outer divertor plasma, relying on Thomson scattering method. The DTS main components are front rack, back rack, neutron shielding and diagnostic mirrors.

Current DTS design has been modified compared to the one described in the previous article dedicated to this object. The most significant changes are:

- Upper neutron shielding has been removed. It is now not connected directly with the DTS system. It helped to reduce total weight of the construction;
- Dielectric insertions were added in order to reduce influence of the ponderomotive forces on construction strength;
- DTS supports were redesigned. Connections of the DTS with radial rails on which the construction is mounted on the sides were explored. Corresponding contact problem was solved and the structure integrity in this area was assessed.

Mirrors made of SiC material are the DTS diagnostic elements. They are installed into front and back diagnostic racks. Other elements of the DTS are made of 316L(*N*)-IG steel. The contact pads on the radial rails are made of 660 steel.

The whole Divertor Thomson Scattering system has to withstand all the loads (thermal, mechanical, electromagnetic and seismic) acting on the in-vessel region in which it is located without compromising its integrity. Its design layout is being modified and optimized according to the outcome of the structural assessment. Every step of the design update brings the construction closer to satisfying all of the criterions of structural integrity. This paper describes some important steps that really help moving forward to the DTS implementation.

1. Introduction

This report accounts for the results obtained from the assessment of the ITER Divertor Thomson Scattering (DTS) performed using the Finite Element Model (FEM) ANSYS software. In this paper electromagnetic (EM) loads, computed as described in detail in Section 2, and inertial loads, estimated according to [1], are considered for the structural assessment of the construction. Also, a contact problem of the construction supports is explored. Main conclusions for the conducted calculations are included. Evaluations of the DTS previous design are reported in [2], [3].

Current design of the DTS is shown in Fig. 1.

2. Electromagnetic loads evaluation and impact

The rapidly changing magnet fields associated with disruptions

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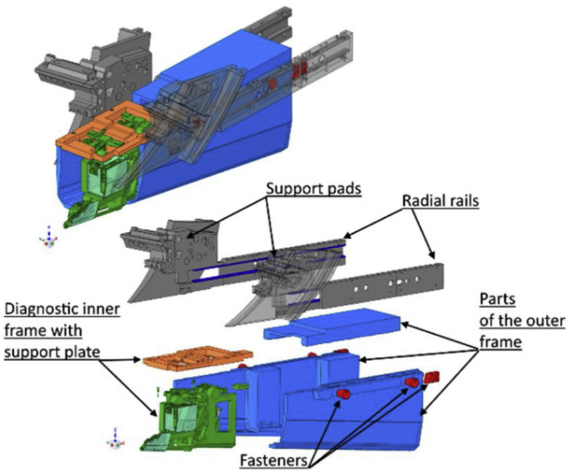

Fig. 1. 3D-model of the DTS current design.

induce electrical eddy currents in the surrounding (conductive) structures, which then interact with the remaining magnetic field, thus producing forces and torques. Eddy currents depend on location and electrical connection of the structure. Therefore, two different design variations of the DTS are considered: solid model without electrical insulation and model with electrical insulation which is represented by dielectric insertion.

FEM software Ansys Maxwell is used to simulate electromagnetic loads due to plasma disruption. Global EM model is shown in Fig. 2. For DTS the worst-case scenario of plasma disruption VDE (vertical displacement event) 3 DW (downwards) was selected. Due to symmetry, a 20-degree model was used for calculating. It consists of Toroidal Field (TF) coils, Poloidal Field (PF) coils, Central Solenoid (CS) coils, Vacuum Vessel (VV), blanket modules nearest to the DTS, secondary excitation plasma filaments and DTS itself.

Vector plot of the eddy currents is presented in Fig. 3.

Electromagnetic force was obtained during EM analysis and equals

$$\boldsymbol{f} = \rho \boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B} \tag{1}$$

where: $\boldsymbol{f}$ – electromagnetic force, ρ – charge density, $\boldsymbol{J}$ – currents density, $\boldsymbol{B}$ – magnetic field.

Integral force and moment could be obtained using these formulas:

$$\boldsymbol{F} = \int_V \boldsymbol{J} \times \boldsymbol{B} dV \tag{2}$$

$$\boldsymbol{M} = \int_V \boldsymbol{r} \times (\boldsymbol{J} \times \boldsymbol{B}) dV, \tag{3}$$

where: $\boldsymbol{F}$ and $\boldsymbol{M}$ – integral force and moment, $\boldsymbol{r}$ – radius vector.

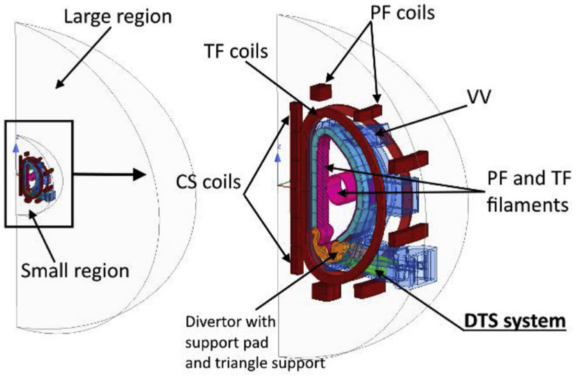

Fig. 2. Global model for electromagnetic analysis in Ansys Maxwell.

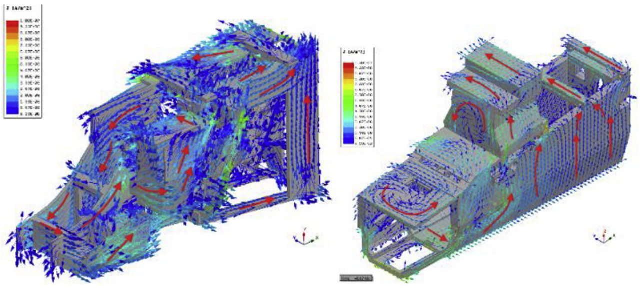

Fig. 3. Vector plot of eddy currents in the diagnostic system, A/m$^{2.}$

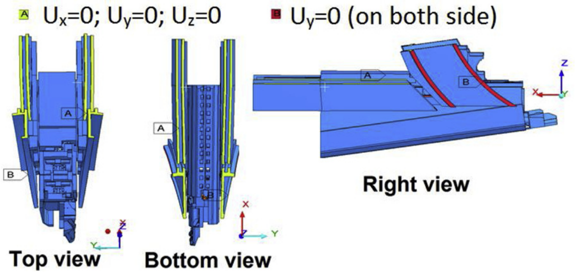

Fig. 4. Boundary conditions for the structural analysis.

Structural analysis was performed following electromagnetic analysis results. Electromagnetic force was transferred from EM analyses. Kinematic boundary conditions for the structural analysis are presented in Fig. 4.

VDE 3 DW scenario of plasma disruption is Category III load according to the ITER classification. It has been analyzed to withstand P type damage using service level C criteria from [4]. Stress assessment is presented in Table 1. Stress linearization is used to estimate construction strength according to [4].

As a result, stress values in the inner frame exceed allowable ones and don`t pass the structural criterion (see the Table 1). Equivalent stress intensity is presented in Fig. 5.

In order to reduce electromagnetic force values and integral force, moment in the DTS front rack, a modification of the front rack construction in terms of electric connections was suggested. Some dielectric insertions were added to reduce the size of current loops. Fig. 5 illustrates the suggested modifications (Fig. 6).

As a result of the model modification, currents have changed their direction. Therefore, integral forces and moments were decreased in the model with electrical insulation compared to the solid model.

3. Strength estimation of the supports

Cylindrical supports were introduced in the current DTS model design to minimize the influence of manufacturing imperfections. The radius of the supports 1–8 is 5 m (see Fig. 8). This type of support was used for all of the contact areas between DTS outer frame and radial rails.

According to [4], there is no direct stress criteria in the contact zone. Therefore, the simple structural criterion was used: stress in the contact area shouldn’t exceed the value of the material yield strength. Rails are not under the scope of this article, but we have to be sure that

Table 1
Summary of structural assessment of the diagnostic rack inner frame for P type damage.

Component	Linearized stress, MPa		Allowable stress criteria, MPa	Is criterion passed?
Upper support	P_m	55	155	Yes
	$P_L + P_b$	302	232.5	No

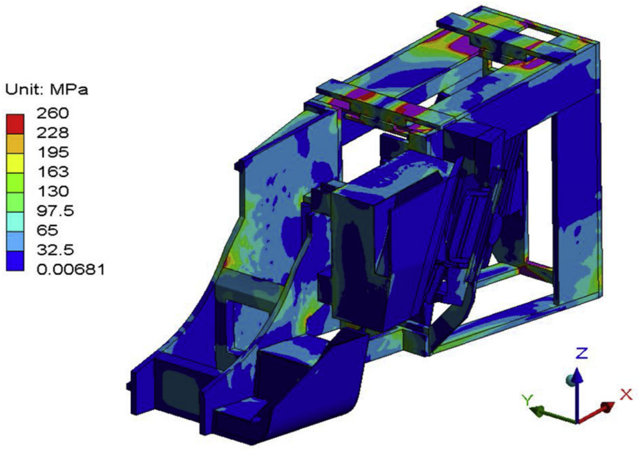

Fig. 5. Equivalent stress intensity in the inner frame, MPa.

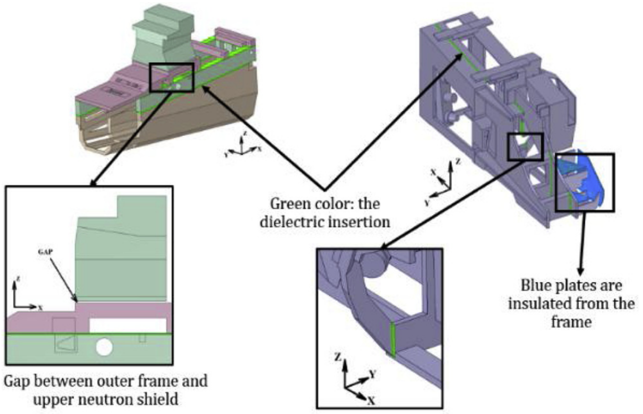

Fig. 6. Dielectric insertions in the front rack model.

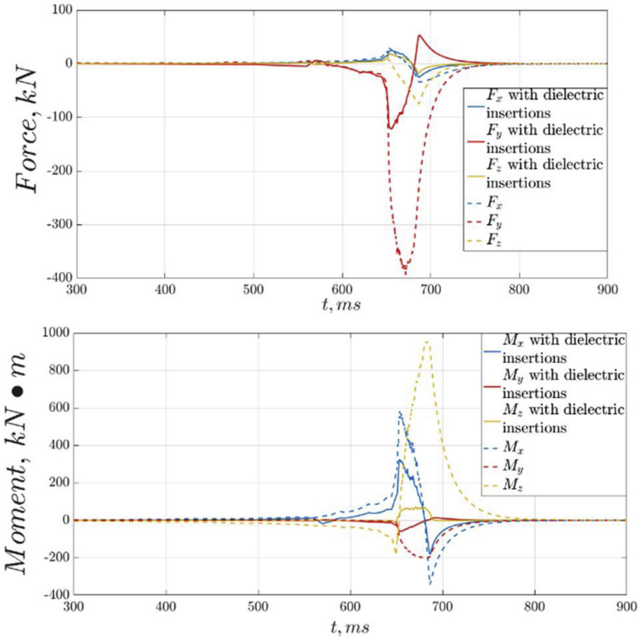

Fig. 7. Forces and moments acting on the DTS during VDE III fast scenario with and without insulations.

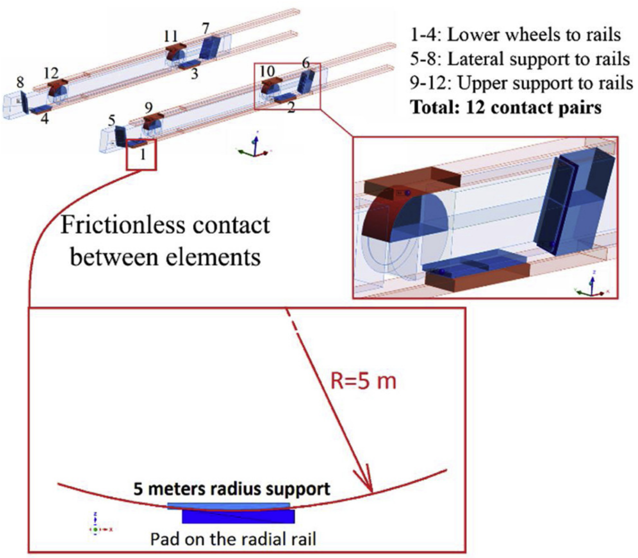

Fig. 8. Contact problem formulation. Contact areas #1–8 of the DTS system have curvature radius of 5 meters.

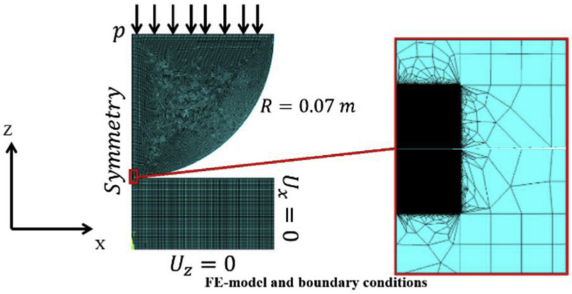

Fig. 9. FE-model and boundary conditions.

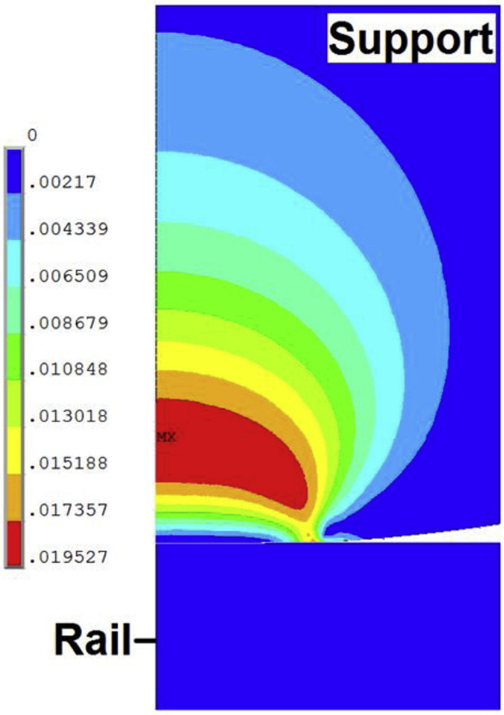

Fig. 10. Equivalent plastic strain for the upper wheel with 0.07 m radius and for the radial rail.

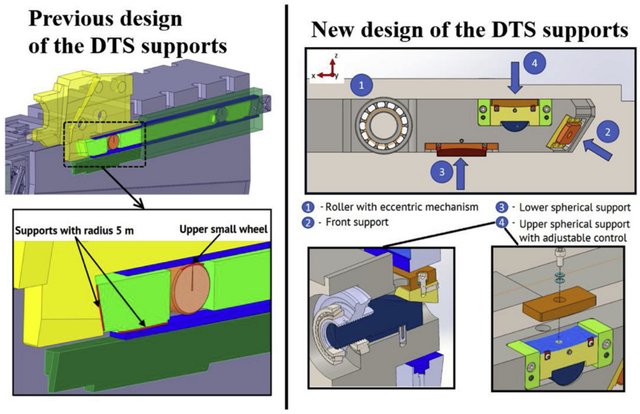

Fig. 11. Old design of the support system is (left side) and concept of new support system (right side). Component of the new support is marked with orange in the right bottom figure.

structure of the DTS will not get stuck in the port and will not destroy pads of radial rails.

Based on the SLS (system load specification) for the DTS system, maximum load in the vertical direction has been determined. Maximum load was considered to be Dead Weight x10 (acceleration in both OZ directions equals 98 m/s^2) because maximum value of acceleration for the SL-2 (seismic level 2) scenario equals 109 m/s^2, so the peak load values are close to each other. So, Dead Weight x10 could be considered as enveloping all of the main loads because all but 109 m/s^2 are much lower.

There are 12 contact pairs in model: 4 pairs between lower cylindrical supports and radial rails, 4 pairs between lateral cylindrical supports and radial rails, 4 pairs between upper wheels and radial rails. All contacts are frictionless. Fig. 7 shows the contact problem formulation.

After the global contact analysis, maximum force reactions were determined. Maximum force value in vertical direction for the upper wheel #9 (cylinder with 0.07 m radius) is 292 kN.

For the detailed estimation of contact stress the classical Hertz contact problem was considered: contact problem between cylinder and elastic half-space was explored. Finite element model formulation for the Hertz problem is presented in Fig. 9. Element size in contact region must be $\boldsymbol{e=0.01a}$, where $\boldsymbol{a}$ is half-width of contact area. Materials of wheel and rail in the FE model are non-linear (elastic-plastic formulation).

The value of the applied pressure is:

$$p = \frac{F_z}{S} = \frac{125kN}{0.00812m^2} = 15.5\,MPa \tag{4}$$

As a result, small plastic zone in the upper wheel was obtained and plastic strain is presented in Fig. 10. Maximum stress intensity in the wheel exceeds yield strength for the 316 L(*N*)-IG steel, which is about 200 MPa. The radius of plastic zone is about 10 mm. Stress intensity in the radial rail doesn`t exceed yield strength for the 660 steel.

Considering this result, we decided to make a new support system based on the spherical support with bigger radius. Support system is now in the preliminary design and it will be explored in detail in the future. This solution is expected to minimize stresses in the contact zone and to make the structural integrity positively assessed.

Concept of new support system is presented in Fig. 11.

4. Conclusions

According to EM analysis, the electrical insulations decreases integral forces, moments and ponderomotive force. This design solution could be good for the structural integrity of the DTS.

As a result of the contact analysis, radial rails will withstand structural integrity; stress intensity value doesn't exceed yield strength. Small wheel doesn't pass the structural criterion. Stress intensity in wheel exceeds the yield strength. This wheel should be modified in the future.

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