Electromagnetic Analysis of the ITER Port-mounted Bolometer Cameras

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Abstract: This paper describes the electromagnetic analysis procedure of the ITER (upper and equatorial) port mounted bolometer cameras. The main aim of the analysis besides the evaluation of the electromagnetic forces caused by changing magnetic fields is to find out the worst load case scenario for a particular bolometer camera. For this purpose, a wide range of load case scenarios has been analysed. The output from 2D axisymmetric code DINA is used as input to a general electromagnetic model of a 20° sector of the ITER structure, taking into account the contribution of all structural parts, in order to calculate eddy currents induced inside the bolometer components. The surrounding structure of the bolometer camera housing was modeled with particular precision in order to take the electromagnetic contributions of these parts into account as precisely as possible. To investigate the worst load case per camera type and position six representative disruption scenarios are analysed. In a second step, the Lorentz-forces resulting from the interaction of these eddy currents with the main magnetic field are deduced. They are an essential input for the structural assessment of the camera housing. This paper discus in detail EM analysis procedures used in case of port-mounted bolometer cameras.

Keywords: Bolometer, ITER, diagnostics, finite element analysis, EM analysis

1. Introduction

The ITER bolometer diagnostic provides the absolutely calibrated radiation emitted by the plasma, which is a part of the total energy balance. The development of its components is especially challenging because of the extreme environmental conditions within the experimental device during plasma operation. Reliable measurements have to be assured while being subjected to high neutron fluxes as well as plasma radiation resulting in temperatures of the components exceeding 200 °C. In addition to the thermal loads, the bolometer camera housing is exposed to mechanical loads caused by electromagnetic forces (EM) during transient events of the plasma operation, called disruptions. The time dependent evolutions of the plasma currents and magnetic fields during such events are the cause of EM forces by inducing eddy currents in the components surrounding the plasma. Bolometer cameras are also subject to the generation of eddy currents and the resulting EM forces. The bolometer cameras are positioned all over the plasma vacuum vessel including in two upper ports and in one equatorial port. These port mounted cameras vary in location and design, resulting in five different camera housing types. The analysis of the EM forces is a vital part of the structural integrity assessment.

The bolometer camera mounted in the upper position of the upper port 1 (UP01_UP) is chosen as representative case for the consideration in this paper.

2. EM analysis description

2.1. Analysis strategy

Temporal distributions of the magnetic fields and associated currents of six representative disruption scenarios for single ports (upper and equatorial) in ITER have been chosen among a wide range of load case scenarios available from simulations by 2D axisymmetric DINA code [1].

The electromagnetic analysis of the bolometer cameras has been carried out within a specific EM models which have been built for the analyses of the port plugs (separately for upper and equatorial port), with an environment based on the geometry of the ITER Global Model (IGM) model from IO [2].

Additionally, an entirely compatible model has been used to determine the static magnetic field, while the both specific port plug models have been used to determine the transient magnetic field according to Fig.1.

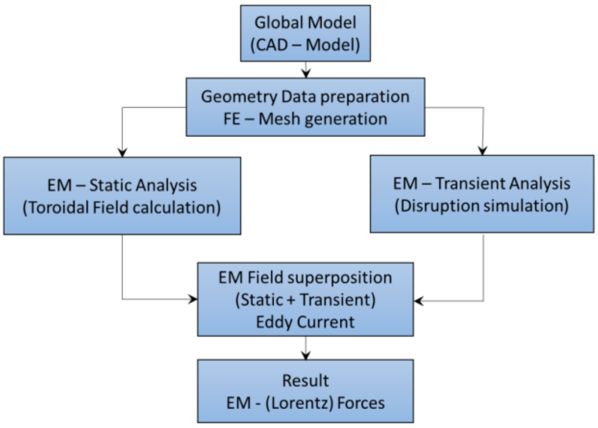

Fig. 1 EM analysis – flow chart

The investigation of the EM forces has been carried out in a post processing according the equation Eq. 1

$$\boldsymbol{F}(\boldsymbol{t}) = \int_{\boldsymbol{v}} \big((\boldsymbol{B}^{\boldsymbol{s}} + \boldsymbol{B}^{\boldsymbol{t}}(\boldsymbol{t})) \times \boldsymbol{J}^{\boldsymbol{t}}(\boldsymbol{t}) \big) \boldsymbol{V} \boldsymbol{d}_{\boldsymbol{v}} \qquad \text{Eq. 1}$$

where *t* is the time step, $F(t)$ is the Electromagnetic force, B^s is the magnetic field obtained in the static analysis, $B^t(t)$ is the magnetic field obtained in the transient analysis, $J^t(t)$ is the current density obtained in the transient analysis and V is volume. According to this

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equation – the static and transient magnetic fields are algebraically summed and multiplied by the eddy current density and integrated over the volume for any given time step. In the transient analysis only the poloidal and toroidal magnetic field variation have been considered, while the halo current was neglected because the port plugs are recessed with the respect to the ITER first wall.

2.2. Global EM model

The global EM model is a 20º sector of the experimental device, and includes the Vacuum Vessel, the Upper and Equatorial Port, the Blanket modules, the central solenoid (CS) and poloidal field (PF) magnets, the plasma secondary excitations (PFV), and the plasma toroidal field variation (TFV) excitation. Fig.2 shows the main components of the EM model with the positions of the bolometer cameras mounted in the upper port. All conducting structural parts are enveloped with air defined as a spherical sector with a radius of 85.0 m. The whole EM model is built of totally 3.612.312 solid elements and 622.729 nodes.

The entire EM analysis is carried out by using ANSYS-EMAG [3] software. The finite elements for all FE models are of Ansys element SOLID97 type. This element type is based on the magnetic vector potential formulation with Coulomb gauge and it is the one most commonly used for eddy currents (transient analyses). For the conducting structural parts like VV and port plug structure the SOLID97 element with degree of freedom (DOF) of AX, AY, AZ and VOLT were applied. In case of non-conducting structure like air, plasma region, CS and PF coils, the SOLID97 elements with DOF of AX, AY and AZ were applied.

In a static analysis the toroidal magnetic field has been calculated only. The corresponding model consists of 18 toroidal field magnets modelled by the Ansys element type SOURC36 fully compatible to SOLID96 element for modelling magnetic fields in a static analysis. This model contains a segment of 20° with all main structural components except the TF coils.

In case of transient EM analysis the cyclic boundary conditions have been used at both side of the 20° sector. In order to define the cyclic boundary condition, a coupled DOF was applied to the pair of nodes on both sides of the sector.

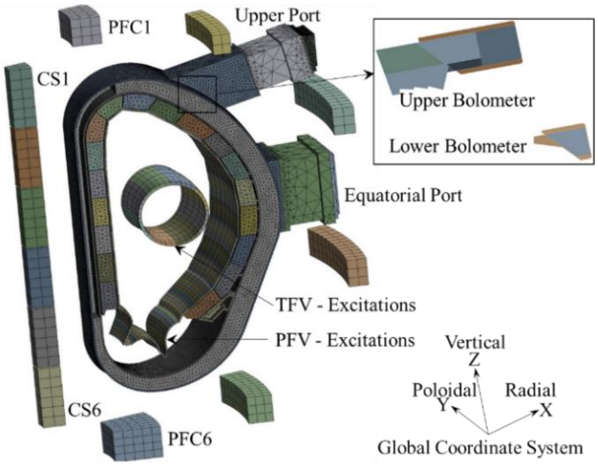

Fig. 2 EM model – main components (segment 20°)

An APDL routine was written for DOF coupling to pick up the nodes on both sides. The node pattern on one side has to be geometrically identical to the node pattern on the other side. For the nodes at the central symmetry line of the machine all DOFs of AX, AY and AZ were locked. The INFINITI111 Ansys elements type was used for the definition of infinite boundary at the exterior air region.

2.3. Bolometer camera EM model

The upper port camera mounted in upper port is chosen as representative in the following considerations.

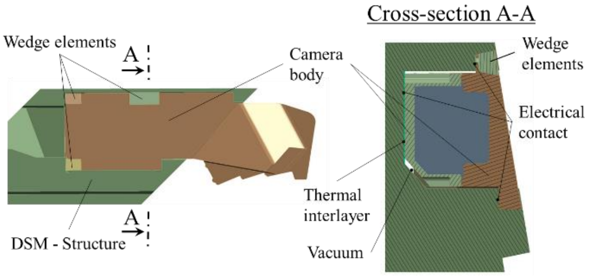

Fig. 3 Upper port upper bolometer camera assembly

Fig. 3 shows the assembly of the body of the bolometer camera mounted in upper port including a part of the port structure directly surrounding and carrying the camera (denoted in Fig. 3 as DSM – Diagnostic Shield Module). Conducting components of the camera structure are modeled only. The EM model contains some camera fixation details important for the analysis like wedge and bolts elements. The bolometer camera housing is electrically connected to the surrounding upper port structure over both flanges, wedge elements and the thermal interlayer only. All other camera body surfaces are insulated by vacuum. The distance between camera body and the surrounding structure amounts in places less than 1.0 mm, which made creating the model quite challenging.

2.4. Material properties

Table 1 shows the material properties of the bolometer camera body and the immediate structural parts electrically connected with the camera body. The values in table 1 have been chosen at a temperature of 100°C [4].

Table 1 Electrical resistivity for component / material

Component	Material	Perme-ability	Resistivity (Ωm)
Vacuum	-	1	-
Bolometer body	CuCrZr (100°C)	1	2.71E-08
Thermal interlayer	Sigraflex® (100°C)	1	2.21E-08
Wedge and bolts	Stainless Steel (AISI316)	1	8.00E-07
Port (DSM) structure	75.5% SS316N-IG+25.5% Water	1	1.06E-06

2.5. Load specification

The EM analysis is defined to cover the EM load cases described in the load specification for bolometers mounted in upper [5] and equatorial [6] port. Fig. 4 shows the evolution of the plasma current for a load case named “VDE_UP_36”. While the typical DINA code output uses a very fine time increment with 492 time steps, for the FE analysis only about 120 points in time have been chosen. Knowing that ANSYS applies a linear interpolation between two points, the distribution of steps in time have been adapted adequately, like indicated in Fig.4 by the red dots.

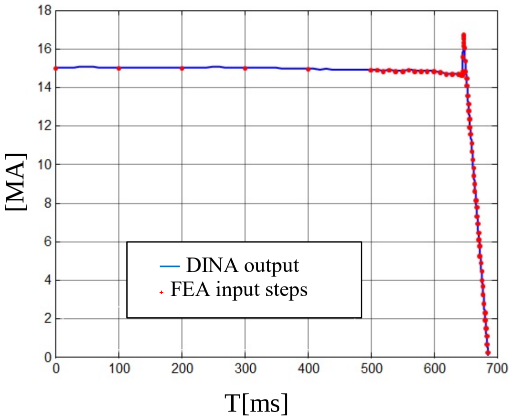

Fig. 4 Total plasma current – load case “VDE_UP_36”

3. Results

The maximal magnetic field flux density determined in the static analysis amounts to 11.1 T. A total of 6 disruption load cases were analyzed in transient EM analysis. The input data for the analysis have been generated by DINA code and the load scenarios were chosen according to the System Loads Specification for Upper Port mounted bolometer cameras [5]. The maximum EM forces for the upper bolometer mounted in upper port have been found for the case of the load scenario called "VDE_UP_36”, closely followed by “FU_VDE_II”.

Fig. 5 shows the magnetic flux density field pattern of the transient analysis in case of "VDE_UP_36” load scenario at the moment of its maximum value of 9.5 T, at time of 10.8658 sec.

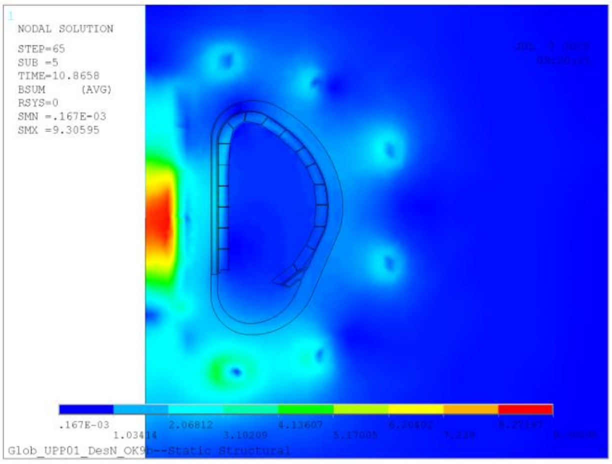

Fig. 5 Magnetic flux density field

Fig. 6 shows the magnetic flux density field pattern of the same load case at the body of the upper bolometer camera mounted in the upper port at time of 10.8658 sec. with the local maximal magnetic field of 0.98 T.

The eddy current density induced in the upper camera body of the upper port during the plasma disruption at the moment of its maximum of 1.43E+08 A/m^2 is shown at Fig. 7.

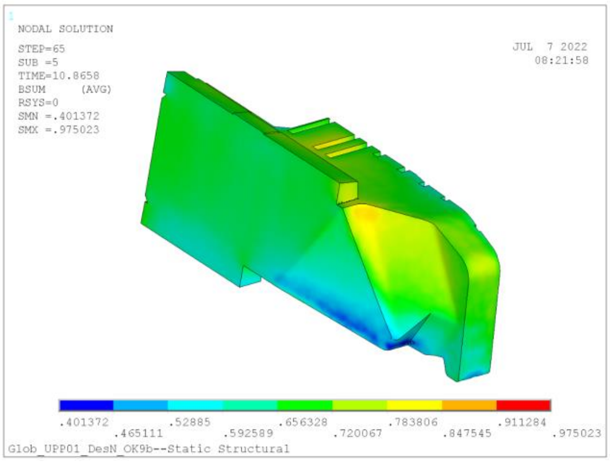

Fig. 6 Magnetic flux density field at the upper camera

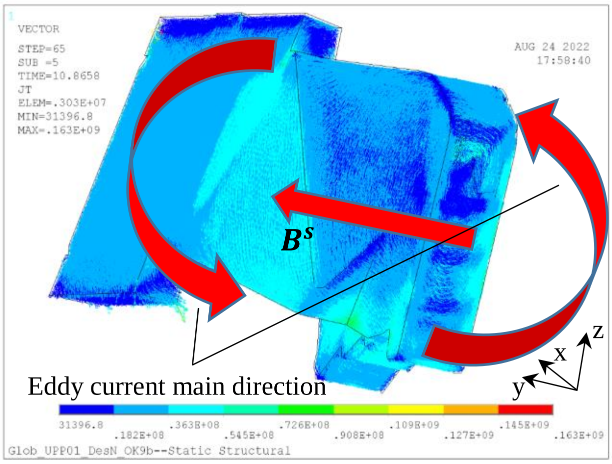

Fig. 7 Eddy current at the upper bolometer camera

While the static toroidal magnetic field ($\boldsymbol{B}^s$) is more or less constant and roughly perpendicular to the camera body (i.e. in y-direction), the eddy current, because of the loop, changes its direction w.r.t. the magnetic field. This constellation causes the generation of electromagnetic forces within the camera body in opposite direction. It follows that the forces acting on individual parts of the bolometer body are higher than the resulting force of the entire bolometer.

Additional results evaluation of the EM analysis shows that the flow of the eddy current through the interfaces between camera body and the DSM supporting structure (flanges and thermal interlayer) is quite low, because of the high difference of the electrical resistivity, according to the table 1.

The highest electromagnetic force has been found for the load case “VDE_UP_36” at time point 10.865s with a value of –96.5 kN. The direction of the main force is along the x-axis of the local coordinate system (Fig. 7), which corresponds roughly to the radial direction of the global tokamak coordinate system. The highest force in y-direction (which corresponds mainly to the toroidal direction of the global tokamak coordinate system) appears for the load case “FU_VDE_II” at time point 10.865s with a value of 7.80 kN. The highest force in z-direction (which corresponds mainly to the vertical direction of the global tokamak coordinate system) appears for the load case “FU_VDE_II” in at time point 10.865s with a value of 27.4 kN.

Table 2 shows the resulting maximum EM forces acting on the upper camera body for both load cases.

Table 2 Maximal total EM forces for worst load case

Load case	Time [sec.]	EM Force [kN]			
		Fx	Fy	Fz	Ftot
VDE_UP_36	10.8658	-96.5	-7.21	-26.7	100.4
FU_VDE_II	10.8658	-82.0	-7.8	-27.4	86.7

Table 3 shows the maximal EM moments acting at the upper camera body reached in the “VDE_UP_36” and “FU_VD_II” load cases, evaluated regarding the camera body center of gravity, with the coordinates x= 6.5106 m, y= 0.12671 m and z= 4.7321 m.

Table 3 Maximal total EM moment for worst load case

Load case	Time [sec.]	EM Moment [kNm]			
		Mx	My	Mz	Mtot
VDE_UP_36	10.8658	0.53	-4.81	29.21	30.1
FU_VDE_II	10.8658	4.3	1.24	24.0	24.4

The highest total electromagnetic force and moment is reached in the “VDE_UP_36” with a maximum force of 100.4 kN and a maximum moment of 30.1 kNm.

The time evolution of the electromagnetic force components for the worst case scenario of the upper bolometer camera mounted in upper port are shown in Fig. 8.

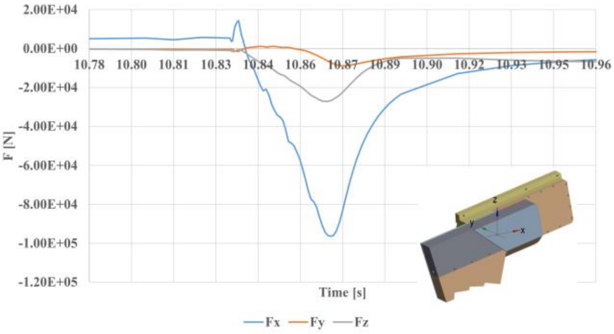

Fig. 8 Time evolution of EM force components

The last step of the EM analysis is the extraction of the volume forces needed for subsequent structural analysis. An interface specifically written for this purpose extracts the electromagnetic volume forces of a single structural part from the whole EM model. This data file contains the centroid coordinates of each single element followed by the 3 components of the volume force and the volume of the element concerned (Table 4).

Table 4 Template for the volume force extraction

Element Number	X [m]	Y [m]	Z [m]	Fx [N]	Fy [N]	Fz [N]	Vol [m3]

4. Conclusions

All main steps of an electromagnetic analysis carried out for the ITER port mounted bolometer cameras have been described in the present paper.

Two fully compatible models were used for each port (upper and equatorial), first to determine the static magnetic field and second to determine the transient magnetic field. The calculation of the EM forces has been carried out within the post processing using a routine specifically written for this purpose.

The main task of the analyses consisted of evaluating the electromagnetic forces caused by changing magnetic fields as well as to find out the worst load case for a particular bolometer camera. After studying a wide range of results made available by 2D axisymmetric code DINA, six load case scenarios representative for ports have been analyzed. The selection of the load cases differs for the individual port mounted cameras.

The upper bolometer camera mounted in the upper port described in this paper is the most demanding one. The maximum EM forces or moments for this camera have been determined in the case of the load scenario called "VDE_UP_36”, closely followed by the load scenario called “FU_VDE_II”.

The highest total electromagnetic force and moment reached for this load case is with a maximum force of 100.4 kN and a maximum moment of 30.1 kNm.

Finally, the volume forces for a subsequent structural analysis were made available.

Disclaimer

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