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The next D-T campaign will push JET ITER-like Wall (IWL) to high divertor power and energy levels. During the 2016 campaign, the Strike Point (SP) sweeping permitted relevant H-mode scenarios without exceeding the temperature limits imposed by JET Operation Instructions (JOIs). In the subsequent shutdown, six outer divertor tungsten-coated 2D carbon fibre composite (CFC) tiles were found to have inter-laminar cracks.

Here we describe the results of a 3D thermo-mechanical analysis aimed at understanding the origin of the cracks. A sensitivity assessment has been carried out on the temperature time-evolution of a realistic tile 3D model during high power pulses, both with fixed and sweeping SPs. Time and space-varying heat flux density loads on the divertor have been calculated using different techniques for reconstructing the power footprint. The results have been benchmarked against the temperature measurements by high resolution infrared diagnostic systems.

The study confirmed the source of the cracks and their localization in the upper part of the tile, giving inter-laminar tension higher than the Ultimate Tensile Stress. Plasma input power, radial location of the SP and amplitude of the sweeping area play an important role on the stress field whose maximum value strongly depends on the SP location. Their influence on the maximum stress value has been investigated and optimized to maximize the performance of divertor tiles without exceeding the limits on input energy and maximum surface temperature imposed by the JOIs.

Keywords: JET, Divertor integrity, ILW, D-T preparation, Synthetic plasma pulses, Experimental validation.

1. Introduction

The Joint European Torus (JET) is the world largest tokamak and the only one able to operate with tritium. The upcoming experimental campaign will be of great importance for ITER, foreseeing the exploration of isotope effects on transport, confinement, L-H mode transition, pedestal physics, and plasma-wall interaction by operating with H₂, D₂ and T₂ using the ILW. Going towards its second D-T campaign (DTE2), JET will be pushed to much higher power levels. Every operational scenario must comply with the JOIs [1] that define limits on JET experiments to prevent excessive heat loads on Plasma Facing Components (PFCs). As the JET divertor targets are inertially cooled, these limits are imposed on plasma input energy and on maximum surface temperatures.

The 2015-16 JET experimental campaign, enhancing the High-performance plasma scenario in preparation for the DTE2, was characterized by plasma pulses performed by sweeping the SP [2]. This technique permitted high power pulses for longer without exceeding the temperature limits on the divertor surface where the hot exhaust plasma streams along the open magnetic field lines, Figure 1. The divertor targets holding the SP are the inboard vertical (3) and horizontal (4) tile rows and the outboard horizontal (6) and vertical (7) tile rows near the pumping duct entrance. After the installation of the JET ILW [3], the divertor tiles are all made of 2D CFC covered by a thin layer of tungsten (~20µm) except the central row that is made of bulk tungsten.

Although the last campaign was one of the most successful for improving plasma physics understanding, cracks were subsequently found in five Tile 6s. The cracks

extended radially along inter-laminar planes. Initially it was not known whether the cracks were superficial (coating delamination damage) or through-thickness of the upper part of the tile (Figure 2). Sometimes the cracks were accompanied by droplets on the upper surface.

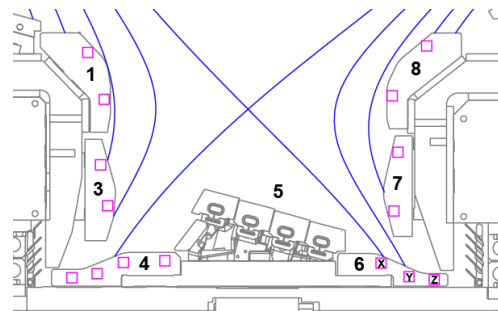


Figure 1. Cross section of the JET divertor after the ILW installation.

Tile 6 integrity is fundamental for DTE2 scenario development as it is the most requested target. Risks connected to its failure are: 1. release of particle impurities into the plasma; 2. tritium absorption by CFC; 3. tile erosion on the high-flux side. In addition, previous studies on the failure of the tie rods which hold the CFC plies together showed that they don't prevent tile cracking [4], and this poses a risk of a combined failure leading to complete tile breakage inside the machine. To reduce the risk of further failure during the upcoming JET restart phase, the cracking damage has led to a deep investigation of the thermo-mechanical behavior of Tile 6. The study, based on modelling the real-time heat load acting on the tile surface, aims to find a relation between the tile stresses and the range of plasma parameters related to this phenomenon.

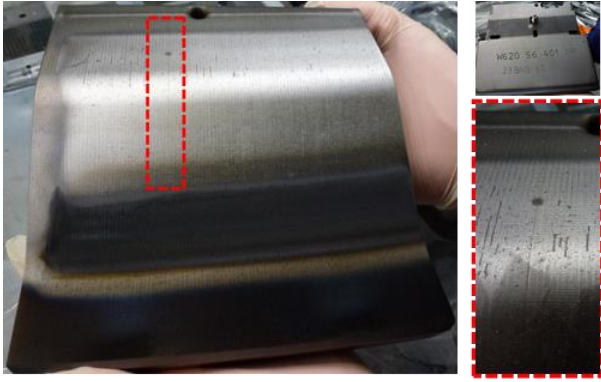


Figure 2. Cracking damage observed on Tile 6.

2. Characterization of the failure mechanism

The risk of delamination of tungsten coating and the tungsten re-crystallization temperature (1200°C) requires real-time protection during operations. Infra-Red (IR) thermography based on image diagnostics (IR Cameras) has been installed and upgraded [5] for detecting hot spots on PFCs and, if necessary, stopping pulses. In this study, the IR data will be used as a reference for validating the results.

The main issue is the calculation of a realistic heat flux load on the divertor tile. Using Finite Element (FE) modelling for transient thermo-mechanical analyses, the study can be divided into two phases characterized by two different assumptions on computing the realistic heat load on the tile surface:

- Phase 1: capturing of the failure modes using IR-derived heat flux loads calculated through inverse analyses [6] and identification of the main machine parameters affecting the behavior of the tile.
- Phase 2: creation of synthetic shots linked to the next C38 campaign using a convolution of a Gaussian with an exponential profile (Eich's function) for calculating the power footprint on the tile surface [7].

2.1 Geometry, FE model and materials

The Tile 6 FE model is shown in Figure 3. Tie rods are not needed in this work for the reason explained in [4]. The tile is made of CFC plies stacked along the toroidal direction (ϕ -axis in Figure 3), covered by 20 μ m tungsten layer. The model includes the temperature dependence and orthotropic nature of the CFC.

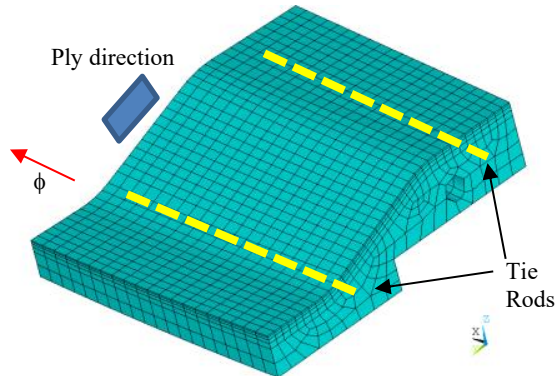


Figure 3. Tile 6 FE model.

From the structural point of view, isostatic constraints have been imposed on Tile 6 FE model.

2.2 Phase 1: cracking damage investigation

Table 1 shows the pulses of interest from the last campaign. Two fixed SP pulses (denoted with the subscript 'f') and two swept pulses (denoted with the subscript 's') have been chosen.

Table 1. JET Pulse Numbers (JPN) of interest.

JPN	Experiment	I_p [MA]	B_T [T]	SP [m]	NBI [MW]	Δt [s]
89297 _f	M15-02 Hybrid scenario for D-T	1.9	1.4	~0.24	13.0	7.0
90287 _f	M15-02 Hybrid scenario for D-T	1.9	1.4	~0.24	13.4	7.5
90271 _s	M15-02 Hybrid scenario for D-T	2.4	2.8	0.24-0.27	17.0	7.5
92025 _s	M15-02 Hybrid scenario for D-T	2.5	2.9	0.24-0.27	23.5	5.5

Applying IR-derived heat flux loads on the tile surface and a Toroidal Wetted Fraction (TWF) of 70%, a good agreement (within 15%) between the experimental data and the modelled T_{MAX} time-evolution has been obtained for all the pulses (Table 2).

Table 2. Summary of experimental and FEM data for each pulse for Tile 6.

JPN	Thermal Results				Mechanical Results
	Experimental Data		FEM Data		Toroidal stress [MPa]
	IR T_{MAX} [°C]	Thermal Energy [MJ]	IR T_{MAX} [°C]	Thermal Energy [MJ]	
89297 _f	873	32.02	794	29.76	6.05
90287 _f	1039	36.48	848	36.48	7.61
90271 _s	1017	50.84	918	48.00	7.32
92025 _s	1107	39.82	936	33.83	6.76
92025 _s 1.12*	1107	39.82	1194	38.40	8.05

*: same JPN:92025 whose thermal energy input the divertor has been incremented by 12%.

In the following, the results related to JPN:92025 are reported in terms of comparison between $T_{MAX,IR}$ and $T_{MAX,FEM}$ time-evolution trends (Figure 4) with temperature and stress contour plots (Figure 5) related to the time instant in which their maximum values are reached. These results are representative of the results obtained for all pulses analyzed.

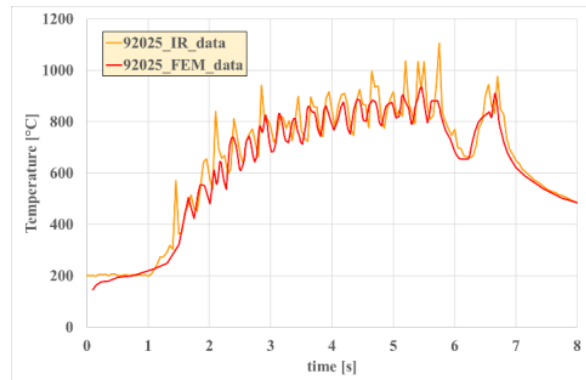


Figure 4. Comparison between experimental T_{MAX} and modelled T_{MAX} - JPN: 92025.

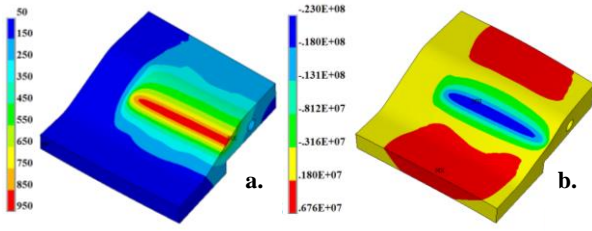


Figure 5. (a.) Time-instant thermal field [°C] and (b.) related stress field distribution [Pa] on Tile 6 for JPN: 92025 swept pulse.

2.3 Phase 1 preliminary conclusions

The results show the synergic effects of two large thermal gradients: radial and vertical. The radial gradient ($\sim 800^\circ\text{C}$) on the top surface between the central area intersected by the SP and the cooler sides (Figure 5a) leads to central compression and tension on the sides (Figure 5b). These side tensile stresses tend to delaminate the tile and are exactly where the cracks appeared (Figure 2) and of magnitude consistent with local failure (the inter-laminar tensile strength is about 7 MPa). This effect is enhanced by the vertical thermal gradient which causes a toroidal bending of the tile with increased tension on the top surface. A relation between these stresses and the tile thermal energy is investigated in Phase II.

3. Phase II: sensitivity analysis using synthetic pulses

The limited number of high-resolution JET pulses, the good agreement with the IR data obtained in Phase I and the need to investigate the relation between stress field and operational parameters (SP position, sweeping amplitude) led to a sensitivity analysis based on *synthetic* shots. **Synthetic shot:** discharge related to the up-coming JET C38 campaign simulated imposing constant values of NBI, ICRH and Ohmic power for 6-7 seconds and using Eich's function for the heat load profile (engineering power footprint) by imposing engineering and plasma parameters (B_t , I_p , n_e , f_{ELM}) [8]. The methodology uses three main steps (Table 3).

Table 3. Summary of the methodology steps.

Methodology			
Rationale	Phases	Data	Outcome
Validation against existing discharges	Step I	Read from JET database: <ul style="list-style-type: none"> B_t, I_p, n_e, f_{ELM} NBI, ICRH, Ohmic power 	engineering footprint vs IR-derived heat flux (checks in T_{MAX} and σ_{MAX})
	Step II	Read from JET database: Imposed constant values: <ul style="list-style-type: none"> NBI, ICRH, Ohmic power 	synthetic swept pulses against IR-derived data (checks in T_{MAX} and σ_{MAX})
Synthetic shots	Step III	Imposed constant values: <ul style="list-style-type: none"> B_t, I_p, n_e, f_{ELM} NBI, ICRH, Ohmic power 	JET C38 experimental campaign synthetic shots and sensitivity analysis

Step I validates the engineering power footprint against the IR-derived heat flux. Step II validates the

swept shots of Table 1 recreated synthetically against IR-derived data. Step III is independent of existing experimental data and studies the effect of operational parameters on the tile mechanical stress using synthetic shots.

3.1 Step I: engineering footprint vs IR-derived heat flux

The two swept shots of Table 2 have been run using the engineering power footprint [8] for modelling the power density on the tile surface. Compared to the results using IR-derived heat loads, the error on T_{MAX} is about 13% and the error on σ_{MAX} is around 38%. Overall, the power footprint gives a good estimation of the heat load, but it needs to be refined during the up-coming restart phase. Main limitations: an average value of n_e ($1.4\text{E}+20 \text{ m}^{-2}$) and f_{ELM} (40 Hz) is imposed during the shot.

3.2 Step II: synthetic pulses vs IR-derived data

The two swept shots of Table 2 have been recreated synthetically using the power footprint validated in Step I as heat load and imposing from scratch the plasma power input. The power going into the SOL has been estimated according to the following conservative assumptions: 1. NBI and ICRH power input assumed constant for 6-7 seconds; 2. constant radiated power loss by fraction of 30% ($P_{\text{RAD}}=0.3 \cdot P_{\text{TOT,plasma}}$). Through forward analyses [6] the estimated power density on the divertor surface was applied in the thermo-mechanical FE model and gave promising results that will be reviewed during the JET experiments. The error obtained on T_{MAX} and σ_{MAX} is of the same order of magnitude as before.

Having validated the procedure against existing pulses, the study has been carried on without relying on existing experimental data.

3.3 Step III: synthetic pulses and sensitivity analysis

This step creates new pulses for Hybrid and Baseline scenarios planned for the next JET campaign. Two different power levels have been set, according to the availability of the NBI (30 and 40 MW), as well as different values for SP location and sweeping amplitude. The sensitivity analysis examines how the last two variables affect the thermally-induced stress for a fixed power level. For every SP location (2.85, 2.90, and 2.95 m major radii), two different sweeping amplitudes have been considered (0.03-0.06 m, see Figure 6).

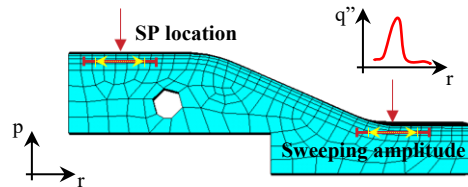


Figure 6. Main parameters involved in the sensitivity analysis.

The sensitivity analysis has confirmed the proportionality between Tile 6 toroidal stress and thermal energy input to the tile. Figure 7 and Figure 8 show the results, in term of T_{MAX} and σ_{MAX} time-evolution, respectively, of the 40 MW pulse with different

combinations of SP locations and sweeping amplitudes. A change in SP location can reduce the stress value by up to 60% when the SP is moved outboard and only slightly affects the T_{MAX} .

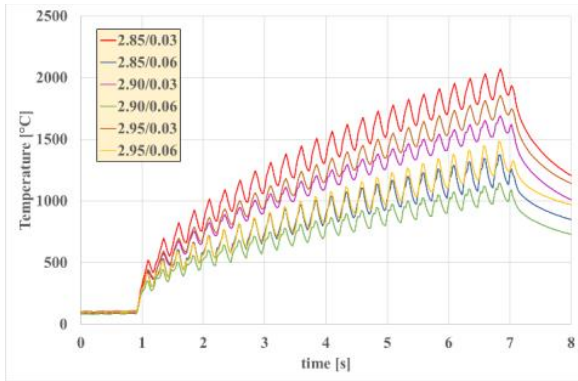


Figure 7. Tile 6 T_{MAX} time-evolution for a 40 MW plasma pulse at different SP locations and sweeping amplitude.

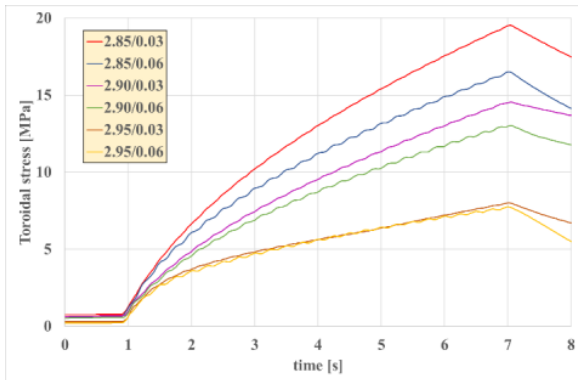


Figure 8. Tile 6 σ_{MAX} time-evolution for a 40 MW plasma pulse at different SP locations and sweeping amplitude.

In contrast, change in the sweeping amplitude has beneficial effects in decreasing the T_{MAX} but not in lowering the stress. A good combination of SP location and sweeping amplitude can help in keeping the stress value under the Ultimate Tensile Strength of the material.

3. Conclusions

The cracks found in some JET divertor Tile 6s during the last shutdown have led to an investigation of the thermo-mechanical behavior of Tile 6s under transient plasma heating. The study has identified the main operational parameters that can be monitored to avoid further cracking during the upcoming campaign (Figure 6).

Preliminary conclusions show the dependency of thermal stress on the energy discharged onto the tile through the SOL, therefore suggesting increasing stress values as the plasma power input increases (see red trend line in Fig. 10 where each point is representative of the pulse in Table 2 having different power levels but the same SP location).

The sensitivity analysis relevant to the next campaign has underlined that the dominant effect on tile stress is due to the SP position, as Figure 9 clearly shows. Each line indicates three SP positions and the associated pulses with different sweeping amplitude (0.03 and 0.06 m represented using open and closed circle markers, respectively) and different input power levels (30 and 40

MW, indicated with light and dark color for the same sweeping amplitude, respectively). For the most outboard SP at 2.95 m (green line), the sweeping amplitude doesn't have such a significant influence compared with the inboard case (2.85 m). For the 2.95 m case, about 17% of the SOL power is released in Tile 7, so the energy sharing between Tile 6 and Tile 7 can reduce the stress by about 40-60%. The sweeping amplitude has influence on the T_{MAX} but very slight influence on the maximum toroidal stress.

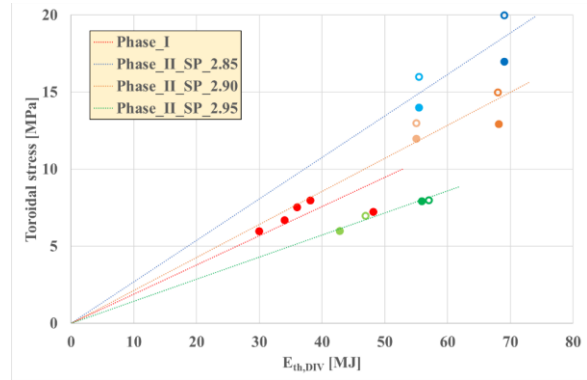


Figure 9. Toroidal stress against Tile 6 thermal energy.

The assumptions and the limitation of the methodology (which will be validated during JET operations) are conservative (T_{MAX} values are higher than expected). This does not affect its goal because it has been useful for understanding the relation among stress, SP location, sweeping amplitude and plasma power levels and in identifying the Strike Point location as the most critical parameter.

Acknowledgments

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