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Power Handling of a Segmented Bulk W Tile for JET under Realistic Plasma Scenarios

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ABSTRACT.

A solid tungsten divertor row has been designed for JET in the frame of the ITER-Like Wall project (ILW). The plasma-facing tiles are segmented in four stacks of tungsten lamellae oriented in the toroidal direction. Earlier estimations of the expected tile performance were carried out mostly for engineering purposes, to compare the permissible heat load with the power density of $7\text{MW}/\text{m}^2$ originally specified for the ILW as a uniform load for 10s.

The global thermal model developed for the W modules delivers results for more realistic plasma footprints: the poloidal extension of the outer strike point was reduced from the full lamella width of 62 mm to $\geq 15\text{mm}$. Model validation is given by the experimental exposure of a 1:1 prototype stack in the ion beam facility MARION (incidence $\sim 6^\circ$, load $E \leq 66\text{MJ}/\text{m}^2$ on the wetted surface). Spreading the deposited energy by appropriate sweeping over one or several stacks in the torus is beneficial for the tungsten lamellae and for the support structure.

INTRODUCTION

The bulk tungsten divertor row was designed in the frame of the ITER-Like Wall project (ILW) at JET for the position of the outer strike point in numerous plasma configurations relevant to ITER. The actual hardware is described elsewhere [1,2]. Figure 1 shows a top view of two neighbouring modules which clearly displays the segmentation of the tiles. They consist of four blocks oriented in the toroidal direction ; these are stacks of tungsten lamellae sandwiched with spacers that ensure 1 mm wide poloidal gaps. The arrangement is determined by the minimisation of the electromagnetic loads under a rate of change of $100\text{T}/\text{s}$ for the magnetic field and halo currents up to 2.5kA per stack [3]. The corresponding thermal modelling was based, for engineering purposes, on a uniformly deposited power density around $7\text{MW}/\text{m}^2$ for 10s, equivalent to a typical JET pulse with a $\leq 10\text{s}$ heating phase and a deposition of $70\text{MJ}/\text{m}^2$ in the outer divertor. The toroidal shadowing of the stacks was considered with a so-called Global Wetted Fraction (GWF) around 0.7 in most cases [4]. A Local Wetted Fraction (LWF) Solid tungsten divertor row was also introduced to account for the geometry of the top surface of single lamellae. First implications of the thermal load for the plasma scenarios were reported in [5].

The poloidal extension of the plasma footprint was not duly considered yet, although the power deposition profile at the strike point does obviously not even cover the full length of a lamella (equivalent to the stack width of 62mm). The present work reports on our estimations in this respect, on the experimental validation of the thermal model, and accordingly on recommendations for operation.

Plasma profiles and results of thermal calculations We assume that the power deposition profiles are exponential in the Scrape Off Layer (SOL) at the outer mid-plane. The elevation of the field lines on the plasma-facing surface θ_\perp varies linearly with the major radius R . The angles of incidence are defined as in Fig.2. The field angle θ_\perp at the position R_{str} of the strike point is used across the full profile and a is a positive fixed value. The mid-plane decay length $\lambda_m = 5\text{mm}$ and

(B_ϕ, B_p) respectively represent the toroidal and poloidal magnetic field components. The poloidal expansion is around 4. The outer part of the power density profile (SOL) reads [6] :

$$q(MWm^{-2}) \sim \frac{1}{\lambda_m} \frac{B_{p,m}}{B_{p,m}} \frac{1}{2p R_{str}} \frac{\sin(a + \theta_\perp)}{\cos\theta_\perp} \exp\left(\frac{-a (R_{str} R_{str})}{\lambda_m} \frac{B_{\phi,m}}{B_{p,m}} \tan\theta_\perp\right) \quad (1)$$

And a similar expression is valid for the Private Flux Region (PFR).

Former thermal calculations with the Global Thermal Model (GTM) [4,5] reported moderate temperatures for a uniform exposure to $60MJ/m^2$, which is roughly equivalent to $60MJ/stack$ at $GWF = 1$. The tungsten surface reaches $T_{W,surf\ lmax} \approx 1330^\circ C$. We can now compare with the following cases, normalised to the same energy of $60MJ$ deposited within 10s on stack 3, for instance (Fig.3a and b):

- the power deposition profile is static, R_{str} is fixed on stack 3 (see Fig.1),
- the strike point is swept over stack 3, triangularly at 4Hz, and the HFS and LFS tails of the profile slightly wet stack 2 and stack 4 respectively.

The temperature at the end of the pulse shows a clear difference between the deposition patterns (Fig.4): whereas the tungsten surface almost reaches $T_{W,surf\ lmax} = 1900^\circ C$ under static exposure, the sweep brings the maximal temperature down to about $T_{W,surf\ lmax} = 1420^\circ C$. This is only $100^\circ C$ more than in the case of uniform exposure. The desirable limits are reminded of in [b]. For tungsten, higher temperatures induce re-crystallisation and a later risk of rupture through a loss of ductility after considerable thermal cycling. The first recommended levels for experimental campaigns are $1200^\circ C$ and $1600^\circ C$. Note that the supporting structure, tile clamping and wedge carrier, equally survives to all three cases but sweeping over several stacks may be advantageous for them as well.

Similarly, if the range can be extended from 100mm to 150mm, triangular sweeping over the three lower stacks permits the deposition of a higher total energy (150MJ) while keeping the tile temperatures to reasonable values. Higher depositions may require an extension of the sweeping strategy. Sweeping is always attractive since it distributes the energy over several stacks, lessening the disadvantage of segmentation. These aspects are summarised in [g]. The discussed examples are synthesised in Table I.

Those results call for two comments. Firstly, the peak temperatures estimated in the last column of the table correspond to a cold start with the divertor in thermal equilibrium with the wall at $200^\circ C$. A following pulse with insufficient cooling time, i.e. the tiles would not be back to the initial temperature, may well produce $T_{W,surf}$ values that are $100-200^\circ C$ higher. In some cases, for instance “static 3”, this is unacceptable for technical reasons (carrier temperature limit at $600^\circ C$) and should be ruled out by the operating instructions.

Secondly, the contribution of transient heat excursions like ELMs is not properly accounted for. Pulses with a plasma current in the range 3.25-3.5MA, a total injected energy around 170 MJ and $W_{plasma} \sim 8MJ$ were used to produce large Type I ELMs with losses $\Delta W_{ELM} \leq 0.6MJ$ (JET Pulse No: 79757-8) in the present JET configuration. The surface temperature of the current tungsten coatings

on a dedicated tile 5 (CFC substrate), measured with pyrometers and with the KL9 IR-camera [8,9], reaches $T_{W,surf} \leq 2000^\circ\text{C}$. This lies beyond the defined limit of 1600°C for those $7\mu\text{m}$ thick layers, in spite of the presence of a continuous substrate (absence of segmentation), and proves that $\Delta T_{W,surf}$ due to ELMs may reach several hundred centigrades.

Moreover, back to the bulk tungsten design, the lamellae profiles are optimised for shallow θ_\perp angles, which makes them less suitable for steep incidence (low values of q_{95}), or large ELM loads as the thermal conductivity of tungsten ($\lambda_{T,W} > 100\text{W}/(\text{m.K})$) may not be fully exploited to distribute the highly energetic, but very short load. A geometrical power amplification, due to the curvature of the plasma-facing top surface, may thus locally result in higher temperatures.

EXPERIMENTAL VALIDATION OF THE THERMAL MODEL USED IN THE PREVIOUS SECTION

In order to validate the global thermal model [4] used in the previous section, a full 1:1 prototype was built and installed in the MARION facility [10,11]. It was exposed to an ion beam of up to $80\text{MW}/\text{m}^2$ on axis under a realistic angle of incidence of 5.5° - 6.7° . The local power density was applied stepwise up to $8.2\text{MW}/\text{m}^2$ for 8s. Technical details and an overview of the highest temperatures reached at various points will be found in [m]. They were close or equal to the engineering limits of 600°C for the carrier and 350°C for the spring elements of the tile clamping. The tungsten surface reached 1800°C locally (pyrometer type: Maurer KTRD 1075).

Figure 5 is an infrared picture of the prototype taken at the end of the ion beam pulse (top view) for an intermediate integrated energy density of $50\text{MJ}/\text{m}^2$. The maximum reading indicated is not normalised to the pyrometer measurements, rather the camera picture was recorded with the deliberate value of $\epsilon_W = 0.20$ for the emissivity of tungsten over the wide range of temperatures expected during the pulse. It is too high in the present case. The picture thus gives an idea of the temperature distribution but cannot be used without correction to derive absolute values (in the present case probably $T_{W,surf|max} \leq 1600^\circ\text{C}$).

The temperature values do confirm the validity of the GTM (Global Thermal Model for tile 5) to a large extent by providing a bridge to the quasi-uniform exposure case. The average cooling times at high power were of the order of 1 hour (2700-4200s with some dependence on the applied energy density above $40\text{MJ}/\text{m}^2$ and more on the initial conditions) but a comparison with the real torus requires more modelling effort. Critical temperatures recorded with thermocouples, especially for the clamping, are close to the model values ($\pm 12\%$), with an error bar of $(+80/-60)^\circ\text{C}$ in the high temperature range and correspondingly lower at the bottom of the wedge carrier. The next step in the validation is the exposure of a refurbished prototype representing the outermost (LFS) shallow wing of the tile, which is by design thermally and mechanically weaker than the other ones.

CONCLUSIONS

The global thermal model developed for the bulk tungsten modules was applied to plasma footprints

more realistic than purely uniform: the poloidal extension of the outer strike point was reduced from the full lamella width of 62mm to about 15mm. Model validation is given by the experimental exposure of a 1:1 prototype stack to an ion beam in the MARION facility (incidence $\sim 6^\circ$, load $E \leq 66 \text{ MJ/m}^2$ on the wetted surface). With these additions, a better estimate of the performance of a segmented bulk tungsten tile is obtained.

It indicates that ILW-relevant scenarios may deposit up to 60MJ/stack (GWF = 1). Owing to the tile segmentation, sweeping over multiple stacks is compulsory for plasma scenarios that bring more than 60MJ at the outer strike zone. Below 60MJ, sweeping is still advisable to reduce the energy per stack : spreading the deposited energy over one or several stacks is beneficial for the tungsten lamellae (*cf.* [2]) and for the support structure.

Further experimental work and improved modelling are required for the shallowest part of the tile (stack 4, LFS) where the shorter clamping is more sensitive to overheating, to better assess the power handling performance in future operation.

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Scenario	Maximal Energy (/MJ) deposited over						Temperature (W)		
	stack 1 (HFS)	stack 2	stack 3	stack 4 (LFS)	tile 6	total	T_{surf} max.	notes	
	<i>(approx., 1st pulse)</i>								
uniform 3	0.0	0.0	60.0	0.0	0.0	60.0	1330°C	academic	
static 3	0.0	0.3	60.0	14.4	0.2	74.9	1890°C	not recommended	
swept 3	0.0	9.3	60.0	32.3	1.9	103.5	1440°C	recommended	
swept 2+3+4	0.4	30.0	60.0	53.8	5.8	150.0	1400°C	acceptable	

Table I: Examples of energy handling estimations for tile 5 ($GWF=1$), normalised to 60MJ on stack3

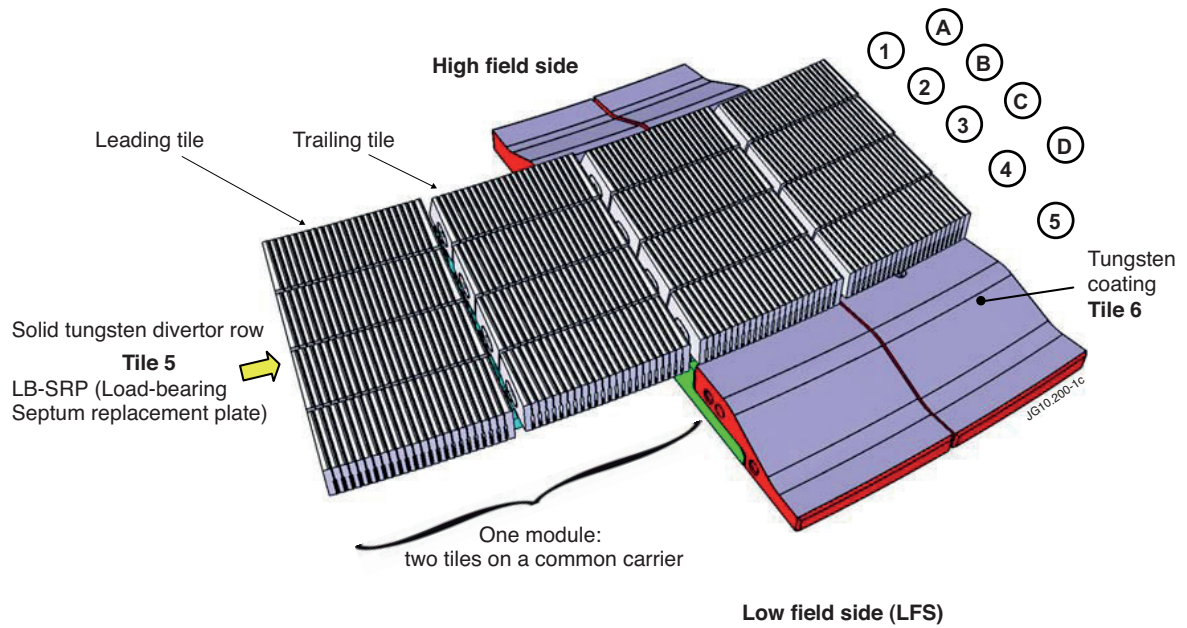


Figure 1: Top view of the bulk tungsten row from the low-field side (2 modules shown). Stacks are numbered 1-4 from the high field side. Stack 5 is a dummy which represents the W-coated tile 6.

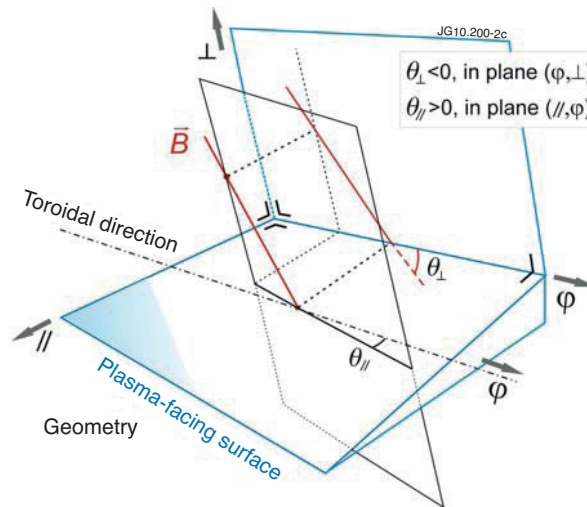


Figure 2: Angles of the magnetic field on the solid tungsten surface.

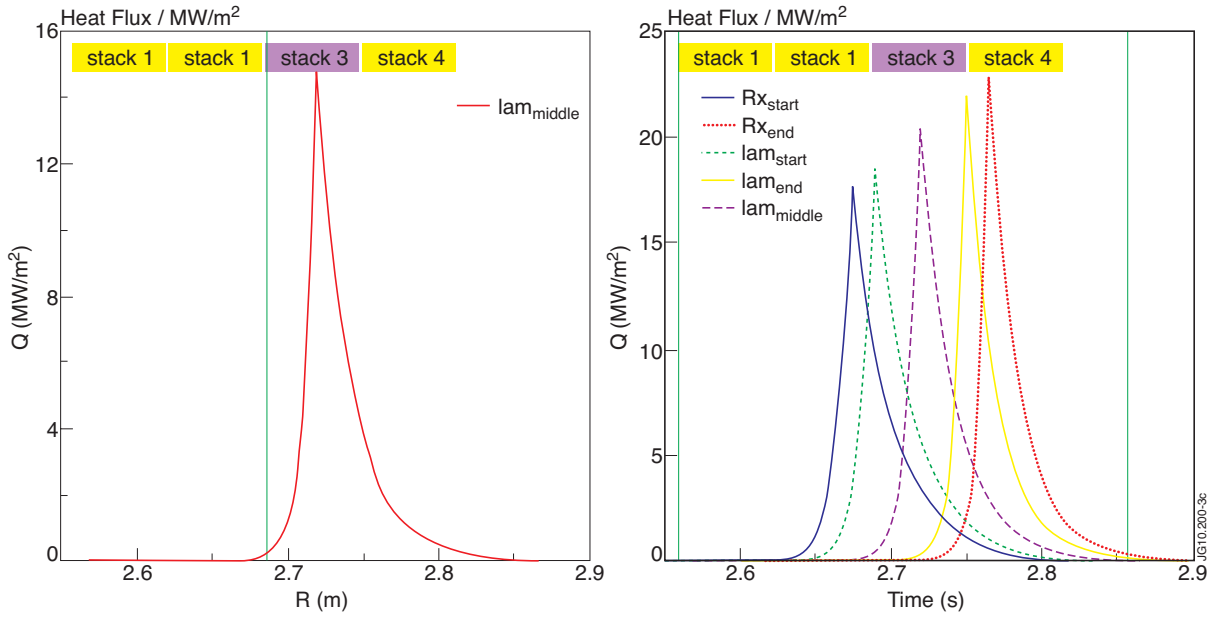


Figure 3: (a) Static power deposition on stack 3. (b) Sweeping scenario over the same stack. The profiles spill slightly over neighbouring stacks (17.5mm on each in poloidal direction). Both cases are normalised to 60MJ over stack 3, R is the major radius.

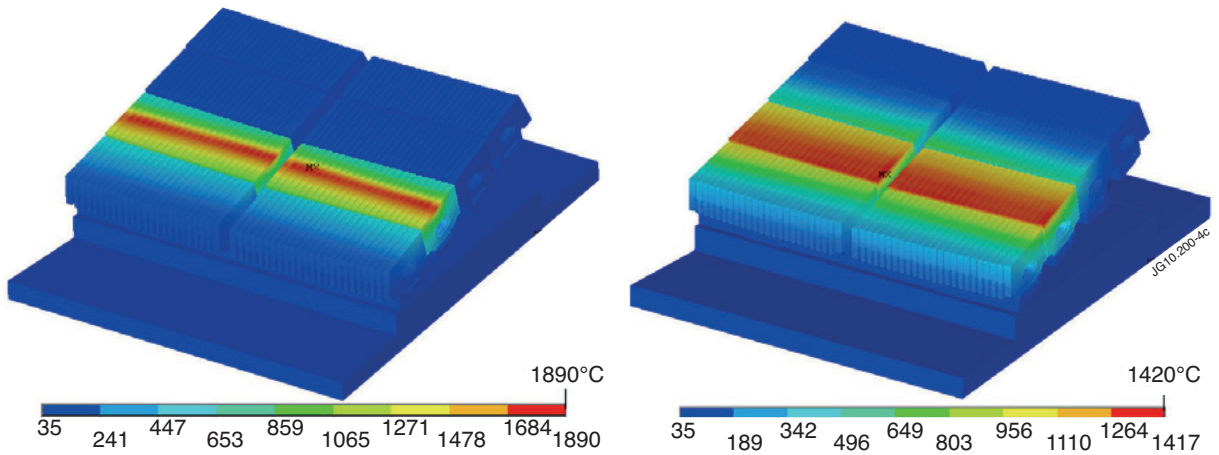


Figure 4: Temperature distribution on the tile surface after exposure to the static and swept cases. The indicated peak values correspond to full scale.

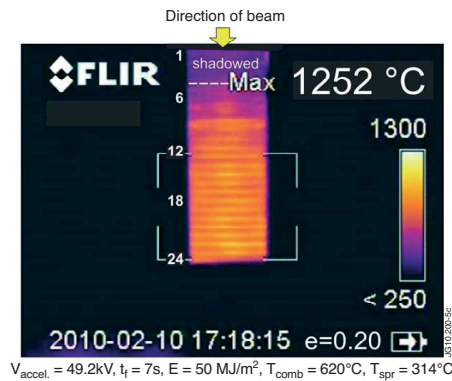


Figure 5: Infrared picture of a bulk tungsten prototype at the end of an ion beam pulse in the MARION facility. The lamellae are numbered from the side of the incident beam. The actual maximal temperature is locally higher than the maximum reading of the camera