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Development and qualification of a bulk tungsten divertor row for JET

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ABSTRACT

A bulk tungsten divertor row has been developed in the frame of the ITER-like Wall project at JET. It consists of 96 tiles grouped in 48 modules around the torus. The outer strike point is located on those tiles for most of the ITER-relevant, high triangularity plasmas. High power loads (locally up to 10–20 MW/m^2) and erosion rates are expected, even a risk of melting, especially with the transients or ELM loads. These are demanding conditions for an inertially cooled design as prescribed. A lamella design has been selected for the tungsten, arranged to control the eddy and halo current flows. The lamellae must also withstand high temperature gradients (2200 to 220 °C over 40 mm height), without overheating the supporting carrier (600–700 °C maximum). As a consequence of the tungsten emissivity, the radiative cooling drops appreciably in comparison with the current CFC tiles, calling for interleaved plasma scenarios in terms of performance. The compromise between shadowing and power handling is discussed, as well as the consequences for operation. Prototypes have been exposed in TEXTOR and in an electron beam facility (JUDITH-2) to the nominal power density of 7 MW/m^2 for 10 s and, in addition, to higher loads leading to surface temperatures above 2000 °C.

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1. Introduction

In the full tungsten divertor of the ITER-like wall in JET, the large power loads at the outer strike point, the high erosion and the risk of melting may lead to untimely damage of metallic coatings similar to those selected for other divertor tiles around (of the order of 10 μm). It was accordingly decided to test a new concept of bulk tungsten tiles at this position, a full toroidal belt of load-bearing septum replacement plates (LB-SRP) [1]. Along with the main goal of testing the compatibility of ITER-relevant plasma scenarios with the wall, bulk tungsten opens new fields of investigation: specific plasma-wall interaction questions can be addressed like thermal fatigue, environment of mixed materials with possible alloying, erosion, deposition and migration through castellated structures, consequences of local melting, etc. The divertor row consists of 96 tiles paired in 48 modules around the torus, a substitute for the current carbon fibre composites (CFC) tiles. The location of these tungsten tiles is shown schematically on Fig. 1.

Two groups of boundary conditions are extremely demanding. Firstly, the bulk-W units are, per definition, metallic to the largest extent. Huge electromagnetic (EM) forces are thus generated by variations in the magnetic field ($dB/dt \leqslant 100$ T/s) and by halo currents that may amount to 18 kA/tile [2]. It is advisable to keep the EM forces as low as possible. Secondly, no active cooling is available [3]. Subject to an energy flow that may theoretically reach 100–200 MJ over roughly 4 m^2, the tungsten tiles have to withstand the mere heat flux (~7 MW/m^2 on the full conical surface of the LB-SRP) and the temperature gradients (5×10^4 K/m). The average temperature goes up to 500 °C as all components tend to equilibrium, and the corresponding heat has to be evacuated through inertial cooling after the pulse.

Moreover, the refractory nature of tungsten leads to embrittlement as excursions through the ductile-to-brittle transition temperature (DBTT) cannot be avoided. The design is thus driven by the need to ensure the mechanical stability of the bulk material.

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2. Overview of the bulk tungsten design

To meet the severe requirements with respect to thermo-mechanical and EM loads, a lamella design with pre-loaded fixings has been selected. The clamping is tightened with forces higher than those expected. The arrangement intends to minimise the eddy current loops by eliminating full metallic frames and to provide adequate paths to the halo currents. Features of more technical nature, for instance those relating to the compliance with remote handling, are out of the scope of the present paper. The interested reader can consult in Refs. [4,5]. A bulk tungsten module comprises, as shown in Fig. 2:

- Tungsten lamellae (thin blades, about 6 mm thick and 60 mm long) made of the bulk material with high purity (≅99.95%). An envisaged upper castellation, consisting in two thin vertical slits, was dropped for lack of shadowing and for technical reasons. Internal thermo-mechanical stresses are relieved by a rear slit instead (Fig. 2(A)).
- Tungsten should be acted upon in compressive manner only. For this purpose, the lamellae are stacked and interleaved with insulating TZM spacers (Ti–Zr–Mo alloy, coated with alumina on one side). The gaps are 1 mm wide. The sandwiched stacks are held together by a flexible clamping system, a kind of chain, the spring elements of which are visible in Fig. 2(B).
- Eight stacks are grouped in one unit and supported by a wedged carrier on eight 'wings' separated by deep toroidal cuts against closed electrical loops (Fig. 2(C)). The wedge is bolted down, in the spinal part, to a previously installed adaptor. The high wings of the wedge are on the high field side (HFS), the shallow ones on the low field side (LFS).
- An X-shaped adaptor (again no metallic frame) provides the link to the CFC base carrier of JET (Fig. 2(D)).

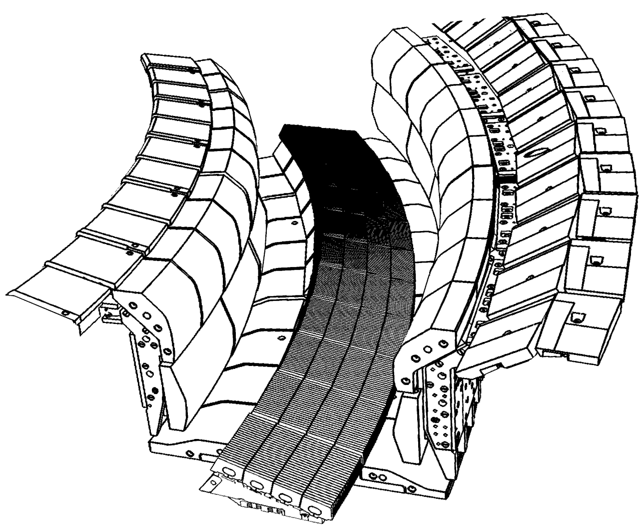

Fig. 1. Location of the bulk tungsten row (LB-SRP) in the divertor of JET.

Still, a bulk-W divertor module is subject to high forces during disruptions or vertical displacement events (VDE). Calculated values: the lift may be as high as 8.5 kN, the torque around a vertical, central axis may reach 650 Nm, and the torque which tends to tilt a single lamella is in the 2–10 Nm range, depending on its actual thickness. The aspect ratio of the blades and stacks, including gap sizing, are dictated in the first line by thermo-mechanical and electromagnetic considerations but also by shadowing issues, by estimations of deposition in the gaps [6], by the not-fully-ruled-out occurrence of molten layers, and by technical feasibility.

3. First tests in JUDITH-2 and TEXTOR

As a first step in the qualification of the completed design, prototypes of tungsten stacks were exposed to an electron beam, a high heat flux (HHF)-test in the JUDITH-2 facility, for a limited number of pulses. The power density ranged from low screening pulses, through the standard 7 MW/m^2 for 10 s, to 9 MW/m^2 for 9 s. The values attained for T in different components substantiate the use of materials that withstand high temperatures (Fig. 3): in the present case, beside tungsten, TZM (see above), Densamet (a registered tungsten alloy with high W content), Nimonic 105, various grades of Inconel (esp. 625 and 718) and several ceramic coatings.

The highest recorded temperatures during the test, starting at room temperature, amount to T_{Wsurf} = 1860 °C for the upper surface, T_{spacer} = 812 °C at the top of the spacers and $T_{Wbottom}$ = 545 °C at the contact pads of the tungsten lamellae with the wedge carrier. Keeping in mind that the expected components temperatures – for plasmas that result in low global wetted fractions of the tile – are locally higher, it is clear that scenario-dependent limits are to be defined in terms of exposure times. Also Fig. 3 reveals the trend for all temperatures to equalise several minutes after the pulse (~10 min) to values that are still around 500 °C, at the limit for parts of the supporting structure. The design was shifted to the point that the carrier would fail just before the tungsten lamellae break down. In JET, thermocouples will help to refine the available calculations during the commissioning phase and keep a sufficient margin during operation. The heat stored in the module must be evacuated after the pulse. Expected cooling times in the torus are much longer than with the current CFC tiles owing to the lower emissivity of tungsten ($\varepsilon_W \approx 0.24$–0.08, with decreasing temperature) and to the poor heat path to the base carrier ($t > 4000$ s for about 100 MJ). Details shall be given in Ref. [7].

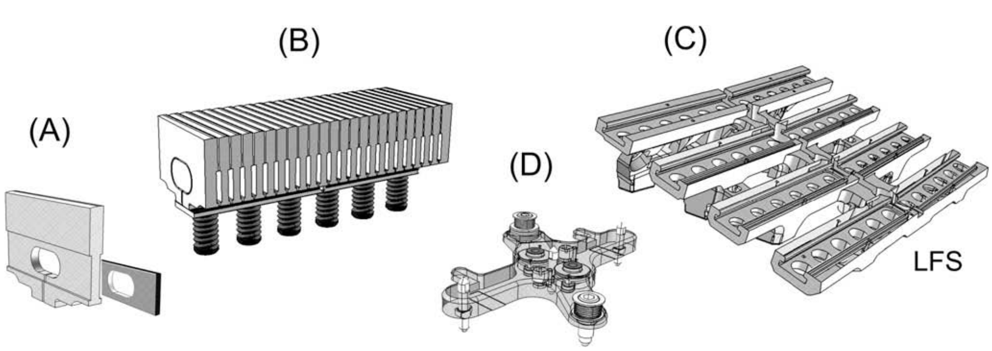

Fig. 2. Components and assemblies of the bulk-W divertor unit.

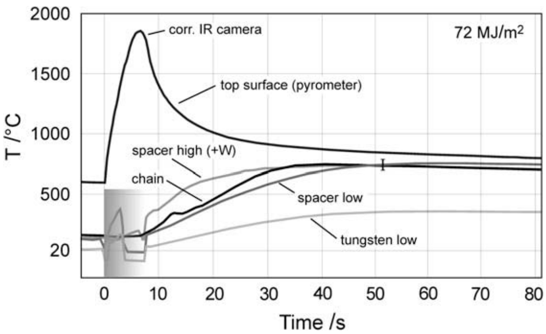

Fig. 3. Temperatures recorded at different points in a prototype stack exposed to an electron beam flux of 72 MJ/m^2 in the JUDITH-2 facility.

As for the upper region of the tungsten blades, the test confirms that the limit for component integrity can be defined by an energy density, not necessarily a power since the characteristic times commonly are of the order of a second. Deleterious energy densities lie between 100 and 130 MJ/m^2, at which point melting takes place, so that the deposited density should be kept below: E_{dep} < 90 MJ/m^2.

A shorter prototype exposed to a TEXTOR plasma to values above this limit at the un-shadowed corners shows evidence of tungsten melting in the form of a 'plasma shaping' which does not prevent the stack to operate properly (Fig. 4). Experiments with other tungsten limiters in the vacuum locks of TEXTOR give clues to the physical mechanisms involved in the movement of the molten material, in brief a thermo-electronic emission, and to the resulting direction of droplets displacement [8].

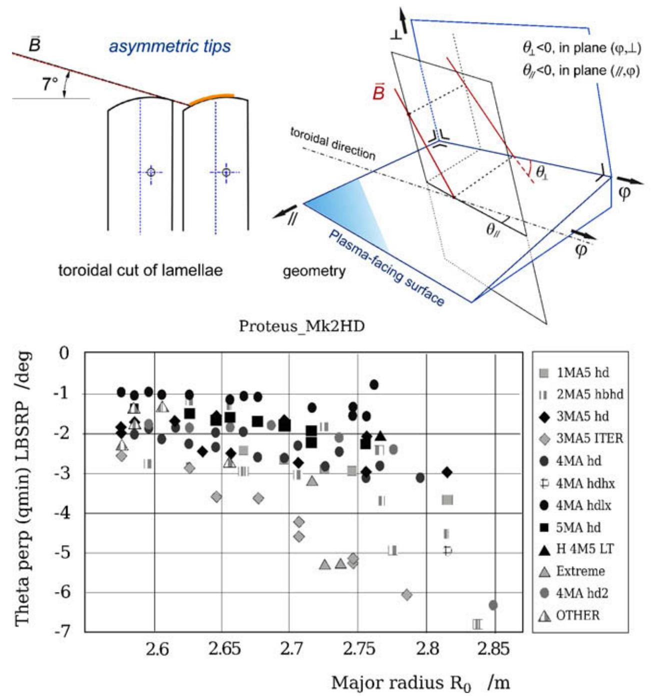

Fig. 5. Angles of incidence of the magnetic field on the bulk tungsten tiles: elevation θ_{perp} versus major radius R_0. The various scenarios are described by the plasma current followed by abbreviations where: 'hd' stands for 'high-δ', 'hb' for 'high-β', 'hx/lx' for 'high/low x-point', etc.

4. Shadowing versus power handling

Shadowing is required not only between tiles, i.e. in the present case also between stacks, but also between lamellae within a stack. Contrary to the initial designs, the lamellae now have an asymmetric 2D profile for the upper, plasma-facing surface: a central flat portion of 1.5 mm width only ends in cylindrically rounded corners with different radii so that a step is created in toroidal direction. The vertical step amounts to 0.4 mm over the 1 mm gap, a value which is comparable to the gyro-radius of hydrogen isotopes, e.g. D^+ at 20 eV–40 eV (the latter presumably too high a value) with r_L = 0.41–0.60 mm. It goes without saying that magnetic field and plasma current must be reversed simultaneously, if ever.

An assembly of tungsten blocks, no matter how good optimised, can never be as flexible with respect to the variety of plasma configurations, as a 3D-shaped CFC tile. The dependence of the angles of incidence of magnetic field lines on the major radius of the torus (Fig. 5) gives an opportunity to improve the power handling of the present tungsten tiles by making tailored shadowing between different wings: lower stacks on the wedge (LFS) are tilted more than higher ones (HFS) [9]. In addition, field lines with small angles to the toroidal direction might penetrate through the inter-stack gaps along a path that hits the vertical end facets of the blades, an undesirable load on tungsten. As a counter-measure, those end faces are slightly tilted in order to produce a funnel-like structure of the toroidal gaps.

Finally, the inter-tile gaps have different toroidal widths between modules and between tiles on the same module. The former may contain diagnostic systems, the latter are given for insertion of the remote handling tools. With due consideration of the 2D-shaped lamellae tip, of the individual tilts of the wings, of the toroidal funnelling and of the inter-tile gap sizes, an estimation of the local (lamella to lamella) and global (over a full tile) wetted fractions is possible [9]. In connection with the heat transfer through the tungsten, this gives a first evaluation of the permitted power for the given exposure time of 10 s or, respectively, of the maximal

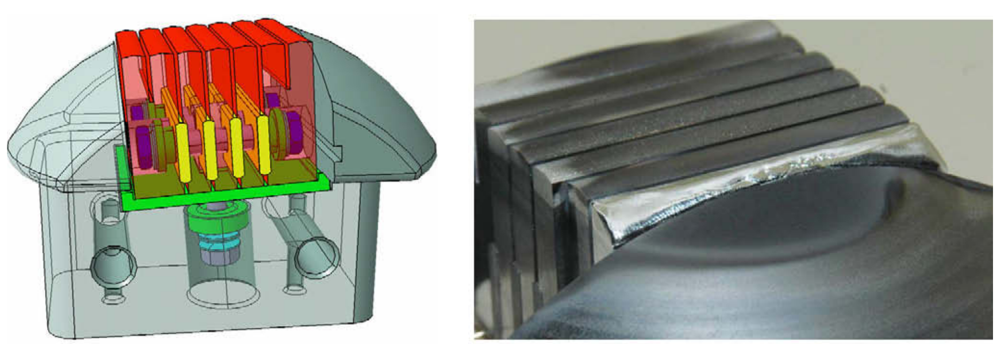

Fig. 4. Partially molten mini-prototype after exposure to a TEXTOR plasma (E_{dep} > 130 MJ/m^2 on front side).

Table 1
Tolerable heating powers for 10 s (first two columns) or maximal exposure time for P_{in} = 40 MW (last two columns) until either the W surface reaches 2800 °C or the supporting structure heats up to 700 °C, both of which are hard material limits which might have to be lowered for actual operation (from [9], preliminary).

Configuration	P_{max}/MW T_{surf} = 2800 °C	P_{max}/MW $T_{support}$ = 700 °C	t_{crit}/s, 40MW T_{surf} = 2800 °C	t_{crit}/s, 40MW $T_{support}$ = 700 °C
1MA5_hd	18.9	19.0	2.4	2.3
2MA5_hbhd	19.2	24.2	2.5	3.7
3MA5_hd	27.1	25.7	4.9	4.1
3MA5_ITER	23.0	25.3	3.7	4.0
4MA_hd	28.0	27.0	5.2	4.5
4MA_hd2	29.7	27.4	5.9	4.7
4MA_hdhx	23.2	28.2	3.6	5.0
4MA_hdlx	46.1	35.8	14.1	8.0

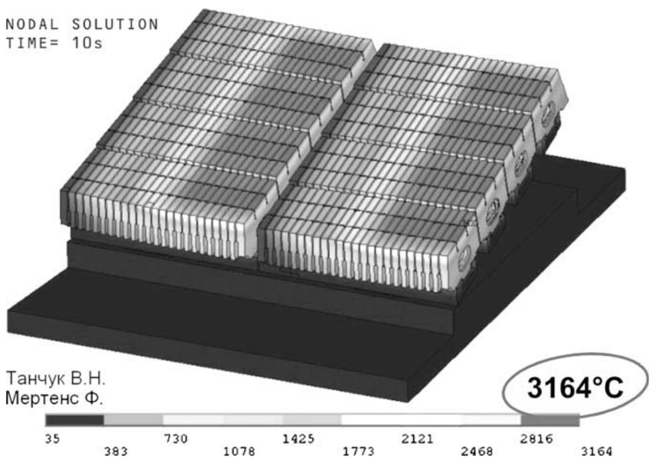

Fig. 6. Temperatures reached on the upper surface of tungsten tiles in the case of low incidence, Global Wetted Fraction *GWF* = 0.4, P_{dep} = 16.1 MW/m^2 for 10 s.

exposure time for several plasma scenarios. It is summarised in Table 1, an excerpt from the currently running calculations. Heat load mitigation through impurity seeding (eventually up to detachment) was not considered in these early estimations.

The thermal limits of the concept are in most of the cases given by the maximum temperature of the supporting carrier ($T_{support}$ columns in Table 1), in agreement with the previous remark: for most pulses, the clamping elements and the wedge carrier are the vulnerable components. A notable exception – very shallow angles and high heating power – is given in Fig. 6, see also [10].

5. Conclusions

While the study of 'Wall compatible' scenarios for ITER is the main goal of the project, the bulk tungsten divertor row should provide in addition the frame for future investigations on thermal fatigue (excursions through DBTT), on an environment of mixed materials (possible alloying), on erosion, deposition, and migration of deposited material into the castellated structure, on implications of local melting.

The concept, metallic per essence, has to deal with high electromagnetic loads: the mechanical pre-load of the components is dimensioned to resist several severe disruptions. From the thermal point of view, the absence of active cooling sets various limits. Input to JET Operating Instructions will mainly take the form of maximal exposure times depending on the impinging energy density with due consideration of: (i) previous pulses and initial temperature distribution of the units, (ii) expected heat flow and (iii) tolerable cooling time, somewhat longer than with CFC modules at the same position.

Temperatures will be monitored with thermocouples at strategic positions so that if the carrier or clamping springs come close to the prescribed limit, preventive actions can be taken, for instance longer intervals between pulses, interleave with pulses of lower peak energy, or plasma sweeping during the pulse to spread the load over a wider area.

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