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ABSTRACT
In the frame of the ITER-like wall project, a new row of divertor tiles has been developed which consists of 96 bulk tungsten Load-Bearing Septum Replacement Plates (LB-SRP). Exposed to the outer strike point for most ITER-relevant, high triangularity configurations, they shall be subject to high power loads (locally 10MW/m^2 and above). These conditions are demanding, particularly for an inertially cooled design as prescribed. The expected erosion rates are high as well as the risk of melting, especially with transients and repetitive ELM loads. The development is also a real challenge with respect to the inevitable excursions of the tungsten material through the so-called DBTT, ductile-to-brittle transition temperature.

A lamella design has been selected to fulfil the requirements with respect to the thermo-mechanical and electromagnetic loads during disruptions ($\partial T/\partial z \leq 5 \times 10^4$ K/m vertically, induction rate of change $\partial B/\partial t$ ≤100T/s, and I_{halo} ≤18kA /module). Care is taken to act on refractory metals solely with compressive forces to a large extent. The dedicated clamping concept is described. Results of a test exposure to an electron beam around 70 MJ/m^2 substantiate the resort to 'high temperature' materials like –among others– high-grade Nimonic® alloys, molybdenum or ceramic coatings.

1. SCOPE OF THE PROJECT

The objective of the ITER-like Wall (ILW) Project for JET is to install in the torus a beryllium wall and an all tungsten divertor. This goal is particularly demanding for the plasma-facing components at the outer strike point: the high erosion rate and large power loads expected on the tiles in ITER-like high triangularity plasma configurations, together with the risk of melting due to transients, were the main reason for choosing a concept based on bulk material. The present paper describes the units for a full divertor row of massive tungsten.

The most stringent boundary conditions can be classified in two classes.

- Those corresponding to the power load deposited on the tiles encompass (i) the given thermal load of 7MW/m^2 for 10s on the conical surface, with the cone determined by the geometry of the so-called 'load-bearing septum replacement plate' (LB-SRP, Fig.1) which is inclined at 16.8^o. Note that shadowing effects discussed in Sect.2.4 may reduce the wetted area dramatically, down to 40% of the full surface thereby raising the load accordingly for specific scenarios. (ii) the absence of any active cooling within reach, which limits the exposure time and increases the cooling time between pulses in comparison to the more relaxed CFC case owing to the lower emissivity of tungsten at comparable temperatures.
- The compliance with possible vertical displacement events and disruptions: the technical assignment are the maximum values $\partial B/\partial t$ ≤ 100T/s and I_{halo} ≤ 18kA/module [1], another demanding condition in view of the fully metallic nature of those divertor modules.

Additional requirements are a size comparable to previous CFC tiles, a vacuum conformity to in-vessel material acceptance, compatibility with remote handling for all parts to be installed in the torus (weight ≤ 80kg), the ability to accommodate available or planned diagnostics as far as possible, and the feasibility of the design to the industrial production of a limited number of modules (roughly 50). The development time was limited to 2 years for the production of “ready to manufacture” drawings.

Two implications among others were on the dimensions of the plasma-facing tungsten pieces that may face a gradient of $\partial T/\partial z \leq 5 \times 10^4$K/m (See Sect.2.3) and in the strict avoidance of closed metallic frames to minimise the electromagnetic (EM) forces. The latter has led to a complete re-design of the supporting structure and of the adaptor to the base carrier of JET.

2. DESCRIPTION OF THE BULK TUNGSTEN MODULES

The selected integral concept is described hereafter in a bottom-up sequence. Each ‘module’ corresponds to a pair of tiles and its supporting structure; this is the smallest unit to be lowered and clamped with Remote Handling (RH) to the adaptor plate which serves as an interface to the existing base plate. Due to the high density of tungsten, a module approaches the given limit of 80kg.

2.1 ADAPTOR

The adaptor plate converts the position of the given base carrier bolts fixings (at an angle of 29.39^o to the toroidal direction) to the radially aligned module bolts, which allows remote handling of modules to be installed after the full circle of adaptors is in place.

As shown in Fig. 2, the adaptor is X-shaped to minimise the EM forces and thus limited to its bare conversion function. It is designed to be made of Inconel“ alloy 706, or a better grade, specified for strength and rigidity (a deep investigation of natural frequencies is unfortunately out of scope of the design study). Production will take place with Inconel“ alloy 718 owing to better availability and guaranteed properties.

The pre-load of 6kN per bolt is unchanged with respect to the conceptual design [2], slightly larger than the vertical pull of modules fixed on top (4.5kN /screw). Poloidal fingers guide modules during lowering and engage before the dowels that ensure accurate positioning and resist the EM torque around the vertical axis [3].

A limited number of additional features, like aluminium-bronze inserts for transport since adaptors are themselves installed with RH, can be seen on Fig.2 as well.

2.2 WEDGE CARRIER

In order to maintain adequate angles to the incident field lines and mimic the CFC tiles to be replaced, the supporting structure takes the form of a wedge carrier with a 16.8^o outward tilt. Made of Inconel“ alloy 625 for cost reasons, it fulfils the expectations in terms of strength (0.2%-yield, FEM analysis [4]).

The views in Fig.3 show important features:

- deep toroidal cuts avoid the shape of a closed frame and lower the EM forces accordingly [3]. The wedge is thus divided in 8 wings with holes for tile fixings.

The wings are reinforced in the spinal region of the wedge to control the bending in the course of installation;

- remote handling features can be seen in the central part, positioning pins and stops as well as inserts for carrying threads;
- the inverted T-shape of slots in the wings for a slide-in rail that holds the stacks of tungsten lamellae down;
- ceramic-coated molybdenum foils on contact surfaces for the tungsten components (TiO_2-doped Al_2O_3 ceramic [5], about 150mm thick) provide sliding path and electrical insulation;
- space is freed below the wedge for diagnostics provisions.

2.3 TUNGSTEN STACKS AND CLAMPING

Tungsten lamellae are made of pure tungsten (to 99.95%). They are assembled in stacks of 24 pieces, all of them 6†mm thick except the outer ones which compensate the toroidal angle of 3.75^o (360/96). The standard tungsten lamella has been much simplified with respect to the conceptual study (cf. Fig.4 in [2]), Fig.4a.

- Guidance in the wedge slot is provided by a nose at the bottom. It is neater than the former centring feet and optimised for manufacturing;
- the optional upper castellation was dropped: it does not only call for a complex manufacturing procedure but may also leave impurities in the EDM cut (wire erosion) and the beneficial effect was marginal to doubtful, raising for instance shadowing issues at the plasma-facing castellations edges or triggering micro-cracks at the keyholes;
- the removed upper castellation is replaced by a bottom slit which relieves stresses better, as shown in Fig.4b, and is much easier to manufacture in one pass with the central oval slot.

This racetrack hole houses the clamping chain, a substitute for the original tie rods for which no feasible material could be found, which would have displayed an extremely low thermal expansion (CTE comparable to tungsten, i.e. $a_T \sim 5 \times 10^{-6}\ K^{-1}$) together with sufficient resistance to high temperatures while being pulled apart (nominal maxima around T_{chain} = 800^{o}C, tensile force F_{chain} ≈ 1.0kN). The chain, Fig.5, is made of Densamet“, a tungsten-based alloy [7].

It combines two equally important functions: on the one side, it maintains the integrity of the tungsten stack by compressing it, this is the pre-load against EM forces that tend to tilt the blades with torques in the range of 2-20Nm. On the other hand, it pulls the stack downwards onto the supporting wedge wing, a pre-load against the EM lift of up to 1kN /stack [3]. At the same time, the differential thermal expansion between chain and stack is compensated by the pre-loading spring elements, represented on Fig.5 by bare helical springs, which are brought below the wedge carrier to lower their operating temperature. With expected wedge temperatures up to 500^{o}C, they are still vulnerable though, a situation which calls for appropriate monitoring after plasma pulses through thermocouples and other diagnostics.

Profilometry is applied on representative samples of tungsten lamellae to control the surface roughness ($R_a \rightarrow 3.2$mm) and the accuracy of the 2-dimensional upper profile, an important consideration to the shadowing capabilities as mentioned in the next section. The 1mm gap between tungsten lamellae is determined by TZM spacers (Mo99/Ti0.5/Zr~0.1) with pure alumina coating for electrical insulation and break of possible eddy current loops.

2.4 TILE ASSEMBLIES

The plasma-facing tiles consist of four stacks, each of which is positioned with two dedicated angles to the toroidal and radial directions to optimise the geometry with respect to shadowing and power handling properties. A distinction can be made between two quantities. The Local Wetted Fraction (LWF) refers to lamella-to-lamella shadowing and depends on the lamella width, gap size and plasma-facing profile. The Global Wetted Fraction (GWF) gives the proportion of the tile surface that is actually exposed to the plasma, i.e. a tile-to-tile value. Accounting for different gaps between tiles on the same carrier (Δx=11 mm) and tiles on adjacent carriers (Δx=13mm), the toroidal wetted fraction can be estimated to

$$TWF = \frac{6}{7\cos\alpha_i}\left[1 - \frac{h_i + g_i \sin\alpha_i}{(L_{tile} + g_i)(\sin\alpha_i + \sin\theta_i)}\right] \tag{8}$$

where g_i represents a gap width, h_i the corresponding vertical step, α_i the angle to the toroidal direction and the factor 6/7 accounts for the ratio of lamella to lamella+gap width (ideal LWF). Optimisation is given by the geometry: stack positioning angles vary with the major radius owing to the dependence of the field line incidence, especially of the elevation $\vartheta_\perp$ [2, 9]. A view of the complete module is given in Fig.6.

3. HIGH HEAT FLUX TESTS

First tests were carried out in the electron beam facility JUDITH-2 in Jülich [10]. A tungsten stack (Fig.7) was exposed for 30 pulses to increasing incident energy densities, up to 80MJ/m^2. The surface temperature was measured with pyrometer and IR-camera [11].

The highest temperature amounted to $T_{surf} = 1860^oC$, not far from the design maximum of 2200^{o}C with contact pads at the bottom of tungsten pieces at 200^{o}C, hence a gradient of $|\nabla T| = 5 \times 10^4$K/m. No noticeable damage was observed. Although the number of pulses does by far not yet allow any conclusion on the component lifetime, the measurements at different parts of the stack and clamping with embedded thermocouples corroborate the use of materials that can withstand high operating temperatures in the range 500–850^{o}C. Typical values for a moderate pulse are given in Fig.8 [see also 12].

Beside tungsten, TZM, Densamet“, molybdenum and ceramics already mentioned, the clamping relies on Nimonic“ alloys for the chain hinges (alloy 105) and other critical components: cover plates at both ends of the stack (alloy 115), which are in direct contact with the hottest tungsten outer lamellae, and clamping screws (alloy105).

CONCLUSIONS

The development of an inertially cooled divertor row at the position of the outer strike point in JET is a major challenge. Plasma scenarios will have to adapt to the new plasma-facing boundary. In the difficult compromise of load sharing between tungsten tiles and carriers underneath, we have shifted the balance towards a safer tungsten handling versus weaker carriers. Main reasons lie in the refractory nature of tungsten which makes it prone to damage through unavoidably large temperature excursions and in the ‘well-behaved’ character of most other materials in the structure underneath. Spring elements are nevertheless vulnerable components, the shallower the wedge wing the worse, so that an appropriate monitoring of the temperature is mandatory.

As the bulk-W modules enter the production phase, final tests with a larger number of cycles shall help in assessing the adequacy of late FEM computations on the frozen model and in refining the future operating boundaries. Samples of material batches for production are further characterised in the SCK.CEN Belgian research centre.

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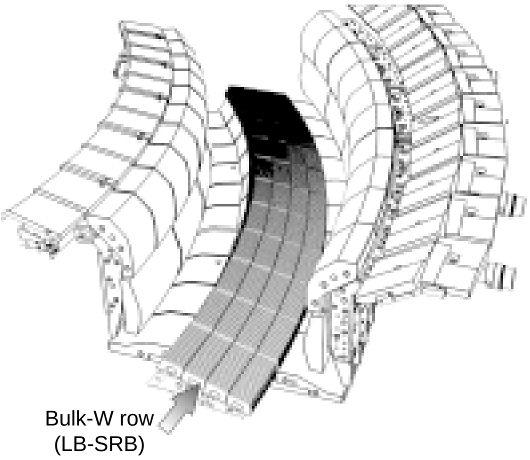

Figure 1: Position and geometry of the bulk tungsten divertor row in JET.

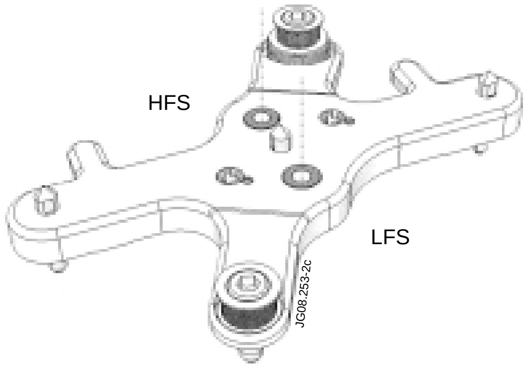

Figure 2: Adaptor (adapts bulk-W divertor module to the configuration of the base carrier)HFS/LFS indicate the low and high field sides, respectively.

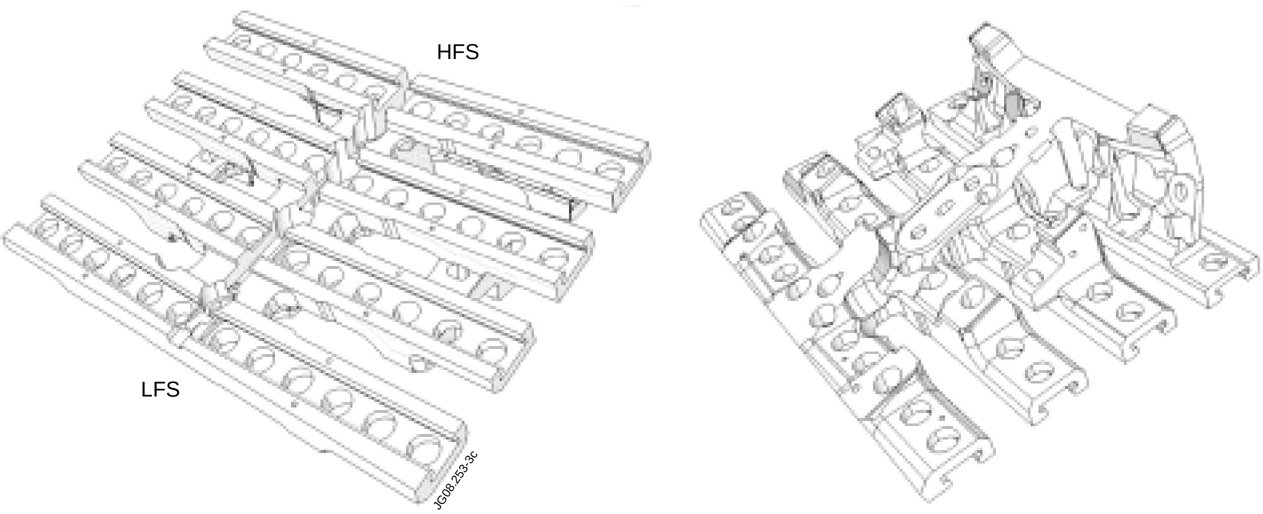

Figure 3: Top and bottom view of the wedge carrier.

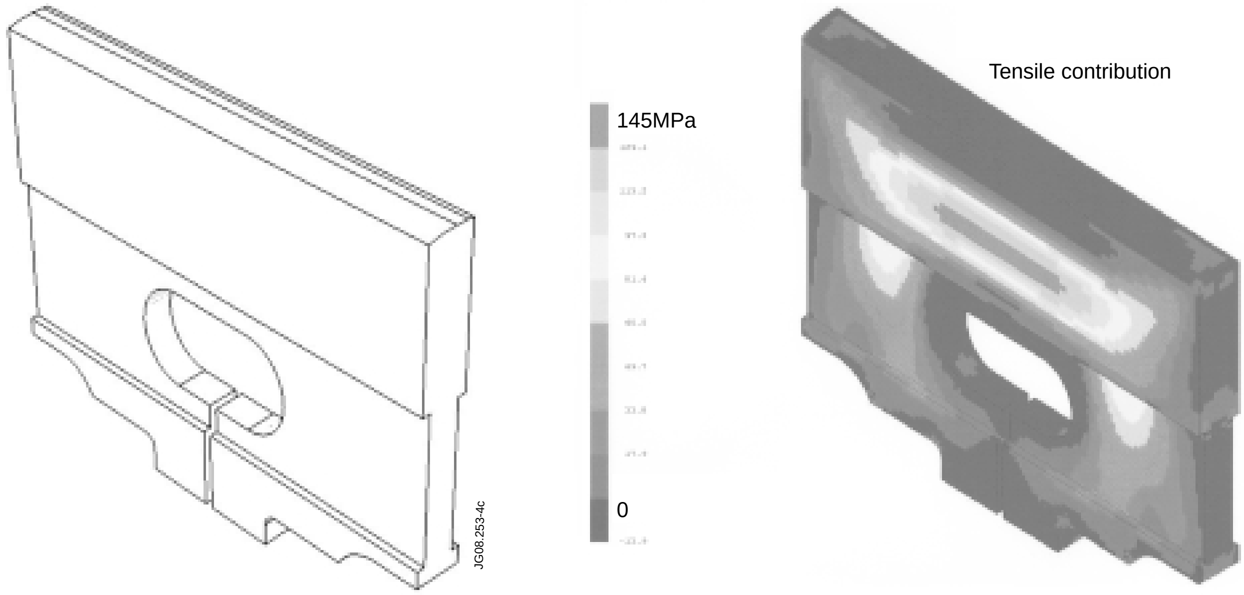

Figure 4: (a) Simplified shape of the standard tungsten lamella (dimension: 62 $\times$ 40 $\times$ 4mm) (b) tensile stresses under thermo-mechanical load (example: 9MW/m^2 for 10s [6]).

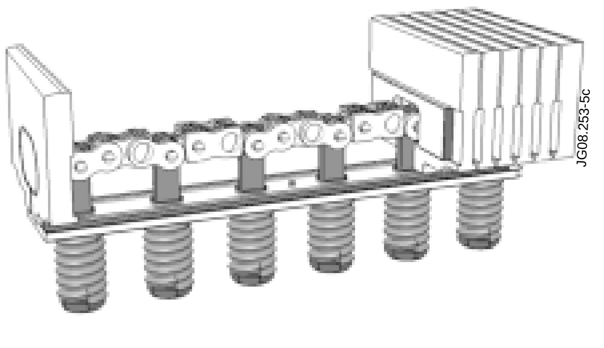

Figure 5: Exploded view of a standard stack with several W-lamellae removed, showing the internal clamping chain.

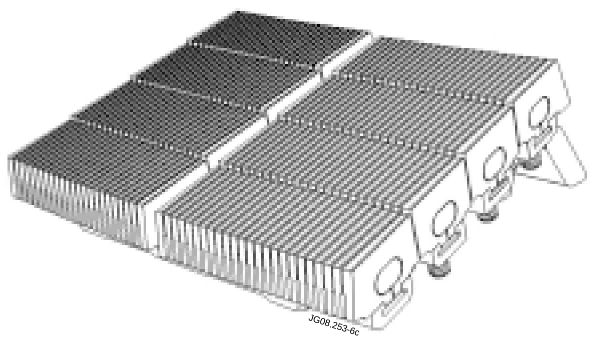

Figure 6: Complete module for the bulk tungsten divertor row in JET.

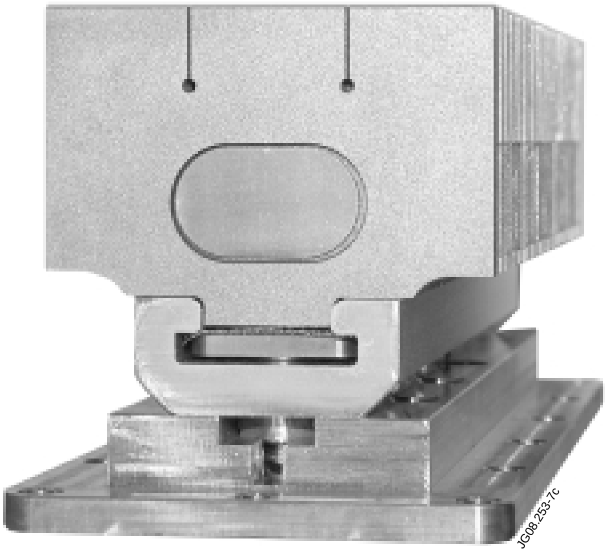

Figure 7: Prototype stack for exposure in the JUDITH-2 e-beam facility.

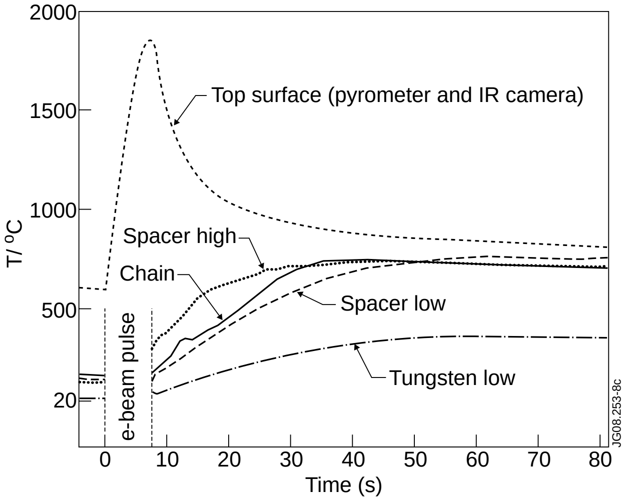

Figure 8:Temperatures of different components in a stack of tungsten lamellae for a few seconds after an electron beam pulse.