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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT
For the bulk tungsten divertor row, a development for the ITER-like Wall in JET, utmost care was taken to limit the stresses in the solid tungsten plasma-facing components. The bulk W tile is located at the position of the outer strike point for most plasma configurations as they are considered for the ILW operation. The absence of active cooling makes temperature cycling of the refractory tungsten material close to or through the DBTT (ductile-to-brittle transition temperature, about 200-300^{o}C) and above the re-crystallisation threshold around 1250^{o}C hardly avoidable.

Each tile is segmented in 4 stacks of 24 solid tungsten lamellae. The clamping scheme minimises the vertical forces applied on the lamellae and provides a compressive pre-load for the integrity of the stack, corresponding to uniform pressures below 6.0 N/mm^2. The higher loads were deliberately moved to the supporting structure : a wedge-shaped carrier, the clamping, and an adaptor to the base plate of the torus. The thermo-mechanical analysis of the lamellae gives a picture of the distribution of temperature and stresses for nominal exposures ≥ 7MW/m^2 (10s). The possible onset of the DBT and of recrystallisation were the main reasons for selecting the design with due consideration of the mechanical properties of the material.

1. INTRODUCTION
A tungsten divertor is foreseen in the frame of the ITER-like Wall project at JET [1]. At the position of the Outer Strike Point (OSP), the lifetime of tungsten coatings might be strongly limited by an insufficient thickness, related to the technical risk associated with thick layers, or by their finite resistance to high loads, related to the difficult matching of thermal expansion with the carbon fibre composite substrate. Bulk tungsten is thus usually preferred at the outer strike point, not only for its low erosion rate at low ion impact energies but also for its expected compliance with the specified heat load, which includes a risk of melting. This load amounts, in the present case, to 7MW/m2 on the full geometrical surface (frustum), a power density that locally reaches much higher values (up to 10–20 MW/m^2 on very small areas) owing to the castellation and to the actual wetted fraction of the tungsten tile. The corresponding nominal pulse length is 10s.

We have accordingly considered from the very beginning of the conceptual design phase that the bulk tungsten (W) material must be handled with utmost care, due to extremely unfavourable boundary conditions which add up to the relative mechanical weakness and to the difficult characterisation of the tungsten material *per se* : an active cooling is not available and the operational temperature range is such that excursions through the Ductile-to-Brittle Transition Temperature (DBTT) cannot be excluded at the low end, and the recrystallisation threshold can easily be reached at the high end.

The above mentioned frame, especially the inherent brittleness of the refractory metal, has lead to a mechanical design that attempts to act on tungsten solely in a compressive manner. As the option of brazing solid tungsten on a carbon-based substrate had to be dropped in an early stage, due to the tight schedule of 18 months for the complete R&D and design, this consideration has added an unwanted complexity to the final component.

An overview of the finalised modules for the bulk W divertor row can be found in [2].

2. MECHANICAL DESIGN

2.1 OVERVIEW OF THE COMPONENTS

The bulk W modules were described elsewhere [b,c]. The assembly consists, from bottom to top, of (Fig.1):

- a star-shaped adaptor, which interfaces to the existing base carrier of JET and is installed first, by Remote Handling (RH);
- a wedge carrier with deep toroidal cuts to prevent eddy current loops;
- two times four stacks of tungsten lamellae, which are clamped to the wedge carrier and constitute two solid tungsten tiles.

The last two items are assembled together to an ~80kg module that can be lowered with RH onto the previously screwed down adaptor.

The segmentation of a tungsten tile into four stacks is dictated by the basic need to minimise the electromagnetic loads [4], the castellation within a stack is determined by similar considerations, together with a sensible compromise between thermo-mechanical stresses and feasible manufacturing. Stacks are thus assemblies of 6 mm thick tungsten lamellae interleaved with keyed TZM spacers to provide 1mm gaps. The spacers are coated with an insulating ceramic on one side (Al2O3) to prevent current loops. The discussion of lamella-to-lamella shadowing properties (profile of plasma-facing upper surface, vertical chamfers, etc) is not in the scope of the present paper, see for instance [3]. A compact description of the tungsten modules can be found in [5].

The total height of standard lamellae, around 40mm, is mainly determined by its heat capacity in order to avoid overheating of the tile carrier (wedge) just below since the whole object has to be cooled inertially. The four types of lamellae are shown in figure 2. Note the stress-relief rear slit, the width of which depends on the position in the stack : wider slits are found only where clamping bolts have to pass through.

2.2 THE TUNGSTEN STACK

Given the lamellae described in the previous section, it remains to stack and attach them firmly, generating only compression forces on the tungsten. The assembly is pressed together using a tie-rod like chain and the clamping is obtained through the spacers, which apply a moderate vertical pressure downwards on the keying shoulders of the tungsten blades. The central hole, in form of a racetrack shown on all pictures, is the channel for the chain. Fig.3 shows the bare chain-like arrangement, with compensating spring elements to maintain tension during thermal expansion cycles, and a fully assembled stack as a CATIA model and as a full scale prototype. The links are made of Densamet [s] and the other parts of Nimonic alloys (grade 105 and grade 115) [2].

The combined function of the chain, ensuring stack integrity by compression and clamping by pull down, reminds of *tensegrity* concepts. It is one of the very few options to cope with the mismatch in thermal expansion between tungsten and the structural materials required for the underlying carrier structure.

An exposure test to an electron beam in the JUDITH-2 facility [6] was successful and was used to validate the thermal model [7] but the number of pulses (<30 with relevant power density) was not sufficient to assess the lifetime of a stack under realistic conditions, for instance with respect to tribology; hence additional tests were planned and are all currently running. Beside the exposure to a beam of ions and neutrals in MARION [8], a cycling test in vacuum with a high number of cycles ($>10^4$) is aimed at checking the chain resistance, a relaxation test is applied to the springs ($T \geq 350^oC$) and a creep test (500^oC, 2000h) to the complete chain.

3. STRESSES IN TUNGSTEN

The tungsten lamellae are maintained in place with compressive forces, horizontally over the full spacer area and vertically over the tungsten shoulders in the spacers recess. In both cases, respectively with a stack compression of 820 N-1.2kN and a pull of 250-350N exerted by the clamping bolts, the applied pressure does not exceed $6.0N/mm^2$. The thermo-mechanical stresses in W were computed with three different FE systems: the SAMCEF software [9], ABAQUS [10], and ANSYS, applied to different cases and lamellae types but with a bridging common calculation of the standard lamella. All results are comparable within the error bars (about $\pm 50^oC$ in case of temperature distributions and ±20MPa for the *von Mises* stresses). Examples are given as follows (Fig.4) : (i) temperature distribution at a nominal $T = 2200^oC$ on the top surface at the end of the plasma pulse (in the worst case of a wide rear slit, the temperatures are higher by a few tenths of ^oC only); (ii) tensile stress in a standard, narrow-slit lamella; and (iii) stresses in an end lamella, which is always thicker than the standard one and has to provide the additional supporting surface for the chain end combs.

The results confirm the beneficial effect of the stress-relieving bottom slit, a feature which is particularly needed as the upper castellation originally foreseen [11] has been removed. Moreover, only a small region is affected by significant tensile stresses of the order of max. 150MPa. Their location corresponds to a temperature range between 200^oC during baking phases and 1500^oC when the top of the lamellae reaches 2200^oC. For commonly accepted values of the 0.2%-yield strength, this is indeed only marginally acceptable. At this point, two effects have to be duly considered.

Firstly, up to now fully elastic behaviour is assumed but it is possible (dependent on uncertain material properties at high temperature), that yielding may occur in the small critical tensile region mentioned above. Hence an elastic-plastic analysis is planned to examine the effect of yielding in detail. However, in the meantime, this effect is believed to be benign by noting that the relevant stress is secondary in nature and so the loading is strain-controlled. This should lead to shakedown to purely elastic behaviour after one cycle provided that the stress is less than *twice* the yield stress which it is predicted to be.

If this limit is exceeded, plastic cycling will result and could ultimately lead to fatigue failure through exhaustion of ductility.

Secondly, the tungsten is certainly weakened by a recrystallisation which takes place in the range 1200–1500°C. An idea of the effect is given by the time versus temperature domain graph represented on Fig.5 (with data from [12, 13], among others). Recrystallisation is a reason for introducing three successive operating steps in the use of the bulk W divertor, starting with an imposed maximal surface temperature on the plasma-facing facet of 1200°C and raising it gradually with an intermediate stage at 1600°C to the nominal surface temperature of 2200°C [14]. Some of the tests discussed at the end of section 2 may contribute to an assessment in this respect. Quantitatively, the chosen tungsten grade displays mechanical properties that lie between those of the annealed and of the stressrelieved materials. The 0.2% proof stress at 300°C, for instance, was specified at >450MPa on delivery, for the poloidal direction in the torus.

CONCLUSIONS

An inertially cooled bulk tungsten divertor plate is evidently pushed to the material limits as far as heat and electromagnetic loads are concerned. This is equally true for the tungsten and for the carrier. The highest temperatures reached for different parts and the temperature excursions weaken the mechanical properties of all materials down to RF≈1. In this difficult balance, it was deliberately chosen to shift the highest loads from the tungsten to all other components: except from hardly avoidable thermo-mechanical stresses, tungsten is acted on solely with compressive forces, the driving reason for the selected design. As the tungsten properties are always difficult to determine, especially in view of the possibly large scatter, we must admit that a definitive assessment of the use of bulk W under these conditions – especially without active cooling – is part of the experiment. The tests that are still running will help with refining the operating instructions. Several operational constraints in the ITER-like Wall campaigns will be wall-driven [14].

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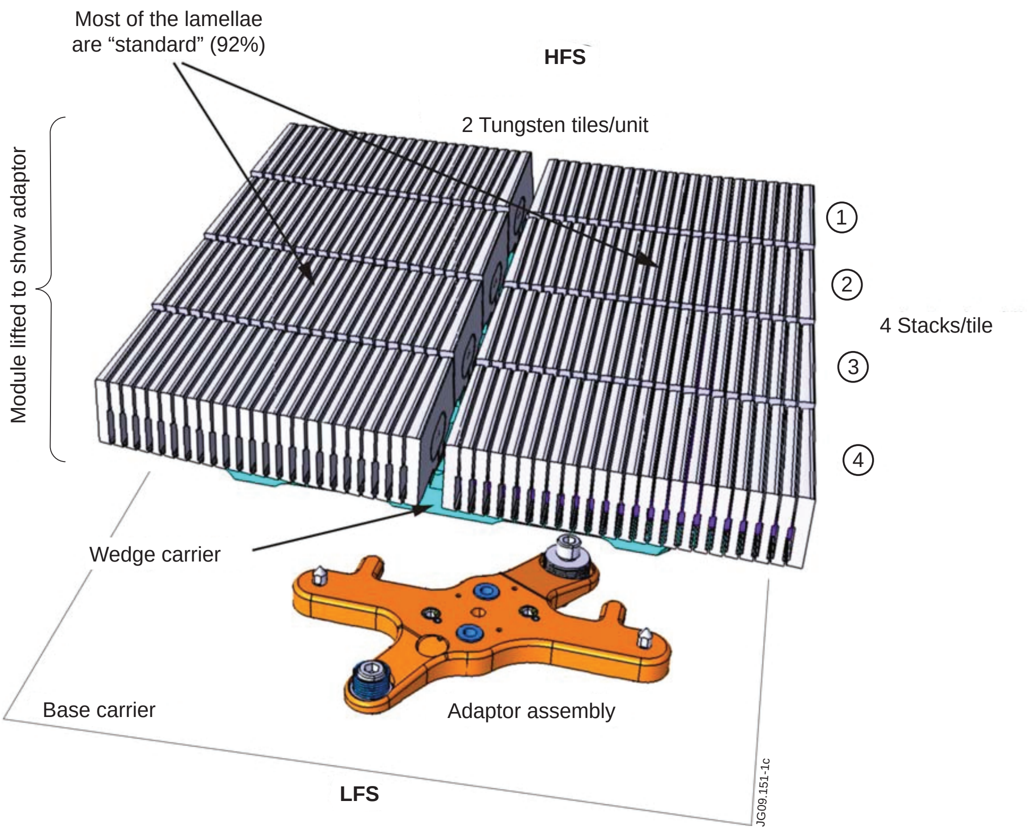

Figure 1: Overview of a bulk W module

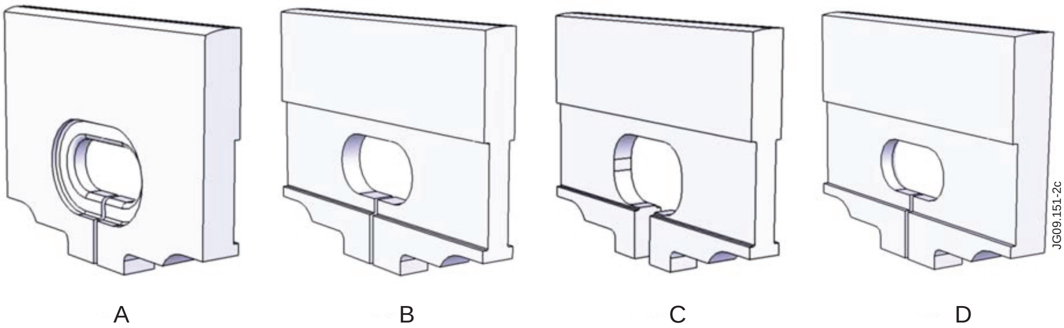

Figure 2: The four types of bulk tungsten lamellae: (A) outer left, looking as usual from the high field side to the centre of the torus; (B) standard lamella; (C) lamella at clamping location; (D) outer right.

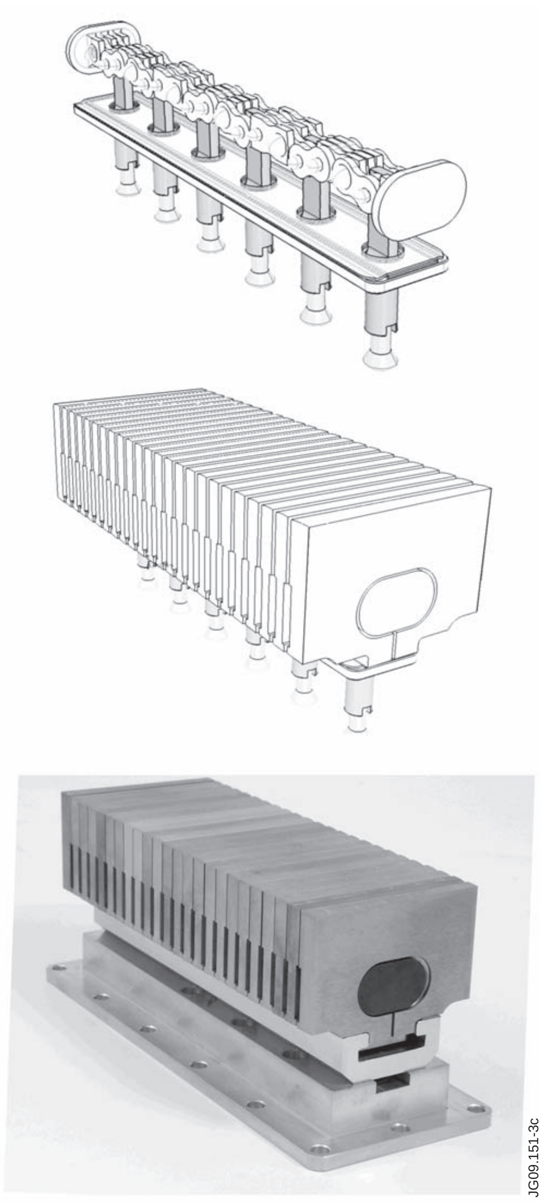

Figure 3: Clamping system and assembled tungsten stack (CATIA model and full scale prototype)

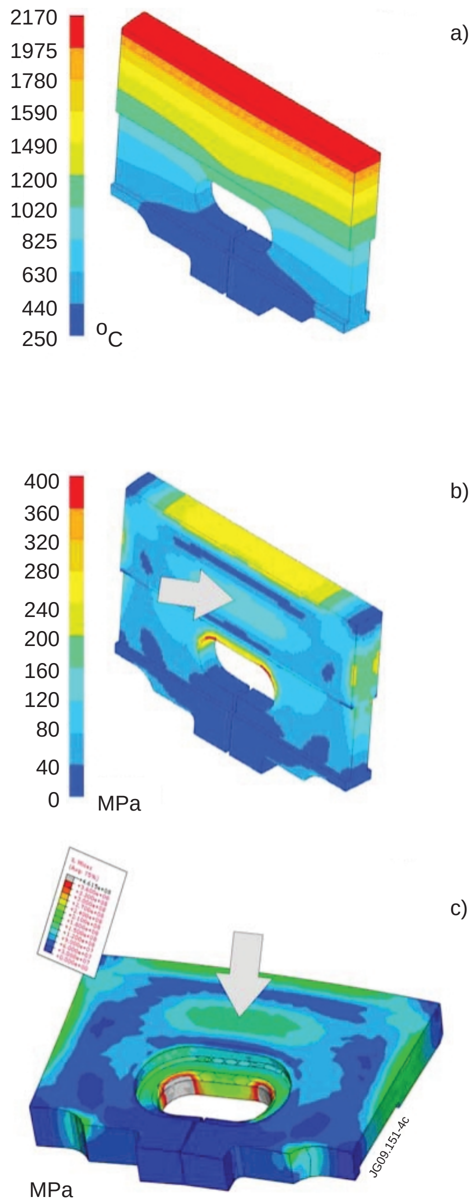

Figure 4: FE computations with $T_{init} = 200^oC$, exposure to $9\,MW/m^2$ for 10s. (a) temperature distribution in a lamella at $T_{surf} = 2200^oC$; (b) tensile stresses in a standard lamella at the end of the plasma pulse (c) stresses in a thicker, outer lamella The arrows show the position where a tensile stress of 150MPa is reached.

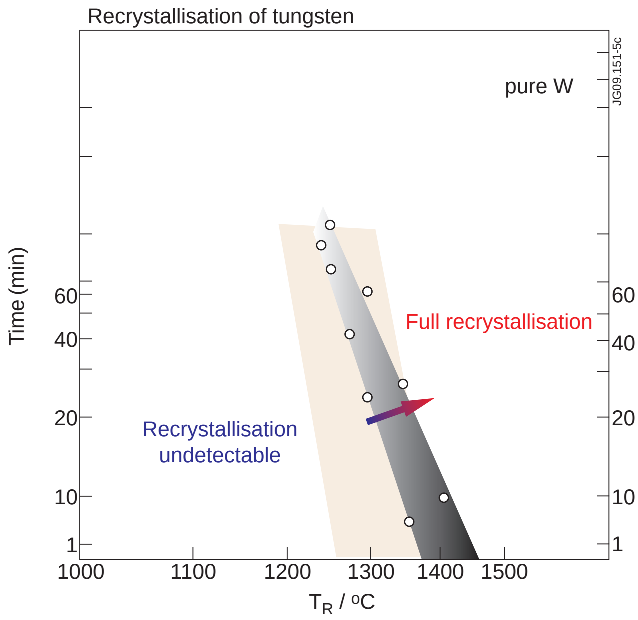

Figure 5: Rough indication of the relevant re-crystallisation domain in a time/temperature plane