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Conceptual Design for a Bulk Tungsten Divertor Tile in JET

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ABSTRACT.

The ITER-like Wall project (ILW) for JET aims at providing the plasma chamber of the tokamak with an environment of mixed materials which will be relevant for the first wall construction on ITER. Tungsten plays a key role in the divertor cladding. For the central tile, also called LB-SRP for “Load-Bearing Septum Replacement Plate”, bulk tungsten is envisaged in order to cope with the high heat loads expected (up to 10MW/m^2 for 10s). The outer strikepoint in the divertor will be positioned on this tile for the most relevant configurations.

Forschungszentrum Jülich (FZJ) has developed a conceptual design for this element, based on an assembly of tungsten blades or lamellae. An appropriate interface with the base carrier of JET, on which modules of two tiles are positioned and fixed by Remote Handling procedures (RH), is a substantial part of the design.

Important issues are the electromagnetic forces and expected temperature distribution, together with compliance with the requirements for the plasma-wall interaction, with the JET configuration and with remote handling possibilities. Material choices combine tungsten, TZM., Inconel. and ceramics parts. The completed design has been finalised in a recent proposal to the ILW project, with utmost ITER-relevance.

1. INTRODUCTION

With ITER on the verge of being built, the ITER-like Wall project (ILW) for JET aims at providing the plasma chamber of the tokamak with an environment of mixed materials which will be relevant for decisions related to the first wall construction. From the point of view of plasma physics, this encompasses aspects of the possible plasma configurations and of plasma-wall interactions. Whereas beryllium will be used for the vessel’s first wall, tungsten plays a key role in the divertor cladding. For the central tile, also called LB-SRP for “Load-Bearing Septum Replacement Plate”, bulk tungsten is envisaged in order to cope with the high thermal loads expected (up to 10MW/m^2 for about 10s). This is indeed the preferred plasma-facing component for positioning the outer strike-point in the divertor. The location of this tile is shown in Fig.1.

A conceptual design for this tile has been developed, based on an assembly of tungsten blades or lamellae. It has been selected in the frame of an extensive R&D study in search of a suitable, inertially cooled component. As reported elsewhere [1], the design is driven by electromagnetic considerations. The lamellae are grouped in four stacks per tile, which are independently attached to an equally re-designed supporting structure, hereafter called “the wedge”. An adaptor plate, a new design too, takes care of appropriate interfacing to the base carrier of JET, on which modules of two tiles are positioned and screwed by Remote Handling (RH) procedures. The compatibility of the design as a whole with RH requirements is another essential ingredient which has been taken into account.

Along with due consideration of the electromagnetic forces and of the expected temperature distributions, compliance with the requirements of the plasma-wall interactions and with the JET configuration is required. Material choices combine tungsten, TZMTM. (a molybdenum-based alloy),

Inconel[®] and ceramic parts (Zr O₂ and alumina). Most of these materials have been tested by exposure of small test modules to an electron beam or to fusion plasmas in the JUDITH facility and in the TEXTOR tokamak [2], respectively. The completed design has been proposed to the ILW project.

2. FRAME FOR THE CONCEPT DEVELOPMENT

The new design for bulk tungsten is expected to accommodate the following boundary conditions and requirements:

- load onto a tile $\leq 7\text{MW}/\text{m}^2$; goal for the present development $10\text{MW}/\text{m}^2$, taking account of the reduced surface with castellation and power deposition by ELMs. All loads should hold for a 10s exposure. The specification is for about 1000 cycles;
- values for the magnetic field, field variation and halo current through the module
- $|B| = 4.5\text{T}$, $|\dot{B}| = 100\text{T/s}$ and $I_{\text{halo}} = 18\text{kA}$ per module, that is 9kA /tile;
- overall weight limited to $\leq 80\text{kg}$ for reasons, among others, related to the application of remote handling through the whole installation procedure;
- in order to be perfect substitutes for the present CFC modules (Dunlop DMS 704, Fig.2), the tungsten modules should have similar dimensions. This means, for example, that the upper tile surface must present a shape close to the original 3D design, and must be positioned identically. A slight vertical deviation, i.e. modules which would be 5mm higher (at most), may be acceptable.
- many additional requirements, such as the feasibility of further operation in case of accidental damage, the suitability of the design with respect to later production of up to about 50 modules (equivalent to 100 tiles; 48 modules needed for complete circumference, together with waste/ reserve makes a total of 54 pieces); and possible inclusion of the current diagnostics, the latter only to a realistic extent at the conceptual stage.

It turns out that the concept involving plasma-facing bulk tungsten cannot simply mimic the present design, attaching the metallic tiles on top of a full-frame metallic structure (for a description of the CFC design and electromechanical analysis, please refer to [3]). The divertor module would be exposed to intolerably high electromagnetic forces. On the other hand, the whole supporting structure – from the wedge directly below the tungsten tiles to the adaptor plate which rests on the base plate – has to be completely re-designed to accommodate the aforementioned specifications of magnetic field strength, field variations and halo currents. The limit of detachment (from the base carrier) for some contact pads would otherwise be exceeded in all cases for a bulk tungsten design.

3. INTEGRAL CONCEPT

The development of a bulk tungsten divertor tile is indeed driven by electromagnetic considerations. However, the idea of a separate supporting “wedge” that fits over a newly shaped adaptor plate is retained. A module thus consists of three main components: two tungsten tiles (each split into four parts), the corresponding carrier in the form of a wedge, and the adaptor plate, which is fastened to the base carrier of JET. These components are described in the following.

3.1. TUNGSTEN TILES

The tungsten tiles are composed of four stacks of blades or “lamellæ” in the poloidal direction, numbered from the inner to the outer side of the torus (Fig.3). Castellation, a common procedure for brittle materials such as tungsten (see e.g. the ITER design), is thus partially ensured with cuts in the toroidal direction. A poloidal span of 60mm without additional castellation, or deep cuts along the poloidal direction, has been considered tolerable if, and only if, the blade thickness does not exceed a few millimetres. Only cycling tests could support the validity of this assumption. The actual blades are shown in Fig.4 for the case of limited castellation. They are 6mm thick in the standard case, which applies to all the central lamellæ of stacks no. 2 and 3. Exceptions are the trapezoidally shaped outer blades of all stacks, and compensation lamellæ which are required to ensure a correct width in the toroidal direction. The shaping of the upper surface is discussed elsewhere [5] and will be checked again during the optimisation of the shadowing properties, see e.g. [6] for a similar exercise.

The assembly of lamellæ is keyed with profiled spacers for better rigidity and positioning. These spacers are made of TZM for temperature reasons. While the upper surface of tungsten can reach 1600°C under normal operation, even 2200°C or higher can be reached for some plasma configurations. The spacers are also exposed to high temperatures and temperature gradients. In view of the ceramics coating (around 100µm alumina), and their lower position, the expected temperature of the spacers around the bore holes for compression should not exceed 700°C. The sandwiched stacks are firmly held by two metallic tie rods (Inconel or better material), which provide pre-stress, reminiscent of the original tie rods used in the CFC tiles. These long bolts do not touch the different sandwich slices (electrical + thermal insulation) and compress the complete stack over disc springs and insulating sleeves made of zirconium oxide.

As mentioned, every second spacer is coated with ceramic to break possible loops for eddy currents. The others are electrically conducting in order to provide a vertical path for the halo currents (>2kA per stack, cf. Sect. 2). The path is provided by the use of the conducting spacers as fixings to the wedge. This topological organisation reduces the electromagnetic forces to the values calculated in [1]. Note that TZM, although seemingly a better material than tungsten in this respect, is subject to brittleness (with low DBTT, ductile to brittle transition temperature) and should rather – as any sintered material – be acted upon in compression. On these grounds, both a comfortable dimensioning and additional tests are indispensable.

An Inconel rail takes care of the mechanical, thermal and electrical connection between the tungsten stacks and the supporting wedge as well as the ‘slide-in’ procedure for assembly. A detailed discussion is beyond the scope of the present paper; it should be noted that the main forces on a single stack average to a vertical lift of about 1.3kN [1]. A stack is also subject to a radial torque of about 200Nm, which means for a single tungsten lamella a peak of 20 Nm on both thicker, outer blades. This tends to tilt them out of the stack. Together with the differential thermal expansion, this is the reason for compressive pre-loading during assembly using the tie rods.

3.2. WEDGE CARRIER

For electromagnetic reasons, the supporting wedge has to adopt a fish bone shape, thereby preventing eddy current loops. A view is given in Fig.5. The preferred material is Inconel 625, but a rather high yield (0.2% proof stress) of 450MPa at room temperature is required (above 400MPa at operating temperature) to accommodate the high tensile, bending and twisting forces which may occur as a result of the currents generated by extreme Vertical Displacement Events (VDE) and plasma disruptions [7].

Aluminium mock-ups are being built in order to assess manufacturing feasibility and to study the procedure to be used for assembly. The wedge is screwed to the adaptor plate by two bolts, which together support a tension of about 8.25kN (lift).

Beside considering the electromagnetic forces under a purely numerical angle, ref. [8] adds structural calculations. The major deformation expected is bending: with the wedge lowered in the middle, all wings are bent up. Since this is mainly caused by preloading through screwing down to the adaptor, the deformation of 0.5 mm at most is negligible in terms of structural mechanics and can be accounted for with an adequate tile shaping. The bending effect should guarantee good contact with the base carrier and provide the electrical paths needed for the halo currents. The extremely low vertical clearance for the heads of the fixing bolts and the given height of the tungsten tiles explain the extra 5 mm of the present bulk-W design in comparison with the original CFC tiles. The latitude of building components with additional height was used.

Features specific to remote handling are implemented, such as a free gap >11 mm in the central part (13mm between modules), adequate guiding pins and inserts, flat docking surfaces and a vertical stop for the spinal part of the RH tool, a thin metallic blade which is inserted between the tiles from the low-field side (lowest side of the wedge). With this type of carrier, the overall weight of a module is kept slightly below 80 kg in spite of the heavy W tiles (corresponding to approximately 200 lamellæ).

3.3. ADAPTOR PLATE

The proposed wedge is a supporting structure that integrates the functions of the former adaptor plate to a large extent. This has an important consequence: different from the original rectangular frame, the adaptor plate is reduced to the conversion of the carrierbolts to wedge-bolts in terms of position and stresses (especially EM-induced lifts and torques). Thus, it became a “minimalistic” adaptor. The view in Fig.6 gives an impression of the star-shaped concept, which has the advantage of reducing the electromagnetic forces to a minimum by dropping the closed metallic frame design. Nevertheless, it incorporates the three dowels or guiding pins at the major reference radius of 2.667m and the indispensable RH features.

Maximal stiffness and adequate sliding properties over the CFC base carrier dictate the preferred material choice, Inconel 706. Attaching bolts are subject to a tensile force of up to 4.2kN in the first estimate, which calls for a pre-load of about 6kN. This is the pull exerted on the base plate

inserts, a force that was reduced with respect to all previous versions of the design to minimise the risk of extraction from the CFC plate.

CONCLUSION AND OUTLOOK

The study of a bulk tungsten tile for LB-SRP (tile No 5) has reached a conclusion with a feasible conceptual design, based on W-lamellae, which is adequate for the intended use. Figure 7 gives an artist's impression which should be compared with Figure 2. Reserve Factors (RF) corresponding to the different forces mentioned above are so far equal to 1.2 or larger. They are considered sufficient. The concept fits in the projected tungsten divertor cladding discussed in [4] and addresses the challenges linked to a highly loaded location in the divertor, the outer strike point. The electromagnetic forces have been taken into account. Optimisation of detailing aspects is in progress, especially in the case of shadowing issues. Whereas the lamella shaping can be optimised for most high- β plasma configurations aimed at for investigation of ITER-like shaped plasmas, an additional difficulty arises from the channels opened in the toroidal direction by the stack-to-stack gaps. This is being investigated at present with the help of the methods applied in [6]. Similarly, the compatibility with the divertor diagnostics has already been considered to a large extent.

The completed design has been finalised in the form of a recent proposal to the ILW project, with strong ITER-relevance and is expected to proceed to the procurement for the bulk tungsten divertor plate.

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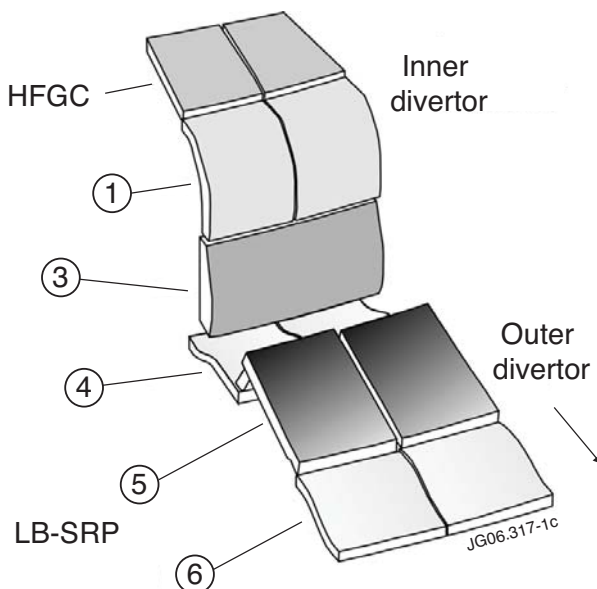


Figure 1: Schematised divertor view (inwards) shows the position of the LB-SRP (tile No.5). The grey shading enhances the readability of the picture but has otherwise no significance. HFGC: High-Field Gap Closure tile LB-SRP: Load-Bearing Septum Replacement Plate



Figure 2: Present mock-up for the LB-SRP (load-bearing septum replacement plates) show the arrangement of two 3D-shaped tiles in a module. A carbon fibre composite is used.

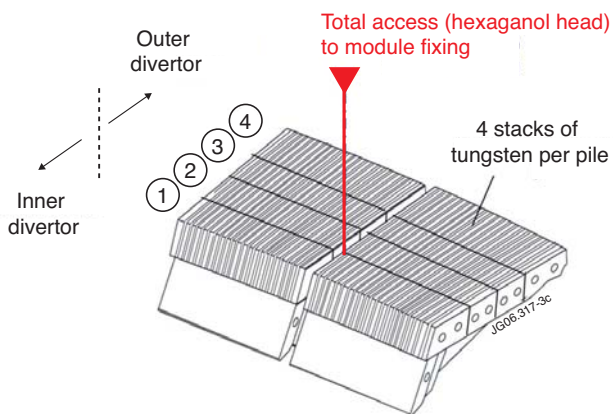


Figure 3; The arrangement of four stacks for the bulk tungsten tiles. Note that the small tiles on the inner side are made of W-coated CFC [4]

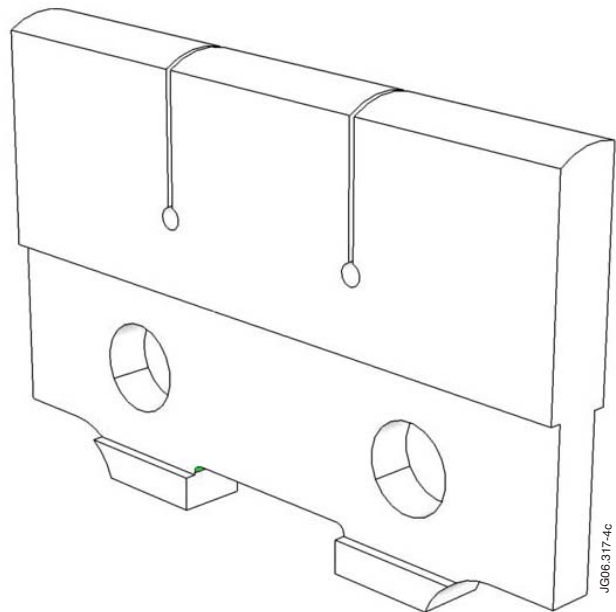


Figure 4: A typical tungsten blade (lamella) for the stack assemblies: 6mm thick, 64mm long. The height of 40mm is a result of the expected temperature gradient and of the total heat capacity required, taking account of the other dimensions. The curved profile of the top surface is asymmetric. Castellations is optional.

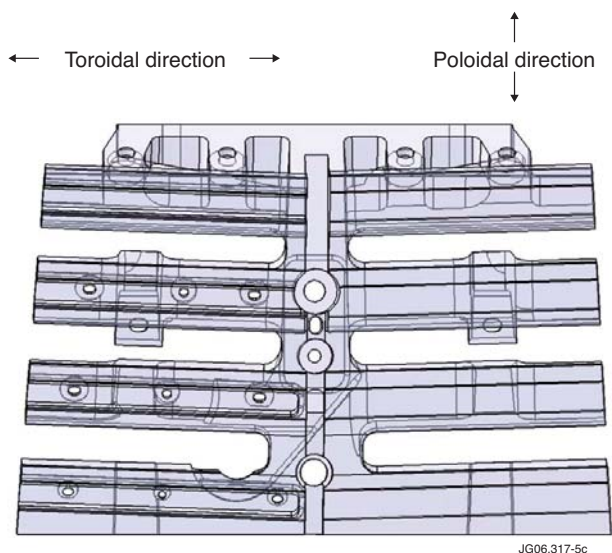


Figure 5: Top view of the Inconel Wedge (only left part shows detailed wing structure)

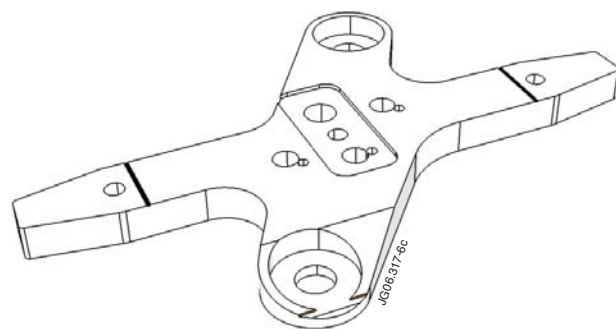


Figure 6: The adaptor plate converts the positions of base plate to wedge bolts.

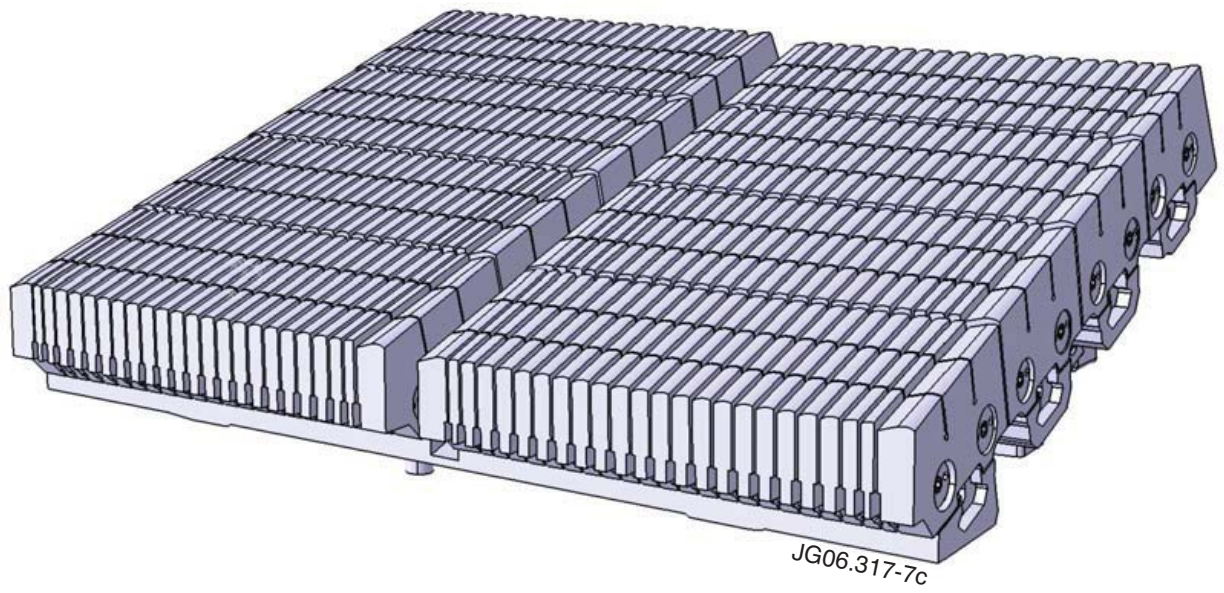


Figure 7: The proposed bulk tungsten divertor module for tile 5 (LB-SRP)