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A bulk tungsten divertor row for the outer strike point in JET

Ph. Mertens[a,b,*,1], H. Altmann[a,c], T. Hirai[a,d,2], M. Knaup[a,b], O. Neubauer[a,b], V. Philipps[a,b], J. Rapp[a,b,e], V. Riccardo[a,c], S. Sadakov[a,b], B. Schweer[a,b], A. Terra[a,b], I. Uytdenhouwen[a,f], U. Samm[a,b]

[a] JET-EFDA, Culham Science Centre, OX14 3DB Abingdon, UK
[b] Institute for Energy Research IEF-4 (Plasma Physics), Forschungszentrum Jülich, Association EURATOM-FZJ, Trilateral Euregio Cluster, D-52425 Jülich, Germany
[c] Euratom/UKAEA Fusion Association, Culham Science Centre, OX14 3DB Abingdon, UK
[d] Institute for Energy Research IEF-2 (Microstructure and Properties of Materials), Forschungszentrum Jülich, Association EURATOM-FZJ, D-52425 Jülich, Germany
[e] FOM-Instituut voor Plasmafysica Rijnhuizen, Trilateral Euregio Cluster,NL-3430 Nieuwegein, The Netherlands
[f] SCK•CEN, Association Euratom-Belgian State, B-2400 Mol, Belgium

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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 10 MW/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 $\partial B/\partial t \leq 100$ T/s, and $I_{halo} \leq 18$ kA/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 7 MW/m^2 for 10 s 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°. Note that shadowing effects discussed in Section 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 $\partial B/\partial t \leq 100$ T/s and $I_{halo} \leq 18$ kA/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 ≤ 80 kg), 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.

* Corresponding author. Tel.: +49 2461 61 5720/5780; fax: +49 2461 61 2660.
E-mail address: Ph.Mertens@fz-juelich.de (Ph. Mertens).
[1] http://www.fz-juelich.de/ief/ief-4/.
[2] http://www.fz-juelich.de/ief/ief-2/.

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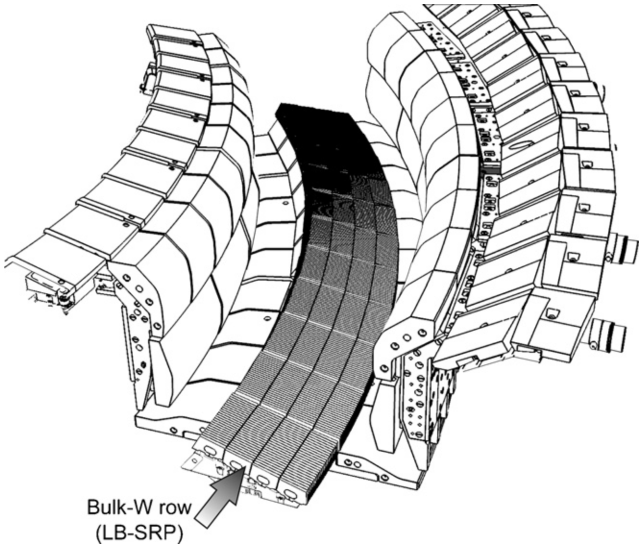

Fig. 1. Position and geometry of the bulk tungsten divertor row in JET.

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 Section 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 specific weight of tungsten, a module approaches the given limit of 80 kg.

2.1. Adaptor

The adaptor plate converts the position of the given base carrier bolts fixings (at an angle of 29.39° 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.

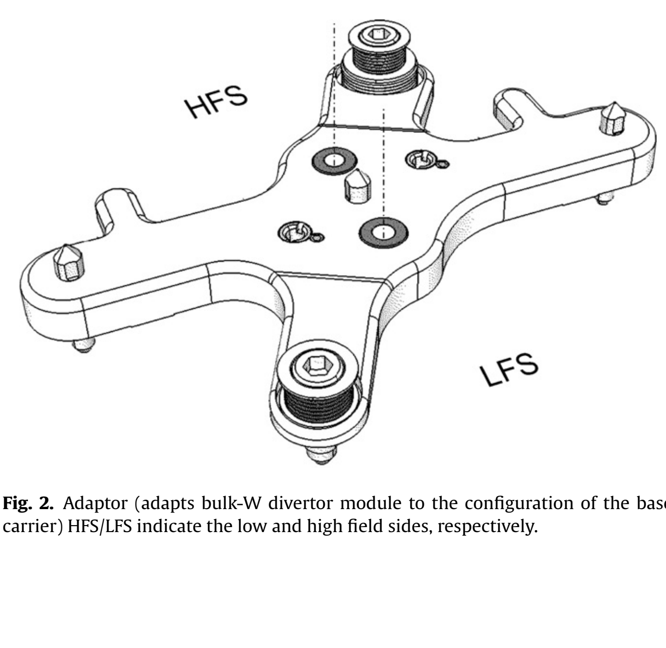

Fig. 2. Adaptor (adapts bulk-W divertor module to the configuration of the base carrier) HFS/LFS indicate the low and high field sides, respectively.

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 6 kN per bolt is unchanged with respect to the conceptual design [2], slightly larger than the vertical pull of modules fixed on top (4.5 kN/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° 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 150 μm 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° (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 centering 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. $\alpha_T \sim 5\times 10^{-6}\,K^{-1}$) together with sufficient resistance to high temperatures while