EFDA–JET–CP(10)07/14

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** See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

Preprint of Paper to be submitted for publication in Proceedings of the
26th Symposium on Fusion Technology (SOFT), Porto, Portugal
27th September 2010 - 1st October 2010

ABSTRACT

In the frame of the ITER-Like Wall (ILW) for the JET tokamak, a divertor row made of bulk tungsten material has been developed for the position where the outer strike point is located in most of the foreseen plasma configurations. In the absence of active cooling, this represents a formidable challenge when one considers the temperature reached by tungsten ($T_{W,surf}$ >2000°C) and the vertical gradient $\partial T/\partial z = 5 \times 10^4$ K/m.

As the development is drawing to an end and most components are in production, actual 1:1 prototypes are exposed to an ion beam with a power density around $7MW/m^2$ on the plasma-facing surface. Advantage is taken of the flexibility of the MARION facility to bombard the tungsten stack under shallow angles of incidence (~6°) with a powerful beam of ions and neutrals (>$70MW/m^2$ on axis). It does help in validating the thermal model that was steadily developed along with the tungsten tile and delivers, with respect to the toroidal wetted surface, experimental values to the expected performance under actual tokamak conditions.

1. INTRODUCTION

In the frame of the ITER-like Wall project (ILW) at JET, a bulk tungsten divertor row was developed for the position of the outer strike point in most of the plasma configurations. The hardware is described in [1]. The bulk tungsten modules are now under final manufacture. The reasons why a sophisticated design had to emerge in order to protect the brittle tungsten material are explained in [2]. Moreover, the lack of active cooling has triggered the development of a detailed thermal model named GTM [3] and the fully metallic nature of the tiles called for due consideration of the electromagnetic loads which had to be held within bounds [4]. Note that the design is based on toroidally oriented stacks of tungsten blades (lamellae), four of which constitute a full solid tile.

With all components in production, a full scale prototype was exposed to the neutral and ion beam of the MARION facility [5]. The idea behind these exposures is to validate the thermal calculations for a few typical cases and, at the same time, gather information on the actual temperatures of individual components. The latter is an important input to a finer estimation of the power handling capabilities and of the expectable lifetime.

All estimations of the thermal behaviour of the bulk tungsten modules were originally carried out to the specification of a uniformly applied load of $7MW/m^2$ for 10s. Several refinements are obviously required:

1. The poloidal distribution of the energy density is much more localized, i.e. narrower. This is accounted for in [6] with sensible double exponential deposition profiles.
2. Owing to the 2D profiles of the lamellae which constitute the tungsten plasma-facing surface, the local wetted fraction LWF in toroidal direction – that is from one lamella to the next – has to be considered, especially if additional ELM loads are estimated [7].
3. Finally, the [global] toroidally wetted fraction GWF (from tile to tile, also called TWF) plays a major role in the power-handling performance. It is the only shadowing property

that is usually discussed in first approximation. Since the experimental work reported here was carried out with representative GWF values, the present work is directly connected to this third aspect.

2. EXPERIMENTAL

Advantage is taken of the flexibility of the MARION facility to bombard the tungsten stack under realistically shallow angles of incidence ($\alpha \approx 6°$ on average). The direction of the field lines with respect to the tile surface are defined by means of two angles, an azimuthal angle $\vartheta_{\perp}$ to the toroidal direction in the torus and an elevation $\vartheta_{\parallel}$to the plasma-facing surface (see [6] for conventions). Note that the small angle of incidence prevents hitting the so-called spacers which define the gap width between lamellae: in the 1mm wide gap, those are 18mm deeper than the exposed flat top of the tungsten lamellae. The heat load is thus rightly deposited on the sole tile surface. With $\boldsymbol{P}_{beam}$ on axis of the order of 70MW/m^2 and more, $\boldsymbol{P}_{beam} \cdot \sin\alpha \geq 7$MW/m^2 as required. Acceleration voltage, power and gas pressure in the source were tuned each morning during the conditioning phase in order to reach, without breakdown, any value between 7MW/m^2 and 9MW/m^2 on the prototype for an adjustable time window of 1-10s. It was accordingly possible to modulate the deposited energy on the prototype stack from 7-70 MJ/m^2. Note that one row of stacks in the torus (96 stacks in queue/bout à bout) roughly corresponds to 1m^2. A standard prototype is shown in situ in Fig.1. The beam comes horizontally from the right side of the photograph.

3. RESULTS AND DISCUSSION

Most MARION pulses were applied under a wetted fraction of about TWF $\approx$70%. The spatial beam profile is fairly flat in the exposed region. A vertical profile is shown on Fig.2 [8] as estimated at the position of the probe with a spatial resolution of 2.5mm from the measured parameters at the source and in agreement with the measurements at the end calorimeter. The upper part is sharply cut by the protecting scraper in order to expose the required height of less than 20mm in a plane perpendicular to the beam axis. With this limited height reportée on the profile in Fig.2, it is clear that the deviation in the power density over the wetted area is roughly below 10%. While the beam is close to axisymmetric, the same conclusion holds true for the horizontal profile, meaning that the energy deposition is uniform over the stack width, which corresponds to the poloidal direction in the torus. For this reason, the poloidal deposition profiles are discussed elsewhere [6].

After a slow ramp up of the beam parameters from pulse to pulse and a careful check of the wetted area, the deposited energy can be adjusted to any desirable value in the above mentioned range. Out of the 300 pulses considered in the present study, more than 180 correspond to an energy deposition $E_{dep} > 40$MJ/m^2 and more than 50 to $E_{dep} > 60$J/m^2. Table 1 shows typical steps in the power and energy levels that were applied. It presents two types of discharges with E_{dep} around 40MJ/m^2 (−5%/+10%) and around 60MJ/m^2 (idem). It all cases, the cooling time is in the order of 3600−4000s. We deliberately decided to wait for the temperatures of all components to fall back to ≈200°C before resuming bombardment. The highest values on the tungsten surface were cross-checked between the front infrared camera [9] and a pyrometer with measurement spot slightly narrower than the lamella thickness (5mm) [10].

The experimental values show that one may expect the tungsten tile to be kept below the recrystallization limit (see [2]) at exposures up to 35MJ/m^2. The upper operational range in terms of power handling is determined by the engineering limit of 330°C for the clamping springs of the bulk tungsten tile and the admissible 600^{o}C for the Inconel carrier. Energy densities up to 40−50MJ/m^2 appear to be safe and 60MJ/m^2 are tolerable. Exceeding the latter by 10% owing to uncertainties in other operating parameters could be occasionally acceptable for the long clamping tested here, for the shallow tungsten stacks at the low field side of the tile, it will be prohibited. Experimental confirmation of this is still pending. The differences in the design are explained in [1].

Specific investigations, experimental as well as in the modeling [3], are still needed on deposited energy densities in the range 5−30MJ/m^2 to refine the operating instructions: the main challenge lies in the fact that the maximal temperatures are reached about 400s after the tokamak pulse, at a time when no corrections are possible. Lookup tables or similar tools are thus required for the session leader to assess acceptable control parameters for the coming pulse.

The temperatures given in Table1 are close to the predictions of the Finite Element modeling [11]. The agreement is within ±15%. Additional calculations are required only for the cooling time, for which the model was not yet adapted to the Marion prototype case, and for lower energy depositions, especially in the range around 30MJ/m^2 which may have to be used extensively for the foreseen experimental programme [12].

CONCLUSIONS

The exposure of a full scale prototype of the standard tungsten stack in the MARION facility shows that an energy density of up to 60MJ/m2 can be handled with the bulk tile. This roughly corresponds to one row of stacks in the divertor under a wetted fraction of 1. The complete tile (row) consists of four stacks in poloidal direction. Note that up to three of them can be used simultaneously with adequate sweeping schemes (see for instance [6]).

The present experimental tests also confirm the temperatures obtained with the Global Thermal Model previously developed [c] for energy density depositions of 40MJ/m^2 and 60MJ/m^2. Further work is required to fill the gap at lower energies.

ACKNOWLEDGEMENTS

The support of the JET Engineering team in Culham and of the MARION team in Jülich is gratefully acknowledged. This work, supported by the European Communities under the contract of Association between EURATOM and Forschungszentrum Jülich, was carried out within the framework of the European Fusion Development Agreement (EFDA). The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]. Ph. Mertens, Fusion Engineering Design **84** (2009) 1289-1293

[2]. Ph.Mertensetal.,Phys.Scr.T138(2009)014032(5pp.)

[3]. S. Grigoriev et al., Fusion Engineering Design **84** (2009) 853-858

[4]. S. Sadakov et al., Fusion Engineering Design **82** (2007) 1825-1832

[5]. D. Nicolai et al., submitted to Fusion Engineering Design (this conference)

[6]. Ph. Mertens et al., submitted to Journal of Nuclear Materials

[7]. S. Jachmich, private communication

[8]. R. Uhlemann, private communication

[9]. FLIR 300 series,

[10]. Maurer, type KTRD 1075,

[11]. Internal report FZJ-BW53-ILT, 173 pp.

[12]. S. Brezinsek et al., submitted to Journal of Nuclear Materials

Number of pulses	Average energy deposited /(MJ/m^2)	W temperature (top average) /°C	W temperature (top max.) /°C	$T_{springs}$ (average)/°C
1 (ref.)	36.0	1010	1263	246
183	41.1	1175	1445	254
1 (max.)	44.1	1290	1590	287
51	61.6	1450	1800	333
1 (max.)	66.1	1608	1820	343

Table 1: Temperatures recorded at the plasma-facing surface of the tungsten tile and at the top of the clamping springs for different deposited energies (see text)

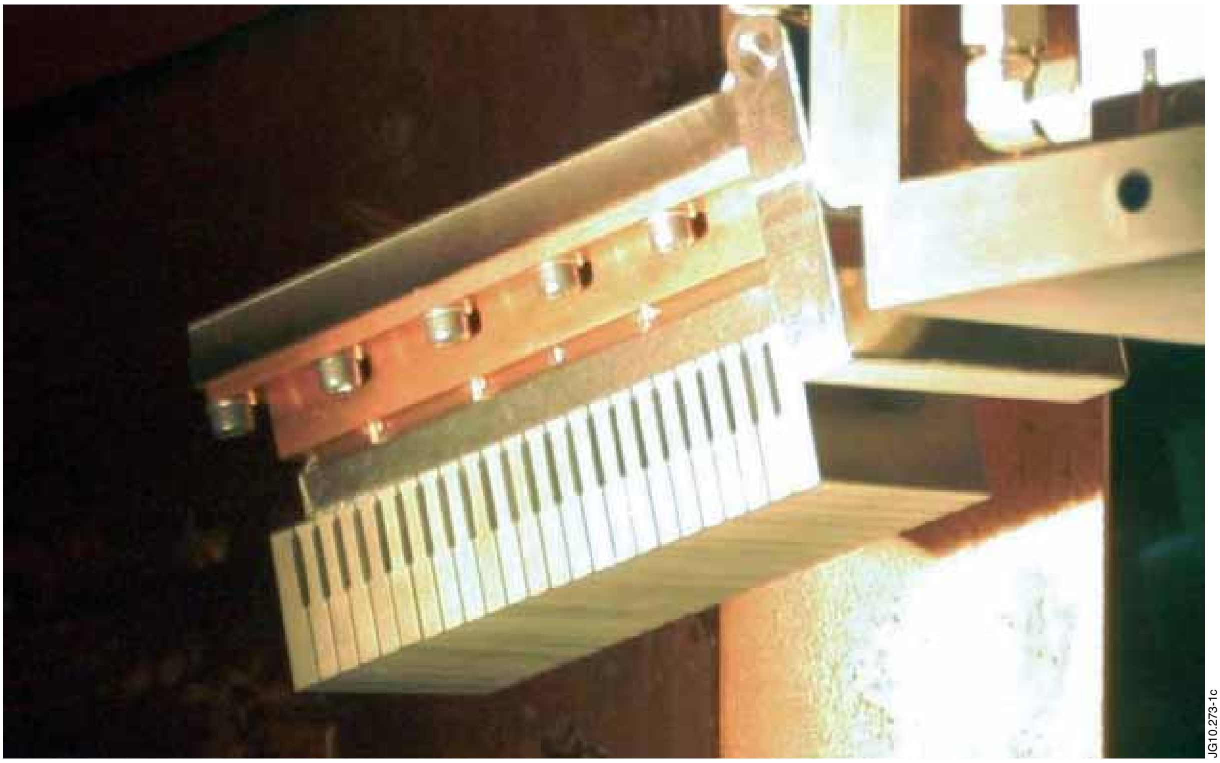

Figure 1: Stack of tungsten lamellae photographed insitu (target station of the Marion facility) before exposure. The beam is horizontal, from the right side of the picture.

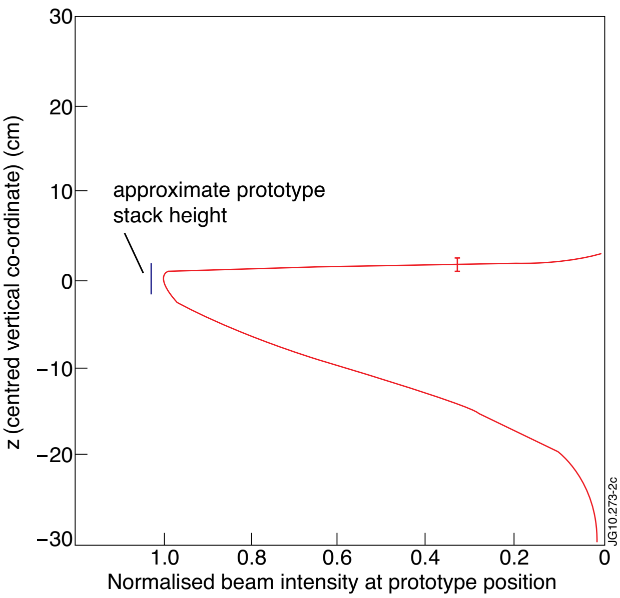

Figure 2: Vertical beam profile as calculated with the Padet code (2.5mm resolution).