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A new look at JET operation with Be as plasma facing material

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Abstract

Experiments at JET with Be as plasma-facing material demonstrate that although Be PFCs are easily damaged, the consequences for plasma operation are mild. L-mode plasmas up to a current of 7 MA and heating power ~30 MW were obtained on heavily damaged Be limiter with ~12 MJ plasma energy, albeit with a very high Be content. The behaviour of H-mode plasmas in contact with a molten Be divertor target was studied. Despite the heavy damage to the target (~3 mm molten grooves) no plasma performance deterioration was observed for medium density ELMy H-modes. Type I ELMs, in these conditions, lead to ~ 40 μm melt layer formation but to an average melt layer loss of only ~4%. Based on these results, conclusions for ITER limiter and divertor operation are extracted.

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Keywords: JET; Beryllium; Plasma facing components; ITER; Thermal load; Liquid metal

1. Introduction

An extensive set of experiments was carried out in JET in the period 1990–1996 to characterise Be plasma facing components (PFCs) both from the point of view of their thermo-mechanical performance as well as of their compatibility with various plasma operation regimes [1–4]. In particular, well diagnosed dedicated experiments to test the implications on plasma operations of severely molten divertor targets were carried out for two divertor designs [5,6]. Beryllium was used at JET in the toroidal belt limiters (and ICRH antenna screens) and divertor targets for two divertor designs (so-called Mk 0 and Mk I). Fig. 1(a) and (b) show the two JET configurations in the period 1990–1996 indicating the materials used for the various components (C or Be). In the 1990–1992 JET configuration, limiter plasmas were obtained up to a maximum plasma current (I_p) of 7 MA and diverted plasmas up to a maximum I_p = 5MA. In the 1994–1996 JET configuration, diverted plasmas (single-null) were obtained up to a maximum I_p = 6MA.

The evaluation of the results obtained in these experiments and the analysis of plasma performance can be found in [1–6]. In this paper, we review this evaluation from a different point of view, in order to identify which are the conclusions to be extracted from these

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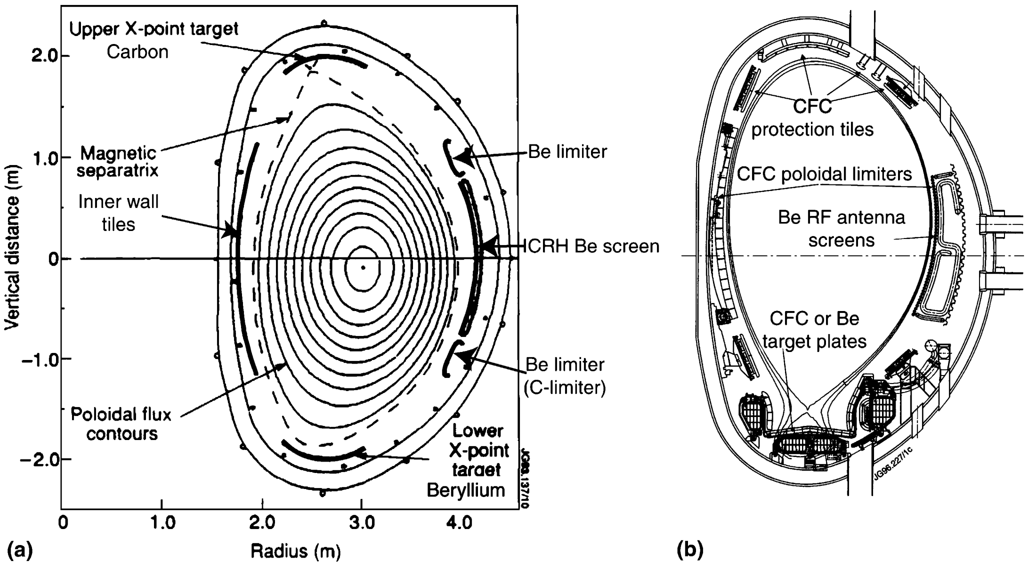

Fig. 1. (a) JET plasma facing components (divertor targets, belt limiters and ICRH screens) for the operation period 1990–1991 and 1991–1992. In the period 1991–1992 the lower toroidal belt limiter was replaced by a carbon limiter. (b) JET plasma facing components (divertor target, poloidal limiters and ICRH screens) for the operation period 1994–1996, in which two materials were tested for the divertor target tiles C and Be.

experiments with respect to the proposed use of Be as limiter PFC and as main chamber PFC protecting the blanket modules in ITER.

2. Be PFC performance under steady state power fluxes in JET and implications for plasma performance

The JET beryllium belt limiters were designed to provide optimum plasma power handling with an average power flux density of $\sim$3 MW/m^2 (peak power flux of $\sim$5 MW/m^2) for a maximum power deposited on the limiter of 20 MW during 10secs and a range of power e-folding lengths λ_p = 0.8–2.4 cm (at the outer midplane) [2]. The power e-folding lengths from Langmuir probe measurements in JET limiter discharges were in the range of 0.4–0.8 cm (at the outer midplane) for ohmic discharges with I_p = 2–5 MA, with an approximate $\lambda_p \sim 1/I_p$ scaling [7]. λ_p was found to depend weakly on power, typically $\lambda_p \sim P_{inp}^{0.2}$ or weaker [7,8]. As a consequence of λ_p being narrower than expected, installation inaccuracies ($\sim$0.5 mm), radial modulation of the field lines at the limiter position caused by field ripple ($\sim$1.5 mm) and up/down power asymmetries [2], the actual power handling capability of the limiter was insufficient for the achieved plasma parameters and substantial Be melting could be observed for global energy deposition levels much lower than those of the design. This was mostly due to local overheating of the tile edges which were exposed to an estimated local power density >100 MW/m^2, although melting was also found on the flat surface of the tiles. The overall damage caused by plasma operation over the 1990 experimental campaign was restricted to about $\sim$10% of the total of 34 200 castellations of the surface of the 1900 beryllium limiter tiles [2]. An example of the observed melting on the beryllium limiter is shown in Fig. 2.

Melting of the tile edges during high power/low density operation lead, occasionally, to the formation of beryllium droplets that fell into the plasma. This caused a large increase of the beryllium plasma contamination

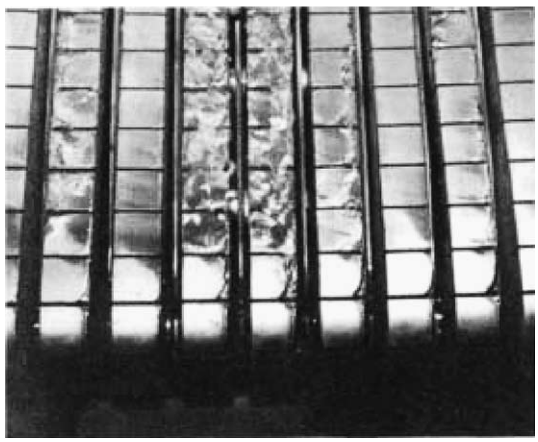

Fig. 2. Photograph of a section of the JET beryllium belt limiter showing heavy melting and melt layer displacement following high power limiter experiments at JET.

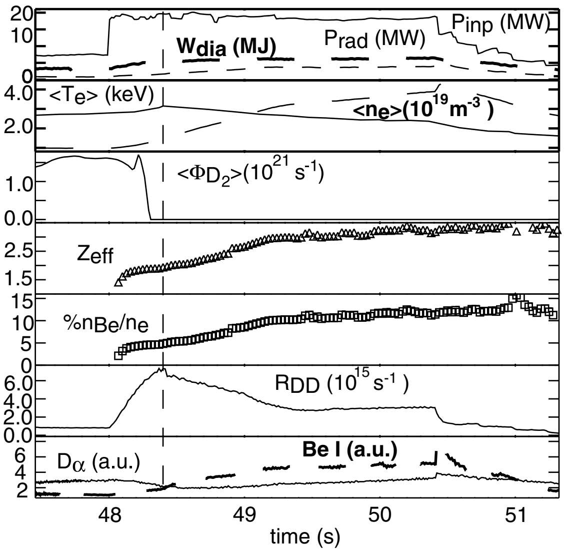

Fig. 3. Plasma parameters obtained during a high power JET beryllium limiter discharge, in which a beryllium droplet is seen to fall into the plasma from the top upper limiter at the time marked by the vertical line.

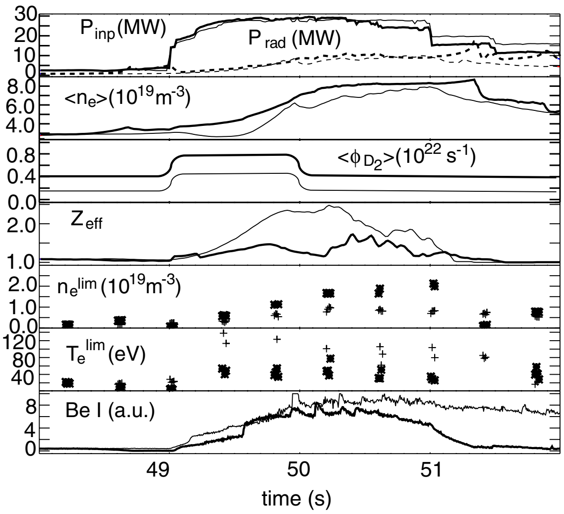

Fig. 4. Plasma parameters obtained during two high power JET beryllium limiter discharges with (thick-blue traces) and without (thin-red traces) strong gas fuelling. For the discharge with strong gas fuelling the Z_{eff} remains low for the whole duration of the high power phase. For interpretation of the references in color in this figure legend, the reader is referred to the web version of the article.

and loss of plasma neutron production [3] as shown in Fig. 3 for a 5 MA L-mode limiter discharge. Hot spots formation (and beryllium droplet ingress into the plasma) was effectively avoided by the use of gas fuelling during the high power heating phase of the discharge. In this way, it was possible to keep a high deuterium concentration in the plasma (60–90%) for powers up to 25–30 MW and periods of several seconds (2–4) up to a maximum level of injected energy into the plasma of ~180 MJ (~120 MJ energy deposited on the limiters). Fig. 4 shows a comparison of two similar discharges at low and high fuelling rates, demonstrating the effectiveness of this technique to obtain clean L-mode limiter plasmas at high levels of input power. However, the elimination of hot spots with gas puffing proved to be limited in application and was effective only for moderate plasma currents ($I_p \leqslant 3$ MA) and for conditions of moderate damage of the limiter. At the highest plasma currents (because of the small $\lambda_p \sim 2$ mm observed at $I_p \sim 7$ MA) and with the progressive melting of the limiter the technique was not effective. As a consequence the typical deuterium concentration at high P_{inp} and I_p was typically ~30% towards the end of the 1992 campaign, time at which the Be belt limiter was very damaged. Despite the heavy melting of some areas of the limiter, disruptions caused by beryllium droplets falling into the plasma were relatively rare and either the plasma survived to the end of the discharge or could be safely terminated by the control systems, following the droplet ingress, avoiding the disruption. This can be understood by evaluating the ionisation potential of Be^{3+} (217.6 eV) and the transient radiation capability of a neutral beryllium atom, as it enters a hot dense plasma. Calculations carried out using data from ADAS for conditions relevant of the ITER pedestal [9] ($n_e = 8 \times 10^{19}\ m^{-3}$, $T_e = 3$ keV), which are not far from those achieved over a large cross section of the plasma in JET high I_p limiter L-mode discharges, show that the transient radiated energy emitted by a Be neutral atom until full ionisation is only ~240 eV. This means that approximately ~0.4 g of neutral beryllium are needed to radiate ~1 MJ of plasma energy and, thus, only droplets containing several grams of beryllium can cause a radiative collapse of a JET high P_{in} and I_p plasma. For high P_{in} and I_p limiter L-mode plasmas in JET, the typical values of the plasma energy are $W_{dia} = 6$–12 MJ and average electron temperatures $\langle T_e \rangle = 1$–3 keV [3].

Following the beryllium limiter experience, divertor beryllium targets were installed in JET for both configurations in Fig. 1(a) and (b). In both targets, a series of well-diagnosed dedicated experiments were carried out to provoke controlled melting of the beryllium surface and, then, to study the behaviour of plasmas in contact with a molten Be divertor target [6,7]. The results obtained for both targets were similar, although the explored plasma regimes were different (ELM-free H-mode for the Mk 0 target and ELMy H-mode for the Mk I target). We will describe here the results for the Mk I experiments because they correspond to a more

ITER-relevant plasma regime and because the diagnostics were better than in the Mk 0 experiments.

In the JET Mk I experiments, beryllium melting was approached by increasing (in a progressive way) the power flux to a restricted area of the divertor target in fuelled ($\sim 2.5\times10^{22}\ \mathrm{s}^{-1}$) medium density ELMy H-mode discharges (P_{inp} ~12 MW). Large beryllium influxes were observed when the divertor target temperature reached ~1300 °C. Inter-shot visual inspection of the target showed that this coincided with the observation of beryllium melting (as expected from the Be melting temperature of ~1280 °C). High power ($P_{\mathrm{inp}} > 15$ MW) medium density ELMy H-mode discharges could be performed on a beryllium molten target for a duration of ~3.5 s (~ $10\tau_{\mathrm{E}}$), while maintaining a reasonable H-mode confinement H_{93} ~0.7 and Type I ELMs, as shown in Fig. 5. Towards the end of the experiment (~25 high power discharges) the damage to the target was significant (up to ~3 mm valleys were seen at the target due to melt layer displacement) [2,6]. In these conditions, it became difficult to run low density ELMy H-mode discharges (P_{inp} ~12 MW) without fast strike point movement (to achieve lower average power load) and the discharges either had very poor performance or disrupted. However, no substantial plasma performance degradation was observed for medium density H-modes with fixed strike point position, or if fast strike point movement was applied in low density H-modes, despite the large scale distortion of the target surface caused by the melt layer displacement and splashing due to the previous ~25 high power discharges [6]. This demonstrated that it was possible to use the damaged divertor target as main power handling PFC if the average power load was decreased, either by increasing plasma density and radiative losses or by strike point sweeping.

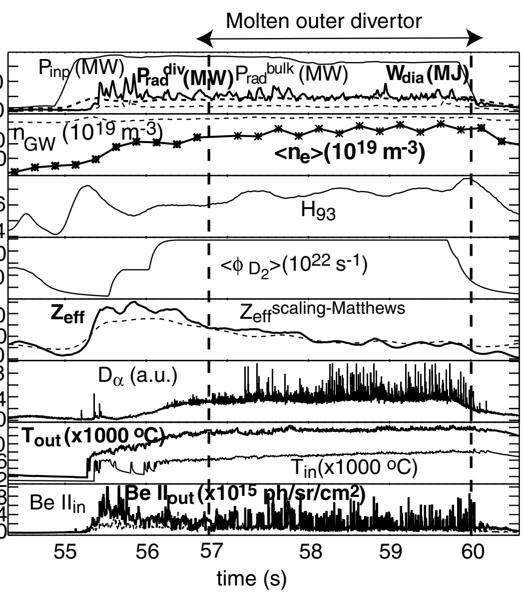

Fig. 5. Plasma parameters obtained during a high power JET divertor discharge on the Be Mk I divertor in which the outer divertor target surface reached the Be melting temperature during more than 3 s. Large Be influxes were measured at every ELM by the Be II line emission from the outer divertor.

3. Be PFC performance under transient power fluxes in JET

Besides controlled experiments on beryllium melting, 'accidental' melting was observed in JET during plasma transients, such as large ELMs and disruptions, in agreement with the expected energy fluxes (>0.5 MJ/m^2 in timescales ~0.1–1 ms) deposited on the Be PFCs. Besides these accidental transient events, a formation of a Be molten layer and large Be influxes were observed after every ELM for discharges in which the surface temperature was close to the Be melting point, as that in Fig. 5. The surface target temperature was determined by infrared camera measurements appropriately calibrated for its use for measurements on a beryllium surface [6]. For this purpose, experiments were conducted to check that the onset of beryllium melting by visual inspection of the target coincided with the measured surface temperature reaching the Be melting point. The estimated ELM energy loss from the main plasma of ΔW_{ELM} ~0.1 MJ in these discharges, as determined by diamagnetic measurements, lead to a formation of a Be melt layer of ~40 μm [10] after every ELM. Despite this, the maximum observed erosion of the Be target (after ~2000 ELMs) was only of 3 mm, which indicates that only ~4% of this after-ELM melt layer is (on average) lost at every ELM.

4. Discussion and conclusions

The use of beryllium in JET demonstrates that, although it is relatively easy to cause serious damage to PFCs made of this material, the consequences for plasma operation and performance are relatively minor, in particular in the areas of interest to ITER. JET operation has demonstrated that it is possible to ramp-up and carry out discharges at high input powers ($P_{\mathrm{inp}} > 20$ MW) and high plasma currents ($I_{\mathrm{p}} = 7$MA) with a significantly damaged beryllium limiter with power fluxes $q_{\mathrm{max}}^{\mathrm{limiter}} =$ 5–10 MW/m^2 and $q_{\mathrm{max}}^{\mathrm{edge,limiter}} > 100$ MW/m^2 at limiter tile edges. This indicates that the proposed Be limiters in ITER (which operate at a nominal power load flux < 8 MW/m^2) will probably be adequate (from the plasma compatibility point of view) for the ramp-up phase of the discharges. However, the lifetime of the limiters could be severely limited if the scale of the Be damage in ITER is similar to that observed in JET.

Depending on the actual energy flux to the Be PFCs in ITER during ELMs and disruptions, melt damage may occur or not. For Type I ELMs which are compatible with the ITER divertor lifetime (~10 MJ convective ELMs [11]), the expected energy flux to the main chamber in ITER will be in the region of 2–3 MJ. The area of the wall over which this flux will be distributed is ~30–60 m^2, for a toroidally symmetric energy deposition. This leads to ELM energy fluxes ~0.02–0.08 MJ/m^2 on the main chamber wall, which cause no Be melting at all. If toroidal asymmetries and/or poloidal structures dominate the ELM energy deposition on the first wall, a substantial reduction of the first wall effective area for energy deposition is expected (by a factor of ~5). In this case the ELM energy fluxes on the first wall would be 0.1–0.4 MJ/m^2, which can cause up to 18 μm of melting, lasting ~300 μs [10]. From the JET Be divertor experience, we expect that only a very small part of this layer will be mobilised (typically <5%) and may lead to a Be influx into the plasma. For estimation purposes, we assume that, at most, an amount of Be corresponding to ~1 μm melting over 12 m^2 (~14 g of Be) could enter, occasionally, the ITER plasma after an ELM. In such case, the entering Be atoms would be fully ionised in ~0.1 ms leading to a total radiative loss of ~37 MJ. This is estimated assuming that the transient radiated energy emitted by a Be neutral atom until full ionisation in these plasma conditions is ~240 eV, as estimated by ADAS modelling [9]. Although this radiative loss is, by no means, small, it is very far from the 350 MJ of plasma energy for the ITER reference scenario and, thus, this beryllium influx will not lead to a plasma disruption (this requires an ingress of ~150 g of Be into the plasma).

Larger ELM energy fluxes onto the Be wall in ITER are indeed possible and would lead to serious problems for the use of Be as main plasma PFC in ITER, both because of lifetime issues and because of plasma contamination. However, for the arguments explained above, a regime with repetitive ELM energy loads which are not compatible with the lifetime of the Be main chamber wall in ITER is not compatible either with the ITER divertor lifetime and will not be the reference regime of ITER operation.

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