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Effects of ELMs and disruptions on ITER divertor armour materials

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Abstract

This paper describes the response of plasma facing components manufactured with tungsten (macro-brush) and CFC to energy loads characteristic of Type I ELMs and disruptions in ITER, in experiments conducted (under an EU/RF collaboration) in two plasma guns (QSPA and MK-200UG) at the TRINITI institute. Targets were exposed to a series of repetitive pulses in QSPA with heat loads in a range of 1–2 MJ/m^2 lasting 0.5 ms. Moderate tungsten erosion, of less than 0.2 μm per pulse, was found for loads of ~1.5 MJ/m^2, consistent with ELM erosion being determined by tungsten evaporation and not by melt layer displacement. At energy densities of ~1.8 MJ/m^2 a sharp growth of tungsten erosion was measured together with intense droplet ejection. MK-200UG experiments were focused on studying mainly vapor plasma production and impurity transport during ELMs. The conditions for removal of thin metal deposits from a carbon substrate were characterized.

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1. Introduction

The response of plasma facing components (PFCs) to thermal energy deposited during Type I edge localised modes (ELMs) and disruptions is expected to have an important impact on ITER operation [1]. Some aspects of these phenomena are still not well understood and require further experimental and modelling studies. These include: (a) erosion effects under realistic plasma parameters and conditions (i.e., adequate pulse duration, high energy density, large number of pulses) and (b) resultant production and transport of impurities in the plasma during and after ELMs and their potential for plasma contamination. The results of these studies will provide a sound physics basis for the evaluation of the PFC lifetime in ITER operating scenarios (with disruptions and Type I ELMs) and, together with the investigation of the associated plasma contamination, will help to determine the size of tolerable ELMs in ITER.

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In order to explore the PFC erosion during Type I ELMs and disruptions, a collaboration between the EU and the Russian Federation has been established. This paper describes the design and manufacture of CFC and tungsten macrobrush targets ($150 \times 60 \times 10\,\text{mm}^3$), the experimental conditions to which they have been subject in the plasma gun facilities at the TRINITI research centre and the results of selected experiments and numerical modelling.

2. Experimental techniques and diagnostics

Conditions typical for Type I ELMs and disruptions in ITER [2] are difficult to achieve in existing tokamaks or plasma simulators. Therefore, experiments are carried out in separate facilities that match some of their key parameters, numerical models are validated with these experimental results and extrapolation to ITER is carried out by these models. The experiments described in these paper were carried out in two plasma guns (QSPA [3] and MK-200UG [4]) located in TRINITI on tungsten and CFC targets similar to those of the ITER divertor. The QSPA facility (see Fig. 1) provides realistic heat loads (i.e., adequate pulse duration and energy density) to simulate the expected Type I ELM loads in ITER [5,6] and was typically used for studying PFC erosion. The MK-200UG facility (see Fig. 2) provides a high energy plasma flux ($E_i \leqslant 3$ keV), as expected in ITER Type I ELMs [5], and is equipped with a strong magnetic field ($B = 2$ T) but has a short pulse duration ($t \leqslant 0.04$ ms, i.e., 5–10 times shorter than expectations for ITER ELMs [5]). Thus, it was mainly used to study vapor plasma production and impurity transport along and across magnetic field during ELMs.

Both facilities have been modified to achieve heat loads and plasma flow parameters typical for Type I ELMs in ITER [5]. For QSPA the absorbed energy density and plasma pressure were measured as a function of gun voltage for 0.2 ms and 0.5 ms pulses. Measurements showed that the range of heat loads expected in ITER ELMs and disruptions could be achieved by varying the QSPA gun voltage in a range ~1.8–4.0 kV. For a pulse duration of 0.5 ms the plasma pressure does not exceed 0.4–0.5 MPa. This pressure is about an order of magnitude higher than that expected in ITER ELMs, which is due to the lower particle energies achievable in QSPA (~100 eV) compared to those expected in ITER (~3 keV). The residual gas pressure in the vacuum chamber before the shot is below of 10^{-2} Pa. The content of oxygen in percent in the plasma stream does not exceed 10^{-3}. The heat loads for simulations of ITER ELMs in MK-200UG were limited so as to avoid tungsten boiling following the plasma energy pulse. As a consequence, the energy density in the plasma was kept below ~1 MJ/m^2, which is a factor of 10–15 lower than in earlier disruption simulation experiments [4,7]. This was achieved by decreasing the gun voltage from 25 kV to 15 kV and by increasing the magnetic field in the mirror region (see Fig. 2) to 2.8 T. Varying the magnetic field in the target chamber (1.3–0.8 T) allows a variation of the plasma energy density from 1.5 to 0.6 MJ/m^2. Besides this calibration, direct measurements of the surface temperature evolution for the tungsten target were performed to determine the threshold energy densities for tungsten melting and boiling in MK-200UG experiments, which confirmed these results.

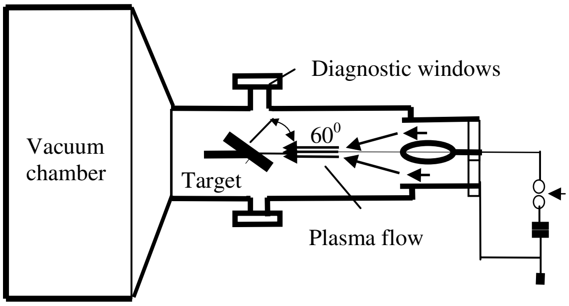


Fig. 1. Scheme of the QSPA facility. Plasma parameters: energy density 0.5–2 MJ/m^2; pulse duration 0.1–0.6 ms; plasma stream diameter 5 cm; ion energy ≤0.1 keV and no magnetic field.

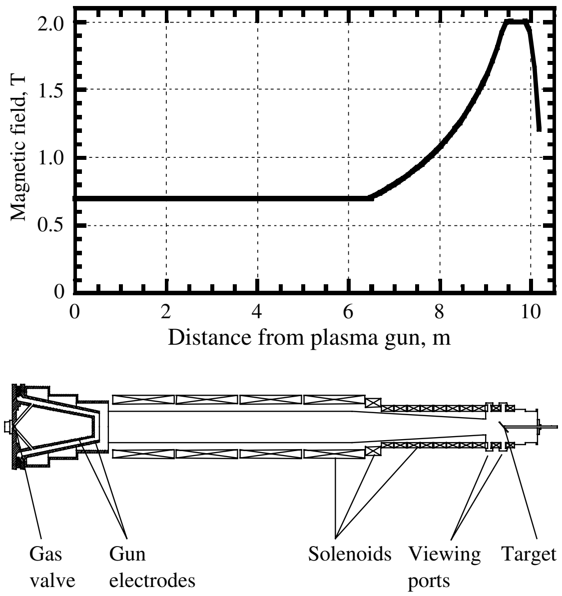


Fig. 2. Scheme of the MK-200UG facility and its magnetic field distribution. Plasma parameters: energy density 0.2–1 MJ/m^2; pulse duration 0.04–0.06 ms; plasma stream diameter 6–10 cm; ion energy ≤3 keV; magnetic field 0.5–1.2 T (at the target chamber).

A castellated tungsten target was manufactured for these investigations. It consisted of separate tungsten elements of sizes $10 \times 10 \times 3\ \text{mm}^3$ and $20 \times 20 \times 3\ \text{mm}^3$ brazed to a common holder copper plate with 0.3 mm gaps between neighbouring elements. The target was wider than that of the plasma stream (diameter ~60 mm) to avoid erosion edge effects. The length of the target was ~150 mm to allow erosion measurements with target/plasma inclination angles from 0 (normal incidence) to 60°. In the initial experiments described in this paper, an inclination of 60° was used. The target was installed on a radiative heater, which can provide target preheating up to 600 °C, although the experiments reported here were carried out at 200 °C.

The diagnostics used in these experiments to characterize the plasma-material interactions included: (a) magnetic probes, pressure gauges and calorimeters to characterize plasma stream parameters; (b) multi-channel calorimeters to measure absorbed energy distribution; (c) analytical balance and mechanical profilometry to study mass losses behaviour and surface modifications as a function of the number of pulses; (d) absolutely calibrated with a hot tungsten strip (2700 K) fast infrared pyrometer for on-line measurement of surface temperature during and after plasma pulse and (e) digital camera imaging for in-situ droplet ejection measurements.

3. Experimental results

3.1. Absorbed energy distribution on the target surface

The absorbed energy Q_{abs} is one of the key parameters determining melt layer erosion. In QSPA the distribution of absorbed energy was accurately measured by means of a 12-channel copper calorimeter. The peak absorbed energy $Q_{\text{abs}}^{\text{max}}$ is reached at the centre of the irradiation spot and is found to be $1.5\ \text{MJ/m}^2$ for a gun voltage of 3 kV and a pulse duration of 0.5 ms (see Fig. 3). The half widths of the energy density distribution was 12.5 cm along the target and 7.7 cm across the target. Under these conditions, the energy density varies from $1.5\ \text{MJ/m}^2$ on the macrobrush elements located at the centre of the irradiation spot (elements 53, 54, 63, 64 in Fig. 3) to $0.9\ \text{MJ/m}^2$ for elements far away from the centre (elements 31, 36, 91, 96 in Fig. 3). According to modelling [8], a pulse with $Q_{\text{abs}} = 0.9\ \text{MJ/m}^2$ lasting 0.5 ms would result in a temperature excursion below the melting threshold for tungsten. To avoid possible errors arising from the fact that copper (calorimeter material) and tungsten (target material) have different values of energy reflection coefficient, the total energy absorbed by the tungsten target was measured as well and was found to be approximately 20% lower than that absorbed by copper. An especially designed tungsten multi-channel calorimeter is being manufactured to provide more reliable and direct measurements of distributions of energy absorbed by W targets exposed in the QSPA and MK-200UG experiments.

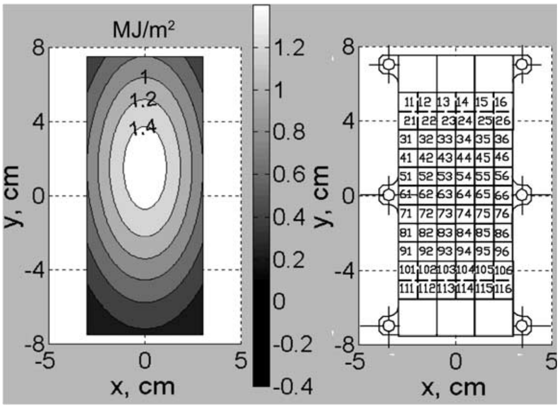


Fig. 3. Absorbed energy distribution on the target surface for QSPA with gun voltage of 3 kV and associated numbering of the tungsten macrobrush elements.

3.2. Melt tungsten displacement under action of plasma stream

The castellated tungsten target was exposed to 100 plasma pulses in QSPA to study, primarily, mass losses and melt layer displacement on the target surface. The target was exposed at an angle (relative to the normal impact) of 60° and was preheated at 200 °C (plasma exposure resulted in heating to 230 °C). The measured absorbed energy density in the centre of the irradiation spot at the target was $1.5 \pm 0.1\ \text{MJ/m}^2$. The pulse repetition frequency was 6 mHz and, thus, in between pulses the target temperature decreased to about 200 °C. After every series of 10 pulses, the target was cooled down to room temperature in vacuum and removed to atmosphere for the following experimental characterisation: (a) the target was weighted to determine mass loss in each series of experiments, (b) the target thickness was determined by measuring the central points of each macrobrush target element (10×10 mm and 20×20 mm) and (c) the surface was inspected by means of an optical microscope to detect the presence of cracks and their evolution as a function of the number of pulses. After a total of 100 pulses, the surface profile of each macrobrush element was measured to find corrugations caused by melt layer motion and material losses.

A large spot of re-melted tungsten at the target surface was observed after these 100 pulses. This spot had an elliptical shape which coincided (within experimental errors) with the contours of $Q_{\text{abs}} \sim 1\ \text{MJ/m}^2$ (see Fig. 3). Thus, the onset of tungsten melting in QSPA (for rectangular pulses in time lasting 0.5 ms) is seen to occur at energy densities ~1 MJ/m^2. This experimentally determined value is in a good agreement with expectation from calculations [6,8]. Fig. 4 shows subsequent images of the central part of the target (elements 53, 54, 63, 64, 73, 74 in Fig. 3) exposed to an increasing number of 1.5 MJ/m^2 pulses showing no catastrophic target damage. The gaps between elements (~0.3 mm wide) remained open, which has favourable implications on the tungsten target performance because it results in minimal stresses at the armour/heat sink interface. Only narrow bridges of re-solidified tungsten form between neighbouring elements consistent with a negligible mass transfer between adjacent elements. Fine cracks were observed at the tungsten surface after the first 10 pulses (see Fig. 4), but they seemed not to propagate with the increase of the number of pulses as expected if the cracks are totally melted in each pulse. Because of a fabrication defect, one row of target elements (row 111–116 in Fig. 3) was approximately 0.2 mm shorter than the others resulting in a leading edge (row 101–106 in Fig. 3). This led to a much higher local heat deposition (~1.8 MJ/m^2) on the elements in the 101–106 row. Strong melt layer displacement was observed in this area during initial exposure, however, as the number of pulses increased, the edge became smoother and the effect disappeared after ~20 pulses. Such leading edges will not be present in the ITER divertor target, as a result of tight control of the manufacturing process. However, it is important to note that, even if they were present, they would not lead to a serious target underperformance under Type I ELM loads.

Surface profilometry, carried out by means of a mechanical profilometer, whose measurement accuracy is estimated to be ±5 μm, showed that for the central elements of the target (exposed to ~1.5 MJ/m^2) the tungsten melt layer shifted from the leading edge along the plasma stream direction. In contrast to this, the surfaces of elements located at the boundary of tungsten melting (exposed to ~1.0 MJ/m^2), remained practically flat as shown in Fig. 5. After 100 pulses the maximum measured surface roughness across the target reached 0.3 mm. The measured profile of the surface for the central elements after these 100 pulses (exposed to ~1.5 MJ/m^2) is reasonably well predicted by the MEMOS code [8] (see Fig. 6), which takes into account the displacement of the melt layer under the plasma pressure and the effects on its motion of the macrobrush geometry. The expected plasma pressure during Type I ELMs in ITER is a factor of 5–10 lower than in QSPA, as explained in Section 2, and, thus, the expected melt layer motion following Type I Elms in ITER will be much smaller than that observed in these QSPA experiments and will have a very minor influence on the tungsten armour life time in ITER. Nevertheless, the effect of slightly irregular surfaces on the production of impurities during normal plasma operation in ITER remains an issue to be addressed. In addition, the effect of currents flowing during ELMs, which in the presence of a magnetic field would lead to forces that could displace the melt layer, will

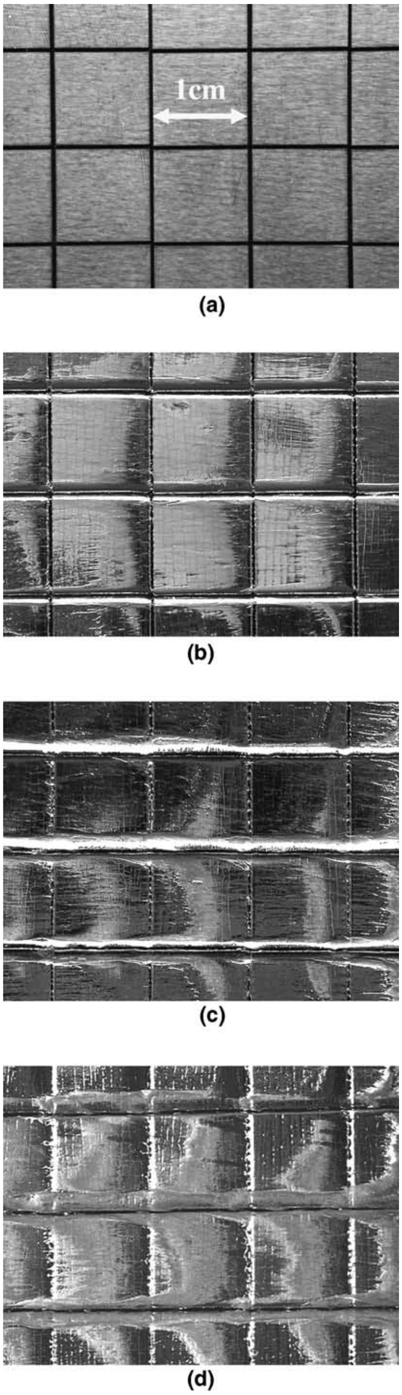
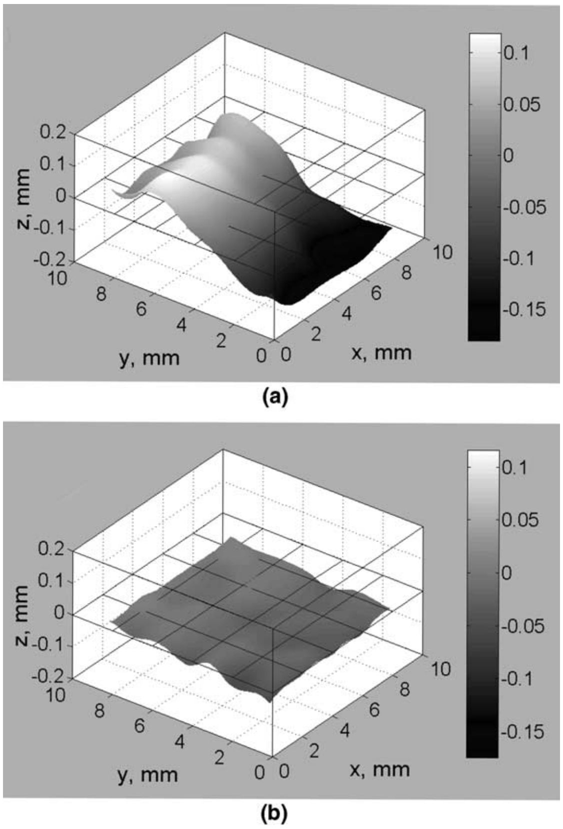


Fig. 4. Consequent images of the damage to the central part of the castellated tungsten target shown in Fig. 3 with increasing number of pulses: (a) initial surface; (b) after 10 pulses; (c) after 60 pulses and (d) after 80 pulses.



(a)

(b)

Fig. 5. Two dimensional profile of the macrobrush elements (see Fig. 3): (a) number 64 and (b) number 25 after 100 pulses.

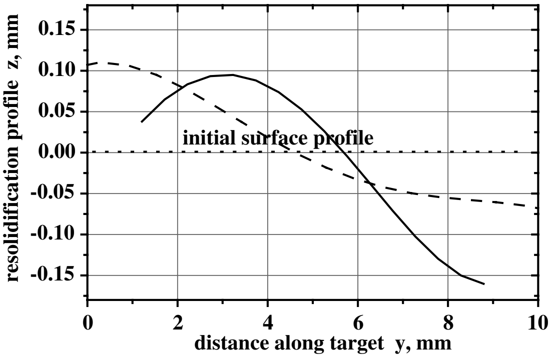


Fig. 6. Comparison of the profile of macrobrush element number 64 measured experimentally (solid line) with the one calculated by means of MEMOS code (dashed line).

be investigated in further experimental campaigns in the QSPA and MK-200UG facilities.

3.3. Mass losses

The target mass loss as a function of the number of pulses was also studied in the QSPA facility for the experiments with $Q_{\text{abs}}^{\max}$ of 1.5 MJ and pulse duration $t = 0.5$ ms, as shown in Fig. 7. The upper curve in Fig. 7 shows the mass loss decreasing from ∼15 μg per pulse after few initial (∼10) pulses to ∼5 μg per pulse after 80 pulses. Averaging the measured mass loss over the observed melt area indicates that the net erosion rate drops from 0.2 μm per pulse to 0.07 μm per pulse (lower curve in Fig. 7) in this series of 100 pulses. This behaviour could be simply due to smoothing of sharp edges with increasing number of pulses. To better understand the nature of mass losses, droplet ejection from the target was investigated by means of a commercial digital camera equipped with a pulsed electromagnetic shutter. Absence of droplet ejection was found for energy densities up to 1.4 MJ/m^2. At $Q_{\text{abs}}^{\max} = 1.5\ \text{MJ/m}^2$ isolated droplets were ejected from the central area of the irradiation spot but their mass was estimated to be negligible in comparison with the total mass loss of tungsten target. The droplets were preferably ejected away from the target along the plasma stream at a speed of ∼10 m/s. The size of the droplets was estimated to be in a range of 5–10 μm. Based on these findings we conclude that the mass losses from the tungsten target observed at $Q_{\text{abs}} = 1.5$ MJ/m^2 were caused by tungsten evaporation only.

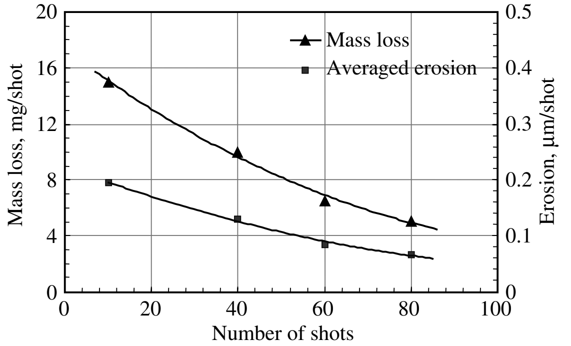


Fig. 7. Measured mass loss and derived erosion rate behaviour as a function of number of pulses.

3.4. Preliminary study of thin film resistance against ELMs heat loads

Due to its low surface binding energy (∼3 eV), beryllium, which is currently considered as reference material for the main chamber wall of ITER [1], will be subject to physical erosion. As a consequence, Be-rich films are expected to form onto the divertor target, that could substantially reduce or eliminate the chemical erosion of carbon and reduce the consequent tritium co-deposition. Experiments to elucidate these effects are ongoing in the linear plasma simulator PISCES-B [9], with encouraging results in this direction. However, the Be-rich surface layer could be removed periodically by the heat loads associated with Type I ELMs and disruptions in ITER. To investigate this problem we carried out some preliminary experiments in QSPA to study the resistance of films of low-Z metals to ELM-like heat loads. In this first set of experiments, a thin (~0.15 μm) film of Al (to mimic beryllium in ITER) was deposited onto the surface of a MPG-4 graphite sample. Prior to depositing the film, the substrate was cleaned by 5 plasma pulses with energy density of ~1.5 MJ/m^2 and typical duration of 0.5 ms. The target covered with the thin Al film was then exposed to few plasma pulses with increasing energy density. After the first two pulses at 0.3 MJ/m^2 the target was removed from QSPA and visually inspected, but no visible modification of the film was observed. Al has low melting temperature (~660 °C) and for pulses at 0.3 MJ/m^2 each lasting ~0.5 ms, the film is expected to reach the melting temperature. Subsequent experiments at high energy density (2 pulses at 0.5 MJ/m^2) showed no Al-film damage. Finally, the sample was exposed to a pulse with energy density ~1.0 MJ/m^2, which lead to the total removal of the film in the target areas in which the energy density exceeded 0.7 MJ/m^2 and where Al boiling took place. These preliminary results indicate that: (a) the Al film deposited onto the cleaned graphite surface by means of sputtering in vacuum has a good thermal contact with a substrate, (b) the thin Al melt layer does not splash from the graphite under the plasma heat loads and (c) it is necessary to reach surface boiling temperature to completely remove the film.

4. Future work

The results of the experiments described in this paper are indeed very promising, but they are only of a preliminary nature and further work is planned in the near future to draw firm conclusions for ITER. A scientific collaboration has been set-up between the European Fusion Organisation (EFDA) and several laboratories in Russia (within the EU-Russian Federation Cooperation Agreement in Fusion Research) to achieve this goal. The main activities to be carried out within this collaboration are:

- fabrication, undertaken by EU, of a total of 15 targets made with CFC (SNECMA NB31) and W (W and W–1%La_2O_3),
- experiments in Russian plasma guns (TRINITI, Troitsk) to study erosion, impurity production and impurity transport under ITER ELMs and disruption heat loads,
- accurate target analysis and characterisation prior and after plasma exposures to determine the extent of damage,
- numerical modelling, to be carried out primarily in the Forschungszentrum of Karlsruhe, to interpret experimental results and to make reliable predictions/extrapolations for ITER,
- experimental study of low Z material erosion (e.g., Al to mimic Be on the first wall) under radiation energy fluxes reached under mitigated disruption conditions.

5. Conclusions

The R&D described in this paper is very important for ITER and its outcome will contribute to the final selection of the best armour material to be used at the divertor target near the strike points and will help determine the size of tolerable ELMs and material damage resulting from ELMs and disruptions. This work is still in progress but the following preliminary conclusions can be drawn:

- no significant net-erosion of a ITER-like W macrobrush target was measured under representative ITER repetitive (up to 100) ELM heat loads. The observed erosion was solely due to W evaporation;
- a thin melt layer of tungsten developed, as expected, in areas exposed to energy fluxes $\geqslant 1.5$ MJ/m^2 but it only shifted within a each macrobrush element (10×10 mm^2) without closing the gaps of neighbouring elements. Furthermore, the maximum of the local erosion at the central elements of the target did not exceed 0.2 μm per pulse. The measured mass loss (average erosion rate) was found to decreased by a factor of 3 with increasing number of pulses from 15 μg/pulse (0.2 μm/pulse) after 10 pulses to ~5 μg/pulses (0.07 μm/pulse) after 100 pulses;
- the experimentally measured heat load thresholds for tungsten melting and boiling in MK-200UG ($\Delta t = 0.04$ ms) are in a good agreement with those calculated by means of MEMOS code;
- thin films of Al (used to mimic Be) deposited on a graphite substrate were found to resist, without deterioration, to energy pulses up to conditions in which the surface reaches the boiling point.

Further planned experiments and modelling will allow to draw conclusions on the effects of ELMs and disruption on ITER divertor materials.

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