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Effects of ELMs on ITER divertor armour materials

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Abstract

This paper is concerned with investigation of an erosion of the ITER-like divertor plasma facing components under plasma heat loads expected during the Type I ELMs in ITER. These experiments were carried out on plasma accelerator QSPA at the SRC RF TRINITI under EU/RF collaboration. Targets were exposed by series repeated plasma pulses with heat loads in a range of 0.5–1.5 MJ/m^2 and pulse duration 0.5 ms. Erosion of CFC macrobrushes was determined mainly by sublimation of PAN-fibres that was less than 2.5 μm per pulse. The CFC erosion was negligible at the energy density less than 0.5 MJ/m^2 and was increased to the average value 0.3 μm per pulse at 1.5 MJ/m^2. The pure tungsten macrobrushes erosion was small in the energy range of 0.5–1.3 MJ/m^2. The sharp growth of tungsten erosion and the intense droplet ejection were observed at the energy density of 1.5 MJ/m^2.

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1. Introduction

CFC and tungsten macrobrush armours are foreseen now as plasma facing components (PFCs) for ITER divertor. During an operation of ITER at the H-mode these components will be exposed to intense plasma heat loads such as Type I Edge Localised Modes (ELMs) and disruptions [1]. It is expected that ELMs will be play the main role in the erosion of the PFCs [2,3]. Experimental data about material erosion under these transient events are not enough now for the evaluation of the PFCs lifetime in the ITER operating scenarios with disruptions and type I ELMs [4].

To produce the data for satisfactory numerical modeling the experimental study of PFCs erosion under ELMs like plasma heat loads were done at

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the quasi-stationary plasma accelerator (SRC RF TRINITI, Russia). The CFC and tungsten macro-brush divertor targets were manufactured by the EU (Plansee AG, Austria) and after pre-characterization in the Forschungszentrum Jülich (Germany) were exposed multiple (up to 100) ELMs like events at the plasma gun facility QSPA [5].

These data are used to validate the numerical modeling being carried at the Forschungszentrum Karlsruhe (Germany) by using the fluid dynamics code MEMOS for W and the three-dimensional code PHEMOBRID-3D [6] and PEGASUS [7] for CFC, which are used then to provide predictions for the expected conditions in ITER.

2. Experimental techniques and diagnostics

Conditions expected for Type I ELMs and disruptions in ITER [1] are difficult to achieve in existing tokamaks. Plasma guns are the more suitable facilities that allow simulate these ITER-events by some key parameters. The results of this simulation can be extrapolated to ITER by means of numerical model. The experiments described in this paper were carried out in quasi-stationary plasma accelerator (QSPA) located in SRC RF 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 ELM and disruption loads in ITER and was typically used for studying PFCs erosion [5,8].

The facility has been modified to achieve heat loads and plasma flow parameters typical for Type I ELMs in ITER [9,10]. 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 0.3–0.9 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 a vacuum chamber before the shot is below of 10^{-2} Pa.

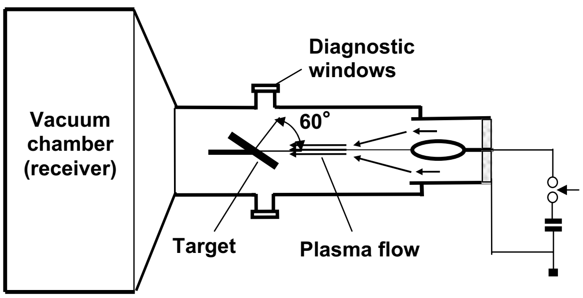

Fig. 1. The scheme of experiments on QSPA facility. Plasma parameters: energy density 0.5–2 MJ/m^2; pulse duration 0.1–0.6 ms; plasma stream diameter 5 cm; ion energy $\leqslant$0.1 keV and no magnetic field.

Fifteen special ITER-like castellated targets (6 CFC, 3 pure W and 6 W–1% La_2O_3) were designed and manufactured for these investigations by Plansee AG (Austria) and pre-characterized by Forschungszentrum Jülich (Germany) by means electron microscopy, profilometry and weight measurements.

The targets consisted of separate tungsten and CFC elements of sizes $9.5 \times 9.5 \times 3$ mm^3 and $19.5 \times 19.5 \times 3$ mm^3 brazed to a supporting stainless steel plate with 0.5 mm gaps between neighbour elements. The loaded surface of CFC target is made of the CFC material Sepcarb® NB31 (Snecma Propulsion Solid, France). The tungsten targets are two types: pure tungsten and tungsten with 1% La_2O_3. The results described in this paper were obtained in the experiments with CFC and pure tungsten. Thermal conductivity of pure tungsten is more than lanthanum tungsten but it is expected that crack formation intensity on tungsten with 1% La_2O_3 under ELM heat loads will be less as compared with pure tungsten [11]. The investigation of W–1% La_2O_3 targets erosion will be the next stage of experiments.

The target sizes and target-plasma inclination angles were chosen both to avoid erosion edge effects and model ITER-like conditions: the target was wider than plasma stream diameter (~60 mm), the length of the target was ~150 mm to allow erosion measurements with angle of plasma stream incidence from 0 (normal incidence) to 60°. The angels more than 60° are unacceptable because it requires target length increasing to eliminate edge effects that lead to rise in price of the target. The maximum of inclination angle of 60° was used in the experiments for more close approximation of ITER condition (see Fig. 1).

The target was placed on a heater, which provided target preheating up to 500 °C. In the experiments each target was exposed to series of repeated plasma pulses with fixed energy density in a range of

0.5–1.5 MJ/m^2 and duration equal to 0.5 ms. The total number of pulses in each series was 100.

The diagnostics used in these experiments to characterize the plasma–material interactions included: (a) pressure gauges of plasma; (b) tungsten and CFC multi-channel two-dimensional calorimeters to measure absorbed energy distribution; (c) precision microbalance to measurement mass losses as a function of number of pulses; (d) scan electron microscope and mechanical profilometer to investigation surface modifications as a function of pulses number; (e) digital camera to study of droplets ejection from the surface under plasma flow.

3. Experimental results

3.1. Absorbed energy density distribution on the target surface

The absorbed energy Q_{abs} is one of key parameters determining material erosion. In QSPA the distribution of absorbed energy density was accurately measured by means of a target-likely two-dimensional multi channel calorimeters. Each calorimeter contains 11 measurement cells that were positioned in two directions: six cells in longitudinal and five cells in a cross directions. This scheme allowed to measure two-dimensional energy density distribution. According to this measurements the absorbed energy density have maximum $Q_{\text{abs}}^{\text{max}}$ at the centre of the irradiation spot and decreasing with moving away from the centre.

Absorbed energy density distribution obtained by means the calorimeters are presented in Fig. 2.

The maximum of absorbed energy density was measured as a function of gun voltage. The regimes of QSPA provided the maximum values of energy density equal to 0.5, 1.0, 1.5 MJ/m^2 and plasma pulse duration of 0.5 ms were chosen.

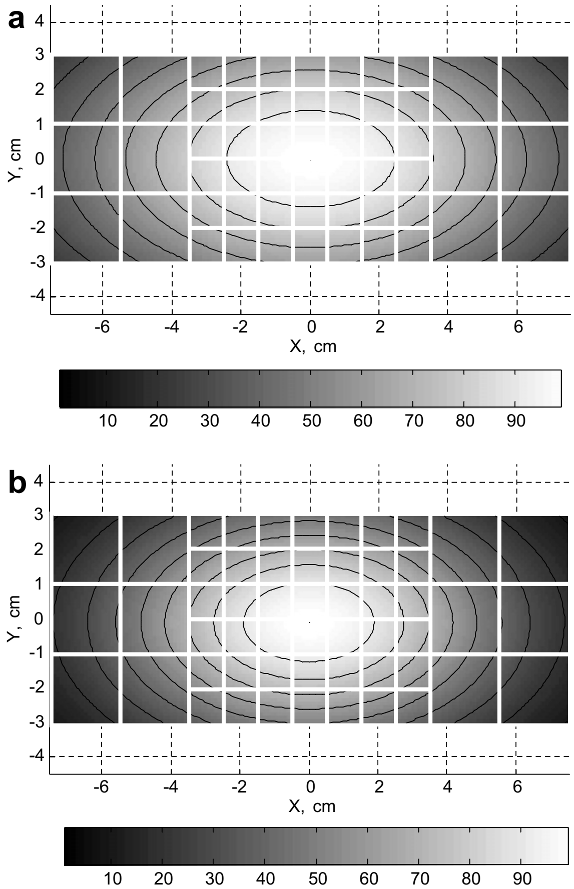

Fig. 2. Normalized absorbed energy distribution on CFC (a) and tungsten and (b) surface for QSPA.

3.2. Erosion of the CFC macrobrushes

Each three CFC castellated targets were exposed by 100 plasma pulses at the energy density 0.5, 1.0, 1.5 MJ/m^2, respectively, and with plasma pulse duration of 0.5 ms. The angle of plasma stream incidence was equal to 60° according to mentioned above points. The targets were preheated up to 500 °C.

After every series of 10–20 pulses, the target was cooled down to room temperature in vacuum and removed to atmosphere for the following characterization: (a) the target was weighted to determine mass loss, (b) the surface was inspected by means of the scan electron (SEM) and optical microscopes to detect the presence of cracks and measure of PAN-fibre erosion and study their evolution as a function of a pulse number, (c) the target thickness was determined by means of mechanical profilometer in the central points of each tiles. After a total of 100 pulses, the surface profile of each target was measured by laser profilometer to find the value of material losses during post-mortem characterization in FZJ.

Noticeable mass losses were observed only for the CFC sample that was exposed at the energy density of 1.4 MJ/m^2 (see Fig. 3). The appropriated average erosion of the sample was equal to 0.3 μm/shot. Before 50th exposures the erosion increased from 0.2 to 0.5 μm/shot and then (after 50th shot) it decreased to initial value. It is difficult to offer an explanation of such CFC mass losses

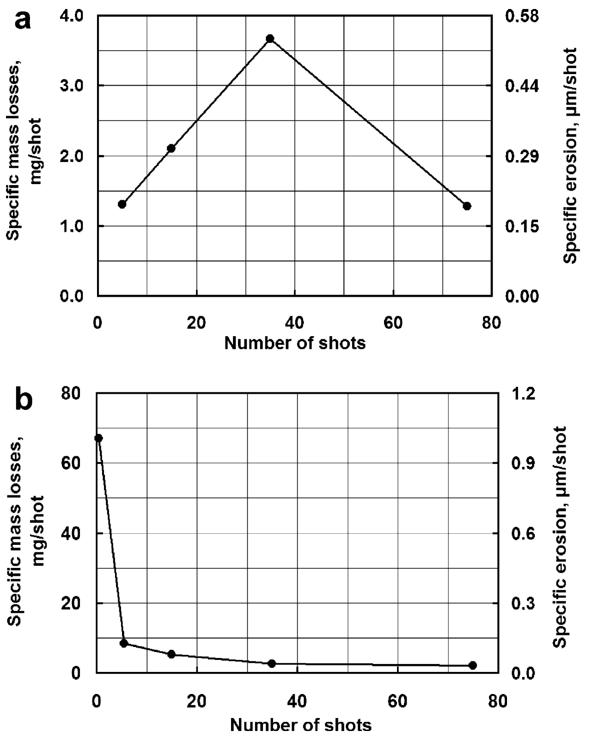

Fig. 3. Mass loss of CFC (a) and tungsten (b) samples and its erosion rate as a function of pulse number.

behaviour without additional investigation. CFC materials have complicated structure so many interdependent processes take place under plasma action. Erosion of PAN-fibers is one of such processes. Due to rather different heat conductivities of CFC fibers a noticeable erosion of the PAN-fibers occurs at a rather small heat loads at which the damage of pitch fibres are not substantial. According to SEM observation and profilometry plasma facing surface of the PAN-fibers deepened under pitch fiber level as a result of plasma pulses number. Such effect leads to decreasing of PAN-fibers erosion and increasing of pitch fiber damage. Another process is a crack formation. Crack formation inside the CFC armour can lead to a significant drop of the heat conductivity, which intensifies the erosion. Simultaneously action mentioned above mechanisms may result in non-monotone behavior of the total erosion.

According to electron microscope observation the erosion of CFC macrobrushes was determined mainly by erosion of PAN-fibres:

- at the energy density less than 0.5 MJ/m^2 erosion was negligible;
- in the energy range from 0.5 to 0.6 MJ/m^2 erosion took place near the plasma facing corners of the tiles;
- at the energy density 0.6–0.9 MJ/m^2 the erosion of PAN-fibres was observed not only near the edges but also on the total surface of the tiles after 100 exposures;
- at 0.9–1.3 MJ/m^2 the noticeable erosion of PAN-fibres took place after 50 exposures;
- at 1.3–1.4 MJ/m^2 the significant erosion of PAN-fibres took place already after 10 exposures.

The value of PAN-fibre erosion as a function of absorbed energy density was measured by means of optical microscope. This data were compared with the calculation by means 3D code PHEMOBRID [6] and PEGASUS code [7] (see Fig. 4).

The code PHEMOBRID take into account 3D heat conductivity properties of CFC and degradation of the CFC structure due to the crack formation as well as phenomenological model of brittle distraction. The code PEGASUS is the powerful tool for simulation of fine detail of brittle distraction and heat conductivity properties of carbon based materials. In the codes simulation geometry was taken similar to the experiment. Typical model structure of CFC brush with diameter of pitch and PAN bundles of 0.06 cm have been used in calculations. Stagnation pressure at the center of plasma stream is estimated in a range between 2 and 5 bars that was included in modelling. Results of calculations and comparison with measurement value are presented in Fig. 4 (the solid and dot lines are the

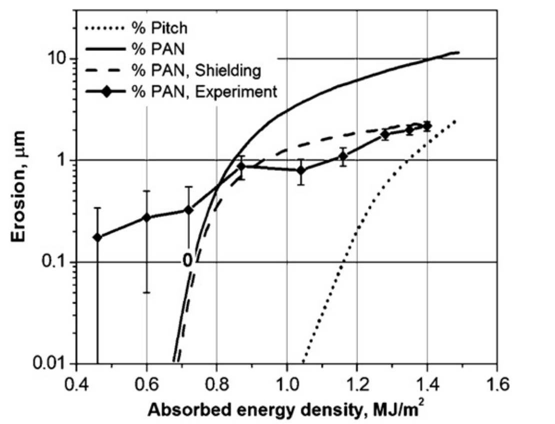

Fig. 4. Comparison between measurements and calculation of PAN-fibre erosion as a function of absorbed energy density by PHEMOBRID-3D and PEGASUS codes. The solid and dot lines are the results of calculation without shielding effect. The dash line is a result of taking into account shielding effect.

calculations of PAN and pitch fibers erosion per one pulse without taking into account vapour shielding effect respectively, the dash line is a result of modelling with shielding effect).

The difference between experimental and theoretical value in the region of energy density lower than 0.6 MJ/m^2 may be explained by the fact that before exposure the some differences between level of pitch and PAN-fibers already exist and equal in some places several tens microns; it is initial roughness of the target. At the energy density more than 1.2 MJ/m^2 the shielding by vapour of sublimated materials play significant role. The numerical simulations are in a good qualitative and quantitative agreement with the experiments. In the whole investigated range of absorbed energy density the value of PAN-fiber erosion was less than 2.5 μm per shot.

3.3. Erosion of the pure tungsten macrobrushes

Each three tungsten castellated targets were exposed by 100 plasma pulses at the energy density 0.5, 1.0, 1.5 MJ/m^2, respectively, plasma pulse duration being 0.5 ms. The angle of plasma stream incidence was equal to 60°. The targets were preheated up to 500 °C.

After every series of 10–20 pulses, the target was cooled down to room temperature in vacuum and removed to atmosphere for the following experimental characterization such as for CFC sample. According to this characterization the erosion of tungsten macrobrushes was determined mainly by melt layer movement and droplets ejection (see Fig. 6):

- at the energy density less than 0.4 MJ/m^2 erosion was negligible;
- in the energy density range from 0.4 to 1.0 MJ/m^2 took place melting of the plasma facing edges of the tiles;
- at the energy 1.0–1.3 MJ/m^2 melting was observed not only near the edges but also on the total surface of the tiles but droplet ejection did not took place; as a the results of melt layer movement along the plasma stream direction and accumulation on the plasma shadow edges separate bridges between tiles was formed after 50 exposures;
- at 1.3–1.6 MJ/m^2 – bridges was formed already after 10 exposures; as a result of this process gaps between tiles was covered by remelted tungsten after 50 exposures;
- droplet ejection was observed at the energy density more than 1.3 MJ/m^2; the intensity of ejection reduced with number pulses increasing as a result edges smoothing under plasma action.

Noticeable mass losses of a sample took place at the maximum energy density equal to 1.6 MJ/m^2. The appropriated average erosion of the sample was equalled to 0.06 μm/shot (see Fig. 3) The erosion of tungsten after fist shot was 1 μm/shot, and then were decreased to 0.03 μm/shot (after 40th pulse). The erosion value correlated with droplet ejection observation (see Fig. 5). This fact shows that droplet ejection was the main mechanism of tungsten mass losses. During each shot the temperature of the tile edges achieve higher value than one of its central part. The droplets ejection takes place when the surface energy density is higher than some threshold value. During the first shot droplets ejected mainly from the edges of the tiles. According to SEM observation melt layer movement took place during each pulse that lead to edge smoothing

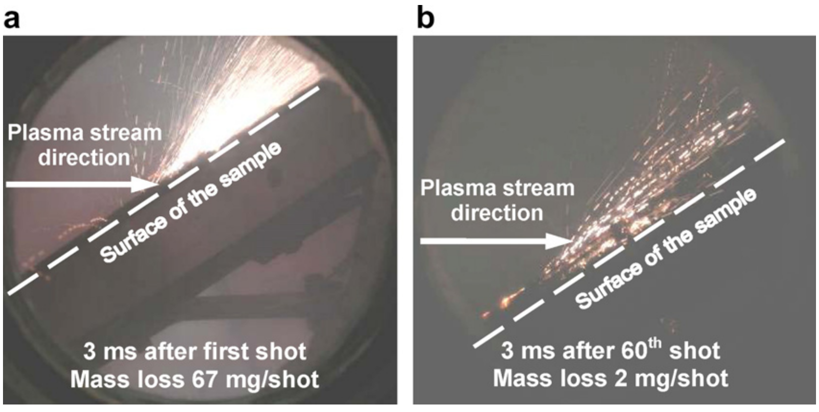

Fig. 5. Micrographs of the tungsten droplets tracks during the fist shot (a) and 60th shot (b).

and bridging of gaps. As a result of such process the droplet ejection was reduced and mass losses were decreased.

Cracks formation was observed at the energy density more than 0.8 MJ/m^2 (see Fig. 7). In the energy density range from 0.8 MJ/m^2 to 1.0 MJ/m^2 the two types of cracks formed the grids on the surface. The cracks of type 1 were observed after 20 pulses (characteristic size of grid cell is about 1–2 mm). The cracks of type 2 was observed after

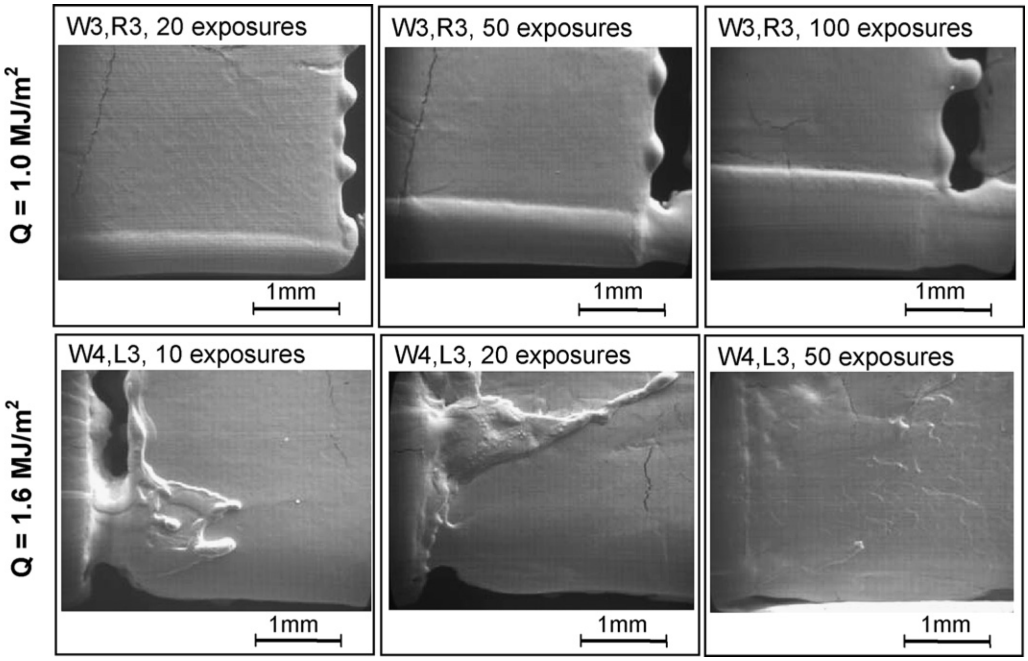

Fig. 6. The view of the tungsten tile surface obtained by means of electron microscope.

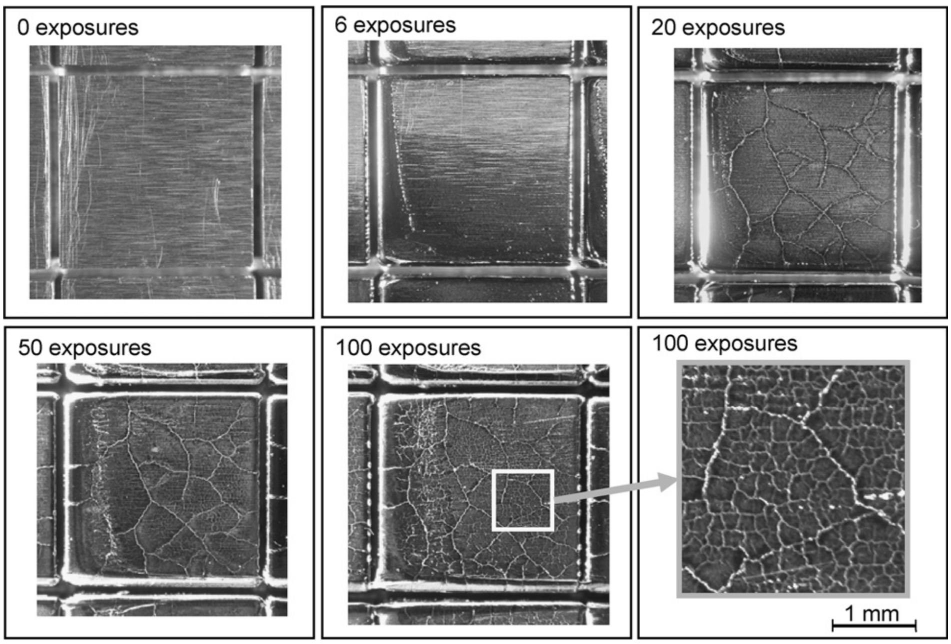

Fig. 7. The images of the tungsten tile surface at the absorbed energy density of 0.9 MJ/m^2.

50 pulses (characteristic sizes of grid cell is about 200–300 μm). The post-mortem metallography show that the depth of the cracks type 1 and type 2 equal to about 500 μm and 50 μm, respectively. At the energy density more 1.0 MJ/m^2 the cracks formed grid with the characteristic cell size 50 μm and are remelted in each pulses.

4. Future work

The results of the experiments described in this paper are indeed very promising for ITER, and further work is planned in the near future to obtain reliable conclusions for ITER.

Joint EU–RF activates of study of CFC and tungsten erosion under ITER-like heat loads will be continued. In addition joint EU–RF study of the damage of Be-clad and Be-coated ITER Plasma Facing Components under simulated Type I ELMs, Disruptions and Mitigated Disruptions will be started. Over this task are planed following works:

- QSPA modification to satisfy requirements for operation with Beryllium (RF);
- producing special Be targets for experiments at QSPA facility (EU);
- QSPA calibration to provide plasma energy loads that are expected for ITER first wall (RF);
- QSPA calibration to provide radiative energy loads that are expected during disruptions mitigated by massive noble gas injection in ITER (RF);
- multiple target exposing to plasma energy loads and radiative energy loads at QSPA facility (RF);
- analysis of target before and after exposures with the required techniques (EU + RF);
- numerical modeling of erosion for Be-clad and Be coated targets in QSPA conditions and prediction for ITER (EU).

5. Conclusions

Under ITER ELM-like plasma heat loads the CFC erosion was mainly determined by PAN-fiber sublimation. Erosion was negligible at the energy density less than 0.5 MJ/m^2. The noticeable erosion of CFC was observed at the energy 1.5 MJ/m^2 and average mean of it was 0.3 μm per shot. The value of PAN-fibre erosion was less than 2.5 μm per shot over all investigated energy density range. This value is in a good quantitative agreement with the modelling of PHEMOBRID-3D and PEGASUS codes including vapour shielding effects.

The tungsten erosion was mainly due to melt layer movement and droplets ejection. Erosion was negligible at the energy density less than 0.5 MJ/m^2. The noticeable erosion of tungsten was observed at the energy 1.5 MJ/m^2 and average mean of it was 0.06 μm per shot. At this energy the gaps filling by melt layer were observed. It is expected that in ITER this effect will be absence because the plasma pressure will be a factor of $\sim$10 lower of compare with this experiment.

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