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Experimental study of PFCs erosion under ITER-like transient loads at plasma gun facility QSPA

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ABSTRACT

This paper is concerned with investigation of an erosion of the ITER-like divertor castellated targets of pure tungsten, lanthanum tungsten and CFC under plasma heat loads expected during the Type I ELMs and disruptions in ITER. These experiments were carried out on a plasma gun QSPA-T at the SRC RF TRINITI under EU/RF collaboration. The targets were exposed by series repeated plasma pulses with heat loads in the range of 0.2–2.5 MJ/m^2 and a pulse duration of 0.5 ms. The erosion value as a function of pulse number and energy density were obtained. The erosion of lanthanum tungsten started at the lower energy density as compared with pure tungsten and was mainly due to a melt layer movement and a droplets ejection. Characteristics of ejected droplets were measured. The erosion of CFC macrobrushes under ELM and disruption heat loads was determined mainly by damage of PAN-fibers.

1. Introduction

During operation of ITER in the reference H-mode $Q_{DT} = 10$ scenario plasma facing components (PFCs) will be exposed to intense plasma heat loads from Type I edge localized modes (ELMs) and disruptions. The erosion of the PFCs under such loads is expected to play a major role in the determining the effective lifetime of PFCs [1]. Experimental data about materials erosion under transient loads similar to those expected in ITER are scarce presently, given the magnitude of the expected transient loads and, thus, the evaluation of the PFCs lifetime in the ITER reference operating scenarios with disruptions and Type I ELMs remains uncertain.

Plasma loads relevant to ITER ELMs and disruptions are not achieved in existing tokamaks. Therefore other devices such as ion source [2], electron-beam facility [3,4], powerful plasma guns [4–7] are applied for armour testing.

A series of experiments of ITER-like PFCs erosion study under ELM- and disruption-like plasma heat loads was carried out at the quasistationary plasma accelerator QSPA-T located in SRC RF TRINITI (Russia) to obtain the data for the empirical evaluation of the PFC lifetime under transient loads in ITER and to validate the available numerical models [9–13] used to predict such erosion under the expected conditions in ITER.

The CFC, pure tungsten and lanthanum tungsten macrobrush samples, which have similar specifications to those proposed for the ITER divertor, were designed and manufactured for these investigations by the EU industry (Plansee AG, Austria). After pre-characterization in the Forschungszentrum Jülich (Germany) these were exposed multiple (up to 100) ELM- and disruption- like heat loads at the plasma gun facility QSPA-T. The samples were examined by means of microbalance, electron and optical microscopes, profilometry and metalography/ceramography for study the main erosion mechanisms and measurements of erosion value as a function of heat loads and number of pulses.

The results of ELM simulation experiments with pure tungsten and CFC has been reported at the 17th PSI Conference and published in the Journal of Nuclear Materials [8]. In present paper primary attention has been focused at the results of ELM simulation experiments with lanthanum tungsten, disruption simulation experiments with lanthanum tungsten, pure tungsten and CFC. Some presented results concerns droplets and solid particles emitting from tungsten surface under mentioned plasma loads.

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2. Experimental techniques and diagnostics

Quasistationary plasma accelerators, which are capable to provide the adequate plasma energy density and plasma pulse duration, are quite suitable for PFCs erosion study [6,7]. The present work refers to new experimental testing of ITER-like divertor castellated targets of pure tungsten, lanthanum tungsten and CFC by plasma heat fluxes relevant to the transient heat loads in ITER, performed at facility QSPA-T. The facility has been modified to achieve heat loads and plasma flow parameters similar for ITER transient loads [7,8]. Measurements showed that heat loads in the range of 0.2–2.5 MJ/m^2 and timescale of 0.4–0.6 ms could be achieved by varying the QSPA-T gun voltage from 1.8 to 4.5 kV [7,8]. Appropriate values of impact energy of hydrogen ions and impact plasma pressure equal to 0.1–0.6 keV and 1–10 bar at the normal plasma incidence. The energy density of the plasma flow is rises from 5 to 150 MJ/m^2 with mentioned increasing the plasma gun voltage. Plasma stream density lies in the range 10^{22}–10^{23} m^{-3}.

Plasma pressure at QSPA-T is much larger than it is expected during ITER ELMs. It is explained by two reasons: (1) the lower particle energies achievable in QSPA-T in comparison with those expected in ITER and (2) higher plasma density that lead to very strong self-shielding effect which has no place in ITER. Because of high plasma pressure QSPA-T experiments are likely to give higher erosion rate than it will take place in ITER ELMs or disruptions. One needs to take this fact as well as the absence of magnetic field into consideration in extrapolating results obtained in QSPA to ITER.

Special fifteen ITER-like castellated targets (6 CFC, 3 pure W and 6 W-1%La_2O_3) were designed and manufactured for these experiments by Plansee AG (Austria) and preliminary observed by Forschungszentrum Jülich (Germany) by means of optical and electron microscopy, laser profilometry, weight measurements.. The targets consisted of separate tungsten and CFC tiles of 9.5 × 9.5 mm^2 and 19.5 × 19.5 mm^2 surface area brazed on a supporting stainless steel plate of 60 × 150 mm^2 surface area with 0.5 mm gaps between neighbor elements. Surface area of CFC targets was produced from the CFC material Sepcarb® NB31 (Snecma Propulsion Solid, France). The tungsten targets are two types: pure tungsten (>99.96%) and tungsten with 1%La_2O_3 (lanthanum tungsten). The pitch fiber of CFC as a tungsten grains were oriented both perpendicularly to plasma loaded surface of the samples.

The basic scheme of the PFCs erosion investigation is presented in Fig. 1. The samples to be tested were placed at 60 cm distance from the gun. The angle of the plasma stream incidence was equal to 60°. The angle of the plasma stream incidence was chosen to avoid erosion edge effects and model ITER-like conditions. The target was placed on the heater, which provided target preheating up to 500 °C.

Each target was exposed to series of 100 pulses in the ELMs simulation experiments and 5–10 pulses in the disruptions simulated experiments with the fixed plasma flow parameters in each series. The regimes of QSPA-T facility provided the values of absorbed energy density at the plasma stream axis (central area of the target) equal to 0.5, 1.0 and 1.5 MJ/m^2 were chosen to ELMs experiments. The heat loads at the disruptions simulated experiments was 2.3 MJ/m^2. Plasma pulse duration was 0.5 ms in both cases.

The absorbed energy is one of key parameters determining material erosion. In QSPA the distribution of absorbed energy density on the target surface was accurately measured by means of a target-likely two-dimensional multi channel calorimeters [8].

According to the performed measurements the absorbed energy density profiles have maximum in the center of the target at the stream axis and these are approximated by Gaussian distribution with half width of 9 cm in longitudinal direction and 6 cm in transversal direction.

The samples were inspected after each 10–20 pulses in the ELMs experiments and after each pulse in the disruptions experiments by means of weight measurement, electron and optical microscopes, mechanical profilometer at SRC RF TRINITI. After full plasma pulse series the samples was also examined by means of SEM, laser profilometry and metalography/ceramography at Forschungszentrum Jülich (Germany).

Melting of tungsten and the following melt motion and melt splashing are expected to be the main mechanisms of damage which determine the lifetime of PFCs. Diagnostics for online registration of the ejected particles and droplets (see Fig. 2) was used in the experiments to determine the onset conditions of droplets ejection and measure characteristics of droplets such as velocities and flight angles distributions, time of droplet formation and its sizes.

3. Experimental results

3.1. Erosion of CFC macrobrushes

Some results of the CFC erosion study under the ITER ELM-like plasma heat loads were published in [8]. As a result of ELM-simulation experiments the CFC erosion was mainly determined by the PAN-fiber sublimation which value was measured as a function of

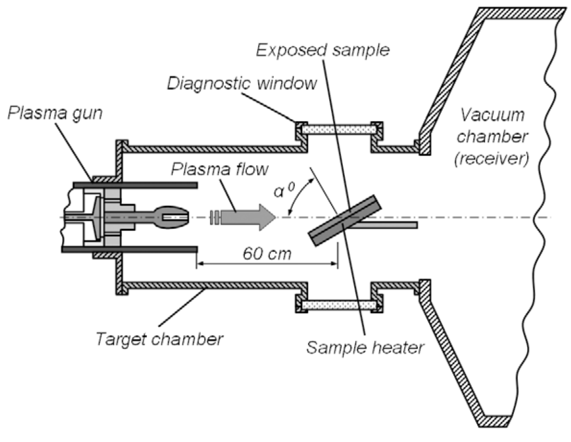


Fig. 1. General scheme of PFCs testing on QSPA-T facility.

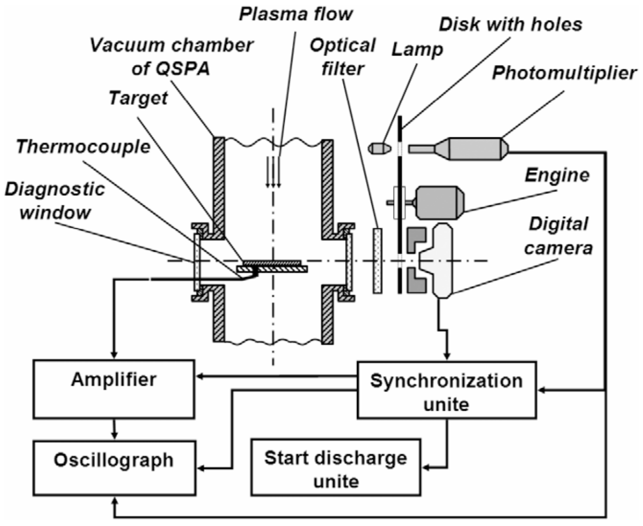


Fig. 2. Online diagnostics for droplets and particles ejection study.

the absorbed energy density in the range of 0.5–1.5 MJ/m^2. In present paper primary attention has been focused at the results of simulation experiments at higher heat load.

For this purpose a CFC castellated target was exposed by 5 hydrogen plasma pulses of 0.5 ms duration with the heat load of 2.3 MJ/m^2 at the center of the target under conditions described in Section 2. Due to energy density distribution the values of the absorbed energy density along the target surface varied in the range of 1.0–2.3 MJ/m^2.

According to scan electron microscopy the significant erosion of pitch fibers was observed only near edges of the tiles in contrast to the PAN fibers erosion that took place on the full plasma facing surface of the exposed macrobrush sample. Thus the difference between pitch and PAN fibers levels was increased with number of pulses which was also confirmed by optical microscope and profilometer measurements. The results of such measurements for the center target region presented in Fig. 3 display linear increasing of the PAN fibers erosion value with pulses number. It indicates that the erosion rate of PAN fibers is constant and equal to 6 μm/pulse in presented case.

The erosion of pitch fibers is expected to start as the results of higher number of pulses and its rate will increase to significant value when the deference between pitch and PAN fibers levels will exceed some threshold point. Such mechanism of CFC damage was early observed in the QSPA experiments at higher heat loads under normal plasma incidence without sample preheating [12] but the relevancy of the mechanism in the present heat load range under the conditions described in the present work is need for confirmation and additional study which is a planned step of future experiments with high number of pulses (up to 1000).

Measurements of the PAN fibers erosion value along the target surface allow to determine the PAN fibers erosion rate as a function of the surface energy density. In the range 1.0–1.5 MJ/m^2 the erosion rate display agreement with values obtained early in the ELM simulation experiments and complete these data up to 2.3 MJ/m^2 (see Fig. 4). The PAN fibers erosion rate increases from 0.2 to 8 μm/pulse in the surface energy density range 0.5–2.3 MJ/m^2.

3.2. Erosion of pure and lanthanum tungsten macrobrushes

Some results of the pure tungsten erosion study under the ITER ELM-like plasma heat loads were published in [8]. In present paper primary attention has been focused at the results of the lanthanum tungsten erosion study and comparison between both materials.

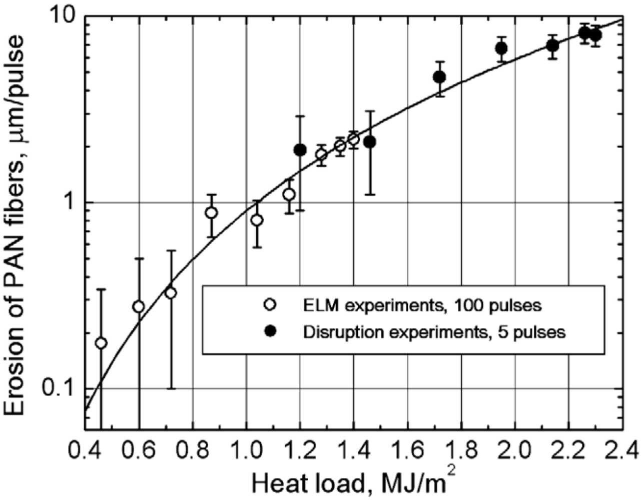


Fig. 4. Erosion rate of the PAN-fibers as a function of heat loads.

Three lanthanum tungsten castellated targets were exposed by hydrogen plasma flow of 0.5 ms duration and 0.5, 1.0, 2.3 MJ/m^2 heat loads at the center of the target. Due to the energy density distribution along the target surface the values of the absorbed energy density varied in the range of 0.2–2.3 MJ/m^2.

According to scan electron microscopy the melting of the tile edges was observed already at the heat load higher than 0.4 MJ/m^2. The movement of melt materials from the plasma facing edges along the plasma flow started at the higher heat load of 0.6 MJ/m^2 as a result of increasing of the melt layer thickness and the plasma pressure. This process leads to the melt material accumulation on the plasma leading edges and bridges grow between neighbor tiles with pulses number. The melting of the full tile surface (not only near the edges) and filling the gaps between tiles were observed at the absorbed energy density higher than 0.7 MJ/m^2. Specific mass loss increasing (see Fig. 5) from 0.1 g/m^2/pulse (erosion rate 0.005 μm/pulse) at 0.5 to 0.8 g/m^2/pulse (0.04 μm/pulse) at 1.0 MJ/m^2 was observed as a result of subsequent intensification of the melt layer movement which leads to splashing and the liquid droplets ejection. Successive energy density increasing up to 2.3 MJ/m^2 was accompanied by growing of the melt layer thickness

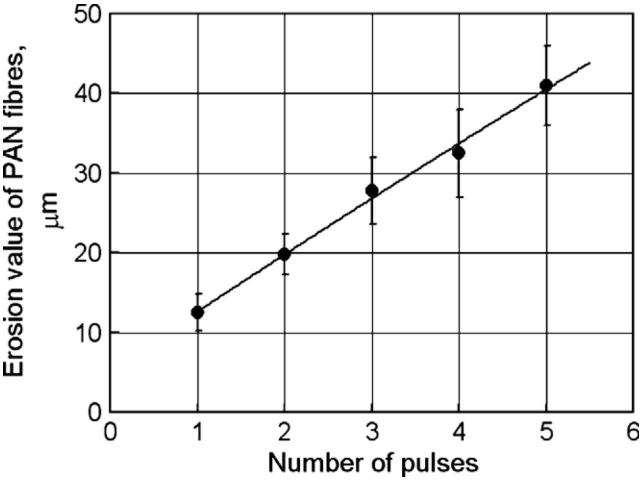


Fig. 3. Erosion value of the PAN-fibers as a function of pulses number (heat loads 2.3 MJ/m^2).

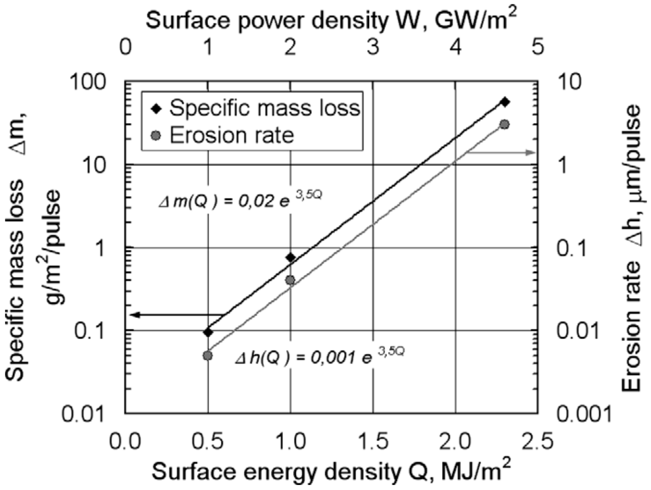


Fig. 5. Specific mass loss and erosion rate of lanthanum tungsten macrobrushes as a function of heat loads.

and the plasma pressure leads to droplet ejection intensification and exponential growth of specific mass loss up to 60 g/m^2/pulse (erosion rate 3 μm/pulse). The erosion rate as a function of pulse number also was determined by features of melt layer splashing (see Fig. 6). In the ELM simulation experiments the erosion rate and the droplets ejection intensity decrease simultaneously with pulse number increasing due to edges smoothing and roughness decreasing which were confirmed by mass loss measurements combined with online diagnostics of ejected tungsten droplets and scan electron microscopy observation. In the disruption simulation experiments on the contrary erosion rate increase with pulse number as a result of surface development and roughness increasing.

This fact indicates that the melt layer movement and droplets ejection are the main erosion mechanisms which determine specific mass loss of lanthanum tungsten and pure tungsten under the plasma heat load in the range of 0.5–2.3 MJ/m^2.

As a result of the experiments the onset conditions of various erosion processes were defined (see Table 1). The comparison between present data and data obtained in the experiments of pure tungsten displays that various erosion processes of lanthanum tungsten start at the lower energy density as compared with pure tungsten. In other words the lanthanum tungsten erosion is higher than the erosion of pure tungsten at the same condition. This point is confirmed by mass loss measurements (see Fig. 6). The specific mass loss of lanthanum tungsten 0.8 g/m^2/pulse obtained at the heat load 1.0 MJ/m^2 is close to the pure tungsten value of 1.2 g/m^2/pulse at the energy 1.5 MJ/m^2.

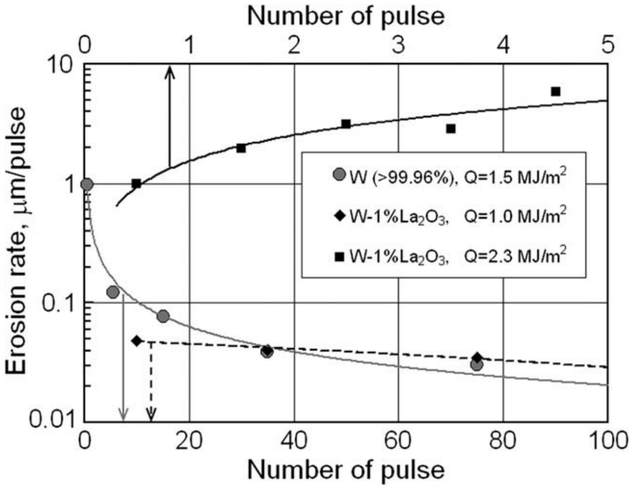


Fig. 6. Erosion rates of tungsten macrobrushes as a function of pulse number.

Table 1
Onset conditions of erosion processes of pure and lanthanum tungsten macrobrushes.

	W (>99, 96%), (Q, MJ/m^2)	W-1%La$_2$O$_3$ (Q, MJ/m^2)
Edges melting	>0.4	>0.4
Melt layer movement	>0.8	>0.6
Separate bridges		0.7–0.8 (after 100 pulses)
	0.9–1.3 (after 50 pulses)	0.8–0.9 (after 50 pulses)
	1.3–1.6 (after 10 pulses)	0.9–1.0 (after 20 pulses)
Surface melting	>0.9	>0.7
Gaps covering by melt material		0.8 (after 100 pulses)
	1.3–1.6 (after 50 pulses)	0.9–1.0 (after 50 pulses)
Droplets ejection	>1.3	>1.0

3.3. Tungsten erosion products study

Onset condition of droplet production, intensity of droplet ejection has been studied on a flat tungsten target that was oriented perpendicularly to the plasma flow in the first case and at 60° in the second one. In both cases the target was exposed to several plasma shots series. Each series consisted of 5–10 shots and was performed at a fixed plasma pressure, velocity, and energy density. The change from one series to another was carried out by gradually increasing the energy density. Statistical measurement of droplets characteristics has been performed at the absorbed energy density 1.6 MJ/m^2 in a case of the normal plasma incidence. The registration of the droplets and its characteristics measurements were performed by using online scheme for solid particles and droplets study (see Fig. 2).

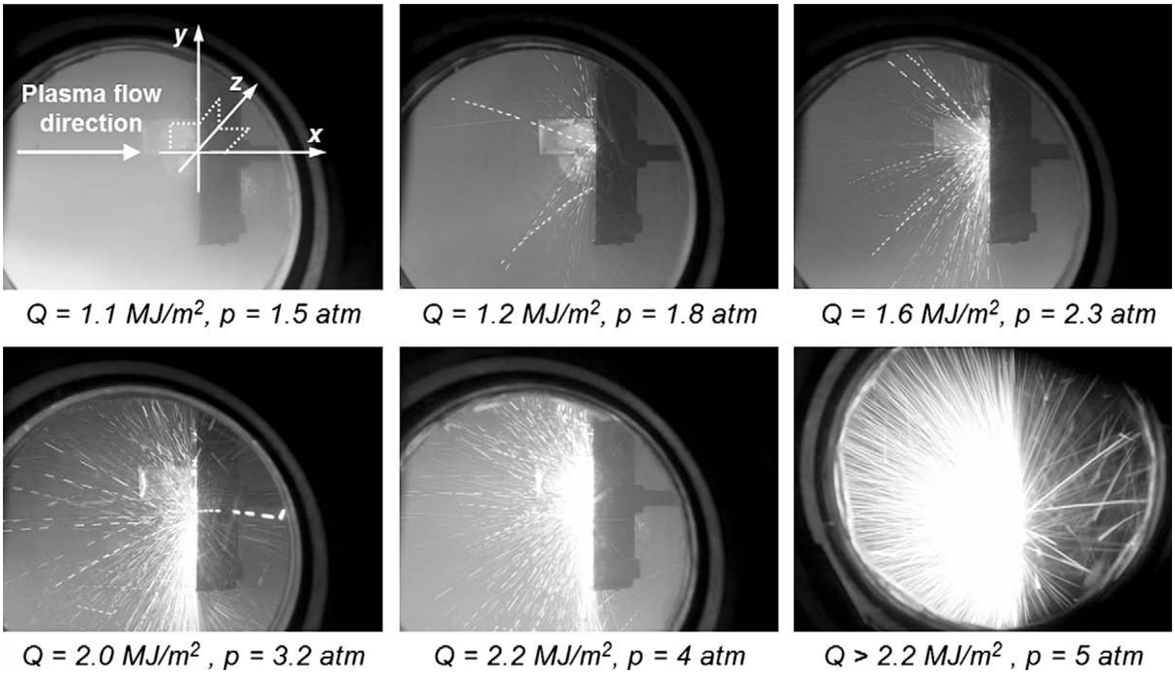
In this scheme droplet tracks are recorded by means of the CCD photo camera through the diagnostic window. The disk with holes shuts and opens the CCD-camera lens repeatedly during the droplet track recording. So the droplets traces have a form of dash line. This system allows to fix a correspondence between real time and droplet track points on the image and so to measure the following characteristics of dust particles ejected from the target surface: (a) components of the dust particle velocity vector; (b) the absolute velocity value and the flight angle of a particle; (c) moment of formation and size of a dust particle.

The total recording time has been fixed at 30 ms. Time delay between end of the plasma discharge and start of particle registration was chosen as 3 ms to eliminate influence of intense plasma radiation during plasma discharge and immediately after one. The optical scheme allows observing the region of 15 cm in front of the target and 5 cm behind it. It is necessary to take into account that particles, which are produced during the plasma discharge and which have the velocity higher than 50 m/s fly outside the observed region before a registration start and they can not be detected. The particles which size less than 5 μm also can not be detected because its radiation is insufficient.

At the first stage, onset condition of droplet ejection was studied for the normal and inclined plasma impact. In both cases obtained onset conditions of droplet ejection correspond to the absorbed energy density about 1.2 MJ/m^2 and the plasma pressure at the target surface about 1.8 atm (see Fig. 7).

At the second stage distributions of the droplet velocity, the flight angle and the time of droplet formation at the perpendicular plasma impact were measured (see Fig. 8). The absolute value of the velocity is below 20 m/s. The main part of emitted droplets has a velocity about 6 m/s. The 80% of droplets are ejected at small angles to the target surface (less than 45°) but there is also a little fraction of the droplets moving at the angles above 45°. Such behavior of the droplets may indicate on existence of various mechanisms of droplets ejection [13]. For example, the droplets moving predominantly along the surface may arise because of Kelvin–Helmholtz instability. The droplets flying at large angles may be formed due to Rayleigh-Taylor instability.

The performed measurement of the time moment of the droplet formation has shown that there are two types of droplets. The droplets of the fist type arise during plasma discharge. The droplets of the second type are formed after plasma exposure. This behavior seems to indicate that the first droplets may arise because of mentioned above instabilities. The second droplets may be as a result of unloading wave or boiling of superheated tungsten liquid after plasma pressure drop. These points are need to verification by the additional experiments.



$Q = 1.1\ MJ/m^2$, $p = 1.5$ atm
$Q = 1.2\ MJ/m^2$, $p = 1.8$ atm
$Q = 1.6\ MJ/m^2$, $p = 2.3$ atm
$Q = 2.0\ MJ/m^2$, $p = 3.2$ atm
$Q = 2.2\ MJ/m^2$, $p = 4$ atm
$Q > 2.2\ MJ/m^2$, $p = 5$ atm

Fig. 7. Typical photos of droplets ejected from the tungsten surface.

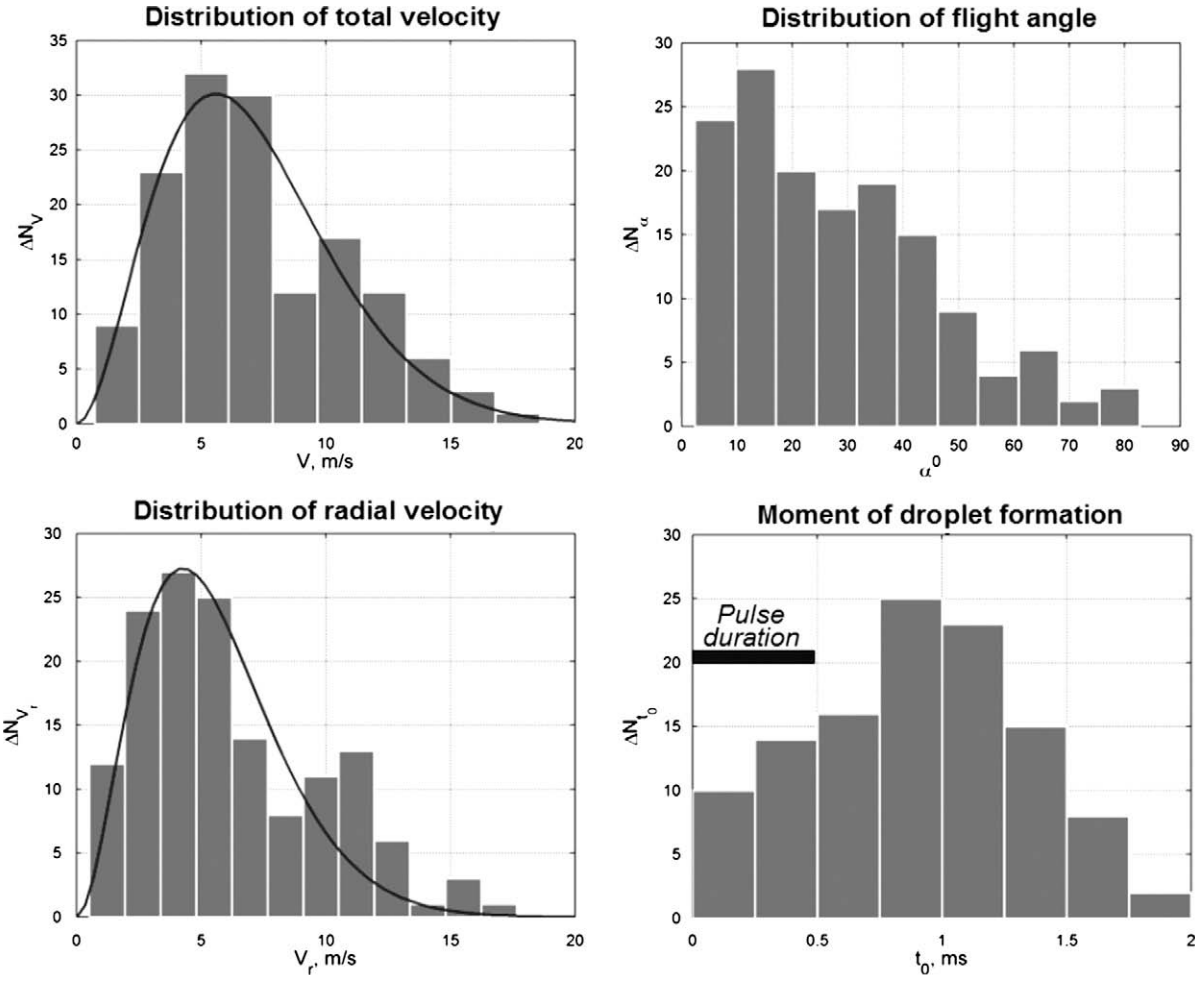


Fig. 8. Characteristics of droplets ejected from the tungsten surface (heat loads 1.6 MJ/m^2).

Because of high temperature the ejected tungsten droplets emits light radiation, which is recorded by CCD camera. Brightness of the droplet depends on its temperature: the higher temperature the higher brightness. The recorded traces of emitted droplets show that their brightness reduces with time. It happens because of droplet cooling due to own thermal radiation. The rate of the droplet radiative cooling depends on its size. This fact was used for evaluation of the droplet size. The sizes of observed droplets were in the range of 10–100 μm.

4. Conclusions

Under ITER ELM-like ($0.5 < Q < 1.5$ MJ/m^2) and disruption-like plasma heat loads ($Q \sim 2.3$ MJ/m^2) the CFC erosion was mainly determined by PAN-fiber damage. The PAN fibers erosion rate increases from 0.2 μm/pulse to 8 μm/pulse in the heat load range 0.5–2.3 MJ/m^2 according to the following law $\Delta h_{\mathrm{PAN}} = 0.9Q^{2.7}$.

The pure tungsten and lanthanum tungsten erosion was mainly due to melt layer movement and droplets ejection in both ELM and disruption experiments. The specific mass loss of lanthanum tungsten increases from 0.1 g/m^2/pulse (erosion rate 0.005 μm/pulse) at 0.5 MJ/m^2 to 60 g/m^2/pulse (erosion rate 3 μm/pulse) at 2.3 MJ/m^2 according to exponential law $\Delta m = 0.02e^{3.5Q}$ as a result of droplet ejection intensification.

The erosion processes of lanthanum tungsten start at the lower energy density as compared with pure tungsten so the lanthanum tungsten erosion is higher than the erosion of pure tungsten at the same condition. The specific mass loss of lanthanum tungsten 0.8 g/m^2/pulse obtained at the heat load 1.0 MJ/m^2 is close to the pure tungsten value of 1.2 g/m^2/pulse at the energy 1.5 MJ/m^2.

Onset conditions of droplets ejection from the pure tungsten surface correspond to following values of the adsorbed energy density and normal to the surface component of the plasma pressure: 1.2 MJ/m^2 and 1.8 atm. The droplets velocities lie below 20 m/s.

The effect of melt layer movement and droplets ejection in ITER may be less because the plasma pressure will be several times lower as compared with these experiments.

The obtained results will be used to validate the codes MEMOS, PEGASUS and PHEMOBRID [9–13] developed in FZK which have been then applied to model the erosion of the divertor and main chamber ITER PFCs under expected transient loads.

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