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Experimental and theoretical investigation of droplet emission from tungsten melt layer

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ABSTRACT

Tungsten in form of macrobrush structure is foreseen as one of candidate materials for the ITER divertor and the dome. 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 plasma facing components. New experimental investigations of droplet emission from the W melt layer for the Edge Localised Mode (ELM)-like heat loads have been carried out at the plasma gun facility quasistationary plasma accelerators (QSPA-T). In these experiments the threshold for droplet emission and the distributions of velocity on emission angles and amplitude of the ejected droplets were determined. In the paper the main physical mechanism (the Kelvin–Helmholtz instability) of the melt splashing under the heat loads being applied at QSPA-T and those anticipated after the ITER transients is analyzed. These numerical simulations demonstrated a reasonable agreement with the experimental data on the droplet sizes and droplet velocities and allowed the projections upon the W melt splashing at ITER conditions.

1. Introduction

Tungsten is foreseen as one of the armour materials for plasma facing components (PFCs) in the ITER divertor and the dome. During the Edge Localised Modes (ELMs) (about 10^4 ELMs per ITER discharge) and the disruptions the armour will be exposed to hot plasma streams. The heat fluxes are expected to be so high that they can cause severe erosion of PFCs thereby limiting their lifetime. During the intense transient events the melting, melt motion, melt splashing and surface evaporation are seen as the main mechanisms of metallic armour erosion. Present knowledge on the material erosion under the high plasma loads is not enough for evaluation of the PFC lifetime for ITER operating scenarios with the disruptions and the type I ELMs.

The plasma loads of ITER transients are not achieved in the existing tokamaks. Therefore other plasma devices such as powerful plasma guns (in particular the quasistationary plasma accelerators (QSPA-T)) are applied for armour testing [1]. The quasistationary plasma accelerators, which are capable to provide the adequate plasma energy density and plasma pulse duration, are quite suitable for erosion measurement [2,3]. To obtain adequate information on the expected damage to ITER PFCs under the transient energy loads the experiments must be supported by numerical simulations using the codes validated against experimental target erosion.

The present work refers to new experimental testing of tungsten targets by plasma heat fluxes relevant to the transient heat loads in ITER in the range 0.5–2.5 MJ/m^2 and timescale of 0.4–0.6 ms, performed at facility QSPA-T located in SRC RF TRINITI. Primary attention is focused at an investigation of melt layer erosion caused by splashing of liquid tungsten droplets. Onset conditions of melt splashing and the properties of the ejected droplets such us size distribution, distributions of velocity on emission angles and amplitude are studied. Supporting numerical simulations are carried out. Influence of different mechanisms causing the melt splashing under expected ITER transients were firstly investigated in [4,5]. It was found that the Kelvin–Helmholtz instability generated by a plasma flow above the melted material is mainly responsible for the melt splashing under the heat loads being applied at QSPA-T and those anticipated after the ITER transients. The main physical mechanism (namely the Kelvin–Helmholtz instability (KH)) of droplet formation under transient pulsed heat loads is analyzed and numerically investigated. At the first stage distributions of the plasma density and plasma velocities above the target surface was numerically estimated using the two dimensional fluid code based on the large particle approach [6]. At the second stage analytical model of the droplet formation developed in [4,5] is applied for estimation of the droplet properties which can be generated

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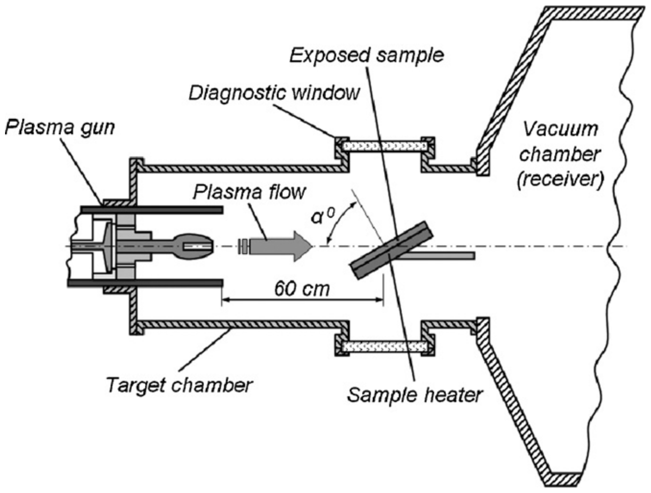


Fig. 1. Basic scheme of experiment at QSPA facility. Plasma parameters: heat loads 0.5–2.5 MJ/m^2; pulse duration 0.1–0.6 ms; plasma stream diameter 6 cm.

by the KH. Numerical results on the droplets ejected by KH are compared with the experimental data obtained at the QSPA-T. The projections upon the W melt splashing at ITER conditions were done.

2. Experimental techniques and diagnostics

The basic scheme of the material erosion investigation is presented in Fig. 1. The tungsten samples to be tested are placed at 60 cm distance from the gun. The angle between the plasma stream and the target surface could be varied from 0° to 90°.

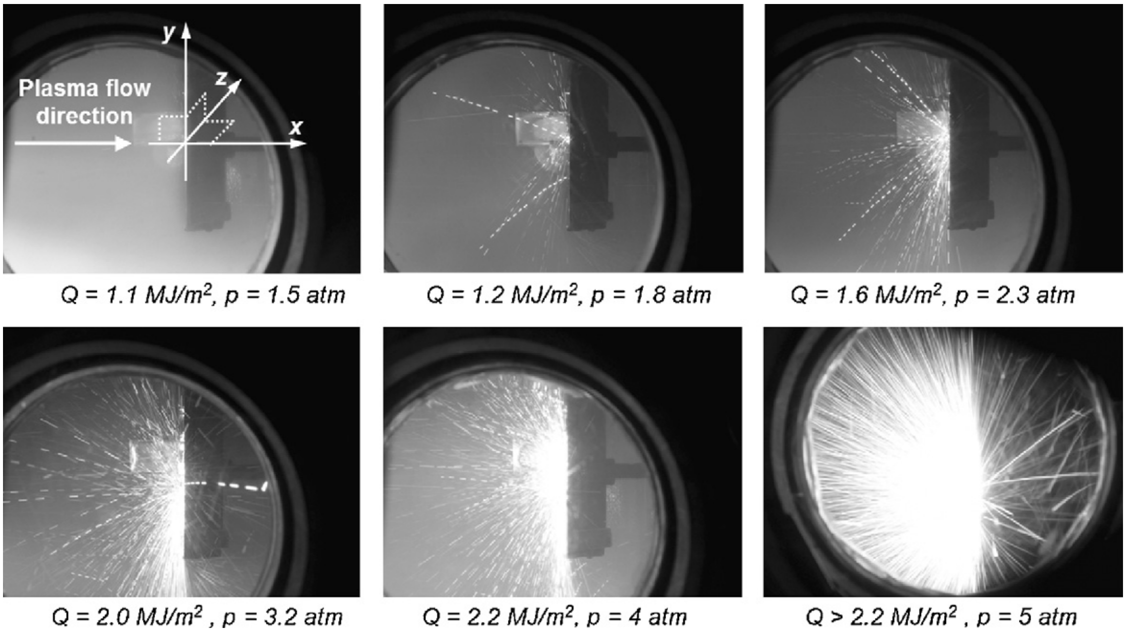
The diagnostics applied in the present experiments included three groups. The fist group is intended for characterization of plasma stream parameters. They allow to measure the plasma pressure, plasma pulse duration, and plasma stream velocity and to evaluate afterwards such parameters as plasma stream energy density and ion impact energy. The second group is used for investigation of material: measurement of energy absorbed by the target and its space distribution along the target surface as well as a diagnostics for characterization of the surface damages as a function of the absorbed energy. The third group concerns investigation of the material dust. It includes diagnostics for online registration of the emitted particles and droplets, and diagnostics for analysis of the collected erosion products.

The operating regimes with gun voltage 2.0–3.7 kV were chosen for ELMs and disruption imitation. Appropriate values of plasma pressure and absorbed energy density equal to 1–7 bar and 0.5–2.2 MJ/m^2 at the normal plasma incidence. The energy density of the plasma flow is varied from 5 to 120 MJ/m^2. The velocity rises from 1.2×10^5 to 3.3×10^5 m/s with increasing the plasma gun voltage from 2.7 to 3.7 kV. The measured velocities correspond to impact energy of hydrogen ions 0.1–0.6 keV. Plasma pulse duration lies in the range 0.4–0.6 ms. According to the performed measurements the absorbed energy density profiles have maximum in the center of the target at the stream axis and they are approximated both by Gaussian distribution with half width of 3 cm.

On-line registration of tungsten droplets emitted from the target surface and its characteristics measurements were performed using the special diagnostic equipment. The droplet tracks are recorded by means of CCD photo camera through the diagnostic window. Rotating disk with holes shuts and opens the CCD-camera lens repeatedly during the droplet track recording. Therefore the droplets traces have a form of dash line. Such diagnostic allows calculating the components of the droplet velocity vector from the measured recorded traces. Time dependence of the droplet track brightness recorded by CCD camera is used for the evaluation of the droplet size: because the rate of the droplet radiative cooling depends on its size.

The system allows to fix a correspondence between real time and droplet track points on the image and thus to determine the following characteristics of the dust particles ejected from the target surface: (a) components of the particle velocity vector; (b) absolute velocity value and flight angle of the particle; (c) instant time of particle formation and size of the dust particle.

In the experiment a 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.



$Q = 1.1$ 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. 2. Typical photos of droplets ejected from tungsten surface under normal plasma action.