CHARACTERIZATION OF QSPA PLASMA STREAMS IN PLASMA -SURFACE INTERACTION EXPERIMENTS: SIMULATION OF ITER DISRUPTION

V.A. Makhlaj

Institute of Plasma Physics NSC "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail*: *makhlay@ipp.kharkov.ua

Experimental simulations of thermal stage of ITER disruptions with relevant surface heat loads (energy density up to 30 MJ/m^2) were performed with a quasi-steady-state plasma accelerator QSPA Kh-50. It was found, that the melt motion driven by plasma pressure gradient dominates in tungsten macroscopic erosion, resulting in droplet splashing and formation of the craters with rather large edge ridges of displaced material. The contribution of mass loss to surface erosion is negligible in comparison with surface profile development caused by melt motion.

PACS:52.40.Hf

INTRODUCTION

The lifetime of the divertor and first wall armor against high heat loads during off-normal events (disruption and Vertical Displacement Event (VDE)) is of concern in the design of a tokamak fusion reactors like ITER and DEMO. The materials at the ITER-divertor surfaces will be exposed to a steady-state heat load with a power density of 5…10 MW/m^2 as well as transient heat loads applied during plasma disruptions (several 10 MJ/m^2 for several ms), VDE (up to 200 MJ/m^2 for 0.5...5 ms) and large edge localize modes (ELMs, in the order of 1 MJ/m^2 for 0.5 ms) [1, 2].

For the transition events, the heat loads to ITER divertor components are far above of that in available tokamaks. Therefore, at present the results obtained with powerful plasma accelerators [3, 4] and e-beam facilities [5, 6] are used for experimental simulation of targets erosion under high heat loads and for validation of predictive models [7-10]. Experimental and theoretical investigations [3, 4, 7-9] have shown that disruption heat loads result in a sudden evaporation of a thin surface layer and produce a cloud of dense vapor plasma, which acts as a thermal shield. Dense vapor plasma stops the incident plasma stream and transforms the incoming energy flux into photon radiation thereby reducing a surface heat load. Due to the vapor shielding effect, material vaporization decreases considerably.

This paper presents the characteristics of QSPA Kh - 50 plasma streams and analysis of contribution of different erosion mechanisms to the material damage under plasma heat loads expected for ITER disruptions.

1. EXPERIMENTAL FACILITY AND DIAGNOSTICS

Experiments were carried out in QSPA Kh-50 device (Fig.1) the largest and most powerful device of this kind [3, 10]. Plasma streams, generated by QSPA Kh-50 were injected into magnetic system of 1.6 m in length and 0.44 m in inner diameter consisting of 4 separate magnetic coils. The maximum value of magnetic field B_0=0.54 T was achieved in diagnostic chamber Z_S = 2.3 m from accelerator output (in the region between 3 and 4 magnetic coils) [10, 11].

Values of plasma stream energy density were determined on the basis of time resolved measurements of the plasma stream density and its velocity. Pressure of plasma stream was measured of piezodetectors [12]. The energy density in the shielding layer was measured by displacing the calorimeter through a hole in the center of the sample. The calorimeter could be moved into the near-surface plasma up to the distance of 5 cm from the target. A surface analysis was carried out with an MMR-4 optical microscope equipped with a CCD camera. Targets were exposed to perpendicular and inclined plasma irradiation with various numbers of pulses. The scheme of the experiment is presented in Fig.1.

2. EXPERIMENTAL RESULTS

2.1. PARAMETERS OF IMPACTED PLASMA STREAMS

QSPA plasma stream parameters were varied by both changing the dynamics and quantity of gas filled the

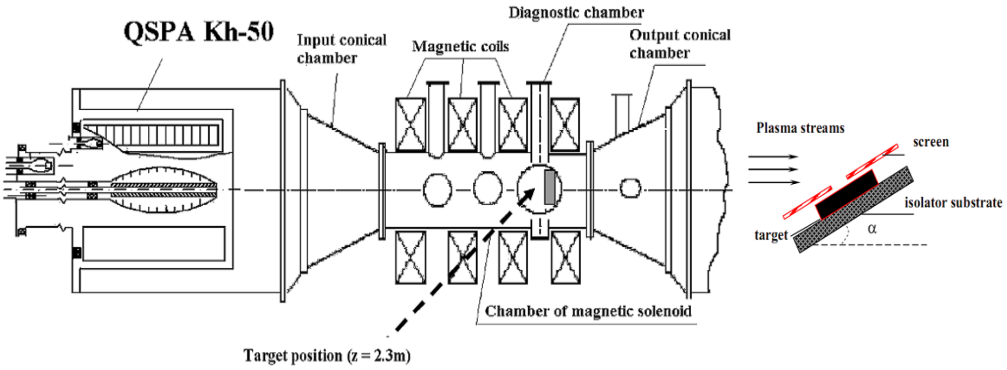

Fig. 1. Scheme of experiment

accelerator channel and changing the working voltage of capacitor battery of the main discharge. To achieve the working regimes for simulation the disruption-like plasma impacts, the main attention in these experiments was paid to possibility of effective variation of plasma stream energy density in wide range and determination of target heat load in dependence on plasma stream energy density.

Special efforts were done to increase the plasma pressure in QSPA plasma stream. As it follows from temporal dependence of plasma stream pressure measured at the target position (Fig. 2), maximum value of plasma pressure achieved 1.6…1.8 MPa. Energy density is up to 30 MJ/m^2.

Injection of powerful plasma streams into magnetic field is accompanied by magnetic field displacement out of plasma. The magnetic field displaced by plasma is of order $\Delta B/B_0 \sim 0.7$. The temporal behavior of the signal of displaced magnetic field is not differs from the temporal dependence of the plasma pressure (Fig. 2). Average $\beta = 8\pi P/B_0^2$ value, calculated on the basis of plasma pressure and vacuum magnetic field is about 0.4…0.6.

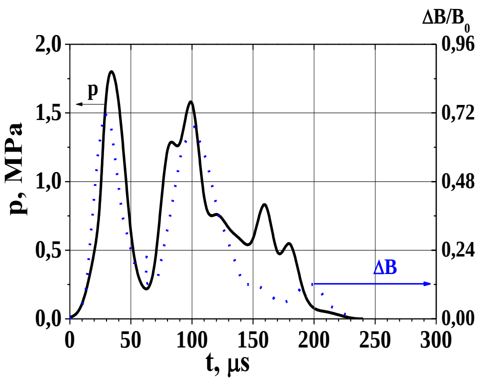

Fig. 2. Time dependencies of plasma pressure (P) and displaced magnetic field (ΔB), normalized by the value of vacuum magnetic field (B_0=0.54 T), in diagnostic vacuum chamber

2.2. FEATURES OF PLASMA–SURFACE INTERACTION

Protective screens of 12 cm in diameter with central holes of 1 and 3 cm in diameter were used to impose a pressure gradient along the target that mimics the pressure gradient found at the strike point locations in a tokamak disruption [7]. Measurements of plasma pressure distribution along the target in the presence of diaphragm are performed with a piezodetector inserted instead of the target. It shows a steep decrease of pressure value at the 5 mm peripheral zone and a practical constant pressure value in central region of about 2 cm in diameter (Fig. 3). Availability of diaphragm allowed to make clear the influence of plasma pressure gradient on melt motion even for QSPA plasma pulse duration and to achieve the melt velocities comparable with ones expected for ITER disruptions [11].

Measurements of target heat load have been performed with small calorimeter inserted into the target surface. In this case, the fraction of plasma energy density delivered to the target surface is monitored (Fig. 3). As it was shown earlier [4] the main feature of high-power plasma interaction with targets is possibility of dense plasma shield formation close to the target surface.

For inclined exposure of the different targets, the diminution of energy density delivered to surface is observed with decrease of incidence angle and diameter of diaphragms' central hole (Fig. 4).

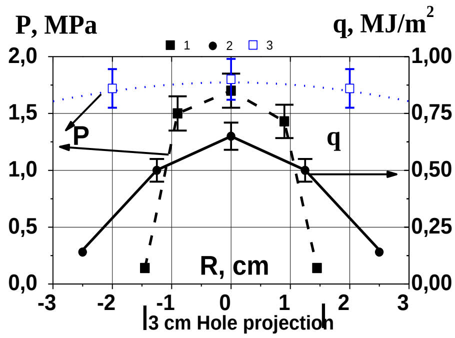

Fig. 3. Radial distributions of plasma stream pressure (1), energy density (2) delivered to surface target through the diaphragm with central hole of 3 cm and pressure of free plasma stream (3)

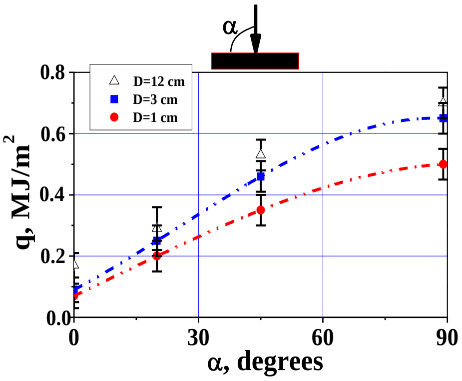

Fig. 4. Heat load to the target surface thought diaphragm of deferent diameter (D) versus the incidence angle of an impinging plasma stream at an energy density of 30 MJ/m^2

2.3. MECHANISMS OF TUNGSTEN EROSION

As it is found from profilometry, the ridges of resolidified material, indicating the melt motion, appeared at the melt edge (Fig. 5). For perpendicular impacts, the height of the ridge achieves 48 μm after 20 pulses (see Fig. 5,a). The distance between ridge peaks achieves 1.4 cm. The high value of the surface roughness masks the erosion crater between the ridge peaks. The melt motion is accompanied by splashing of the metal droplets of the sizes up to 100 μm onto unexposed target surface [13]. The plasma pressure gradient is the main force initiating the melt motion [11].

For inclined exposure of the tungsten target under the angle of 30º to the surface, the formation of a mound of resolidified material is observed only at the downstream part of the melt spot (see Fig. 5,b). The mound height is 26 μm, which is almost twice less than that found for perpendicular plasma impact. Mass loss measurements indicated that the contribution of evaporation to the target erosion remains below 0.1 μm/pulse.

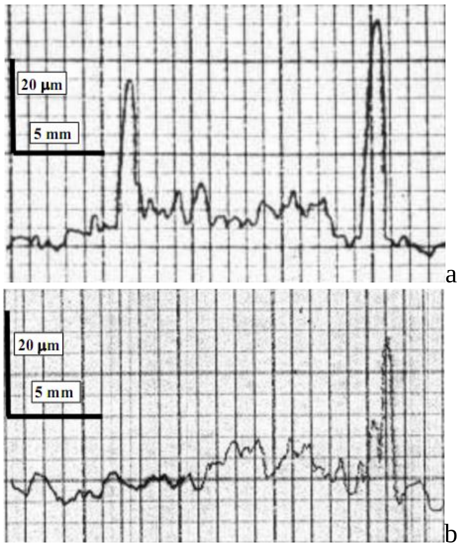

Fig. 5. Melt layer erosion profiles for tungsten targets under perpendicular (a) and inclined (b) impact of plasma stream. Hole diameter is 1cm

For surface cracking the balance of the 2 processes is observed for increased number of exposures: the cracks become completely covered by the molten material but new thin cracks meanwhile appear.

CONCLUSIONS

Operation regime of QSPA Kh-50 with plasma energy density of about 25…30 MJ/m^2 was used for experimental simulation of disruptive heat loads. The value of energy density absorbed by the target surface is not exceeded 0.7 MJ/m^2 for incident plasma energy density up to 30 MJ/m^2. This is an influence of a vapor shield formation close to the surface under the plasma impact.

The melt motion driven by plasma pressure gradient dominates in tungsten macroscopic erosion, resulting in droplet splashing and formation of the craters with rather large edge ridges of displaced material.

This work is supported in part by STCU project # P405. The author would like to acknowledge I.E. Garkusha for very helpful discussion and interpretation of experimental results and QSPA Kh-50-team for assisting in the experiments.

REFERENCES

1. G. Federici et al. // *Nucl. Fus.* 2001, v. 41, p. 1967.
2. A. Loarte et. al. // *Plasma Phys. Control. Fusion* 2003, v. 45, p. 1549.
3. N. Arkhipov. et al. // *J. Nucl. Mater.* 1996, v. 233–237, p. 686
4 V.V. Chebotarev et al. *// J. Nucl. Mater.* 1996, v. 233-237, p.736-740.
5. P. Majerus et al. *// Fus. Eng. and Design*. 2005, v. 75–79, p. 365–369.
6. V.T. Astrelin et al. *// Nucl. Fus.* 1997, v. 37, p. 1541.
7. H. Wuerz et al. *// J. Nucl. Mater.* 2002. v. 307-311,p. 60.
8. H. Wuerz et al. *// J. Nucl. Mater.* 2001, v. 290-293, p. 1138-1143.
9. A. Hassanein, I. Konkashbaev *// J. Nucl. Mater.* 1996, v. 233–237, p.713–717.
10. V.I. Tereshin et al. // *Brazilian Journal of Physics.* 2002, v. 32, №1, p. 165-171.
11. V.I. Tereshin et al. // *J. Nucl. Mater.* 2003, v. 313–316, p. 685–689.
12. A.N. Bandura et al. *// Phys. Scr.* 2006, v. T123, p. 84-88.
13. I.E. Garkusha et al. // *J. Nucl. Mater*. 2005, v. 337–339, p. 707–711.

Article received 14.11.2012

ХАРАКТЕРИСТИКА КСПУ ПОТОКОВ ПЛАЗМЫ В ЭКСПЕРИМЕНТАХ ПО ПЛАЗМО-ПОВЕРХНОСТОМУ ВЗАИМОДЕЙСТВИЮ: МОДЕЛИРОВАНИЕ СРЫВОВ ТОКА В ИТЕР

В.А. Махлай

Экспериментальное моделирование тепловой фазы срыва тока в ИТЭР с соответствующими тепловыми нагрузками на поверхности (плотность энергии до 30 МДж/м^2) было выполнено в квазистационарном плазменном ускорителе КСПУ Х-50. Было установлено, что движение расплава, обусловленное градиентом давления плазмы, доминирует в макроскопической эрозии вольфрама и приводит к разбрызгиванию капель и образованию кратеров с большими горами перемещенного материала на их границах. Вклад массовых потерь в эрозию поверхности пренебрежимо мала по сравнению с развитием профиля поверхности, обусловленным движением расплава.

ХАРАКТЕРИСТИКА КСПП ПОТОКІВ ПЛАЗМИ В ЕКСПЕРИМЕНТАХ ПО ПЛАЗМО-ПОВЕРХНЕВІЙ ВЗАЄМОДІЇ: МОДЕЛЮВАННЯ ЗРИВІВ СТРУМУ В ІТЕР

В.О. Махлай

Експериментальне моделювання теплової фази зрива струму в ІТЕР з відповідними тепловими навантаженнями на поверхні (густина енергії до 30 МДж/м^2) було виконано в квазістаціонарному плазмовому прискорювачі КСПП Х-50. Було встановлено, що рух розплаву, обумовлений градієнтом тиску плазми, домінує в макроскопічній ерозії вольфраму приводить до розбризкування крапель і утворення кратерів з досить великими граничними горами переміщеного матеріалу. Внесок масових втрат в ерозію поверхні э незначним в порівнянні з розвитком профілю поверхні, що обумовлений рухом розплаву.