PLASMA-SURFACE INTERACTION DURING ITER TRANSIENT EVENTS: SIMULATION WITH QSPA Kh-50 AND GOL-3 FACILITIES

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The paper presents experimental investigations of plasma-surface interaction (PSI) and materials behavior under plasma loads relevant to giant ELMs in ITER. The experiments were performed with QSPA Kh-50 and GOL-3 devices located in Kharkov, (Ukraine) and Novosibirsk (Russia) respectively. QSPA provided repetitive plasma pulses of the duration of 0.25 ms and the energy density up to 2.5 MJ/m^2. In GOL-3 multimirror trap the impacting plasma was heated up to 2…4 keV temperature by a high power relativistic electron beam (0.8 MeV, ~30 kA, ~12 µs, ~120 kJ). Surface morphology of the targets exposed to QSPA and GOL-3 plasma is analyzed. Development of cracking on the tungsten surface and droplets splashing are discussed.

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1. INTRODUCTION

Divertor armor response to the repetitive plasma impacts during the transient events in ITER remains to be among the most important issues which determine the tokamak performance and the lifetime of plasma-facing components. Energy loads to the divertor surfaces associated with the Type I ELMs are expected to be up to Q = 1-3 MJ/m^2 during τ = 0.1-0.5 ms. It is important that about million ELMs will be generated during the ITER operation cycle. Tungsten is a candidate material for major part of the surface, but its brittleness can result in substantial macroscopic erosion after the repetitive heat loads. Transient loads in ITER will result in both material erosion and plasma contamination by impurities.

Quasi-Steady-State Plasma Accelerators (QSPA) well reproduce the energy densities (Q) and pulse durations (τ) of ITER ELMs [1, 2]. Experimental investigations of plasma-surface interaction in ITER relevant conditions are aimed the determination of main erosion mechanisms for the divertor armour materials, dynamics of erosion products, vapor shield effects under plasma heat loads. In turn, the obtained results are used for validation of predictive models developed for ITER [3], estimation of tolerable size of ITER ELMs and lifetime of divertor armour.

Primary task of the GOL-3 facility is development of a multiple mirror magnetic confinement scheme for fusion. This approach differs from other magnetic confinement schemes by higher plasma density and multimirror (corrugated) magnetic field of linear topology. Principal feature of GOL-3 experiments is the use of a high-power relativistic electron beam for fast collective plasma heating. In the discussed experiments the beam parameters were 0.8 MeV, ~30 kA, 12 µs, ~120 kJ. The temperature of deuterium plasma of ~10^{21} m^{-3} density was 2-4 keV [4]. Such plasma parameters are extremely attractive from the point of view simulation of PSI issues in fusion reactor.

2. EXPERIMENTAL SETUP

In GOL-3 facility the relativistic electron beam loses ~40% of initial kinetic energy in average during the collective relaxation in the plasma. Several linked collective processes occur during the beam relaxation which results in fast effective heating of plasma electrons and ions. The energy confinement time reaches ~1 ms in best regimes. The relaxed beam electrons and plasma exhaust from the trap are dumped to the exit beam receiver whish is placed in a decreasing magnetic field in order to reduce energy load to the collector below the safe margin (Fig.1). Energy density in the exhaust plasma stream reaches ~30 MJ/m^2 in the exit mirror and then it decreases correspondingly with the broadening of the magnetic flux tube in the exit expander. At the collective beam relaxation in the plasma a significant fraction of initial beam energy is transferred to suprathermal electrons with energies up to and above the initial beam energy. Energy distribution of electrons in the plasma stream was carefully studied in previous experiments on action of hot-electron plasma stream with graphite targets [5,6]. Fig. 2 shows general shape of power density spectrum in the exit mirror (taken from [6]).

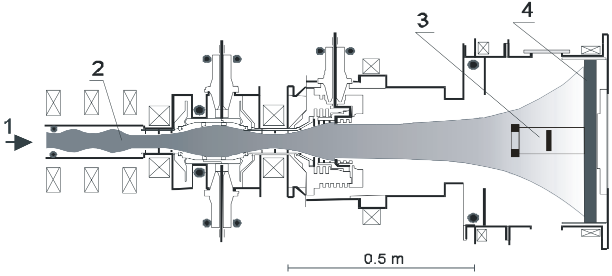

Fig.1. Layout of experiments on targets exposing by hot-plasma stream on GOL-3 facility. 1 – exhaust of plasma, 2 – end of multi-mirror trap, 3 – target, 4 – plasma dump

The energy density of the plasma stream was reduced down to ~2 MJ/m^2 in current experiments with targets. This corresponds to estimated transient energy density in ITER ELMs type I regime. The targets of tungsten and graphite were exposed to such flow of hot plasma with different dose.

The experiments with quasi-steady-state plasma accelerator QSPA Kh-50 [1,2] were performed using repetitive pulses of hydrogen plasma of the duration of 0.25ms and the energy density in the range of (0.5…2.5) MJ/m^2. The plasma stream diameter is 18 cm, the ion energy is about 0.4 keV, and maximum plasma pressure achieves 3.2 bar. Scheme of target irradiation is shown in Fig.3. It is described in details in [7]. In some experiments an Ohmic heater was installed behind the tungsten target to study the influence of target preheating up to $t_{init} \approx 650°C$ on surface cracking [7, 8].

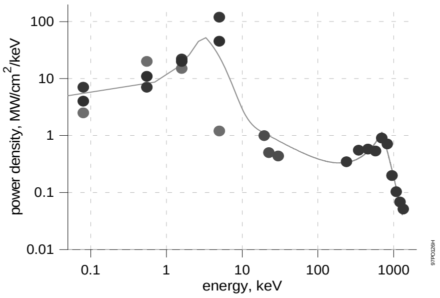

Fig. 2. Energy distribution of power density of irradiating electron stream in the exit mirror

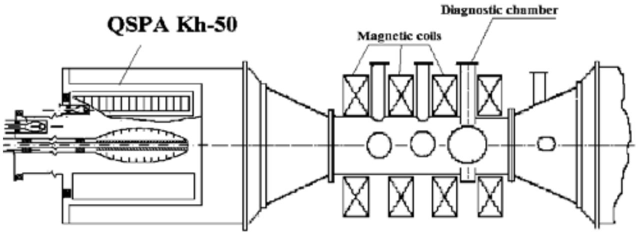

Fig.3. Scheme of targets exposures in QSPA Kh-50

Calorimetry (both at plasma stream and at the target surface), piezo-detectors, electric and magnetic probes, Rogowski coils, spectroscopy and other diagnostics were applied for measurements of plasma parameters and surface heat loads in different regimes of operation.

3. EXPERIMENTAL RESULTS

Fig.4 shows surface morphology of tungsten targets exposed with 5 pulses of QSPA Kh-50 (a) and GOL-3 (b,c) respectively. In both cases the energy load was sufficient to provide strong melting of the surface and also evaporation. Boiling bubbles are observed with microscopy. Surface changes for irradiation in both devices are similar. This means that in spite of qualitative differences in energy distribution function of bombarding particles (essentially different directed energy of particles), surface heat load plays key role under powerful plasma impact.

Plasma exposures of tungsten targets with initial temperature at RT level resulted in formation of large size cracks and fine inter-granular cracks on the surface.

Surface cracking leads to essentially increased surface roughness of tungsten and swelling of the surface profile as whole according to initial reference line. Crack pattern is shown with larger magnification in Fig.5. It is seen that cracking is source of the tungsten dust, which can be deposited to surrounding areas. It should be mentioned that even for heat loads, which not resulted in complete melting of the surface, dust melting can be achieved in result of dust covered surface exposure with next plasma pulses. Microscopy analysis shows growing width of the cracks with increased number of exposures.

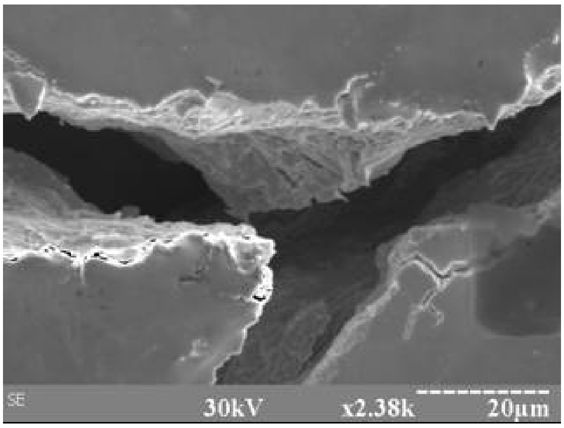

Fig.5. Enlarged view of crack structure after 5 pulses of GOL-3

For plasma exposures with high energy loads above the tungsten boiling threshold, tungsten erosion is dominated by droplet splashing. Images of droplet traces, velocity and angular distributions of ejected droplets are presented in Fig.6. The velocity of the droplets can be estimated from the lengths of their traces. Movement in perpendicular direction to the image plane is derived from consecutive frames. Consequences of the images form movie with possibility to analyze the dynamics of droplets splashing from the surface. Droplets continue to be ejected from the melt after plasma impact during ~ 10 ms. Tungsten cracking causing decrease of the heat transfer between the melt layer and a cold bulk, as well as the vapour shied formation in front of the surface, may influence significantly on the resolidification time and, thus, on the measured duration of droplets splashing. It is obtained that droplets velocities may achieve several tens m/s. Fast droplets are generated at earlier time moments. Smaller velocities are observed for late stage of observation. During intermediate stage both groups of droplets with fast and lower velocities are observed.

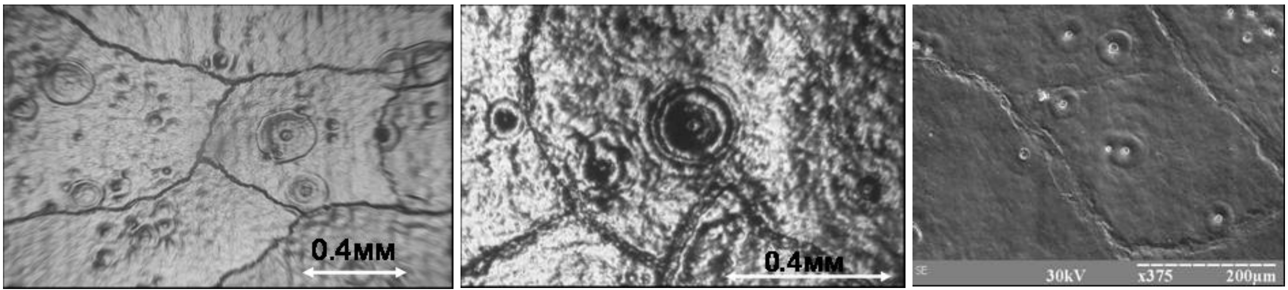

Fig. 4. Tungsten surface after 5 pulses of 1.1 MJ/m^2 in QSPA Kh-50 (a) and after 5 pulses of 2.1 MJ/m^2 in GOL-3(b,c)

4. CONCLUSIONS

Comparative studies on tungsten targets irradiation with powerful plasma streams generated in GOL-3 and QSPA Kh-50 are performed. It is shown that for applied high energy loads > 1 MJ/m^2, similar evolution of surface morphology after exposures is observed, in spite of qualitative differences in energy distribution function of bombarding particles. Thus, surface heat load plays key role under powerful plasma impacts.

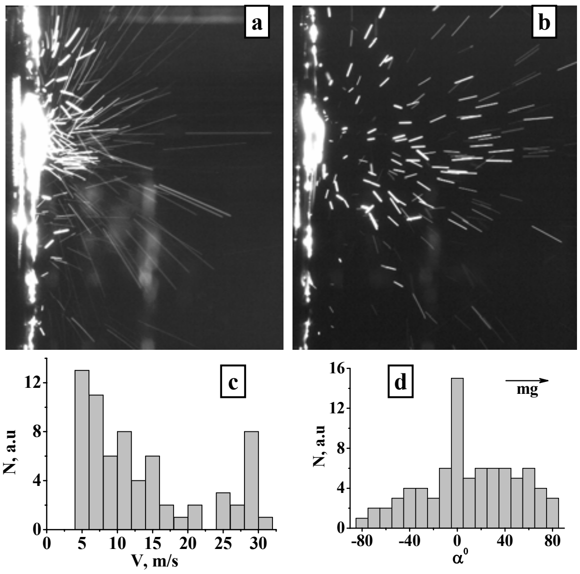

Fig.6. Droplets splashing from the tungsten surface in the course of plasma exposures in QSPA Kh-50. Images of droplet traces $t_{exposure}$= 1,2 ms, t=3.0 ms after plasma pulse (a), t= 9.0 ms (b),velocity (c) and angular (d) distributions of ejected droplets for t=3.0 ms

The plasma impacts cause cracking, dust formation and the droplet splashing from the tungsten surface. Angular distribution of splashed droplets was analyzed. The W-droplets continue to be ejected from the melt for about 10 ms after the impact. The droplets velocities may achieve several tens m/s. Fast droplets are generated at earlier time moments, and small droplet velocities correspond to the late stage of observation.

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ВЗАИМОДЕЙСТВИЕ ПЛАЗМЫ С ПОВЕРХНОСТЬЮ В ПЕРЕХОДНЫХ РЕЖИМАХ ИТЭРа: МОДЕЛЬНЫЕ ЭКСПЕРИМЕНТЫ НА УСТАНОВКАХ КСПУ Х-50 И ГОЛ-3

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Представлены результаты исследований взаимодействия плазмы с поверхностью и поведения материалов при плазменных нагрузках, соответствующих граничным локализованным модам в ИТЭРе. Эксперименты проводились на установках КСПУ Х-50 (Харьков) и ГОЛ-3 (Новосибирск). Облучение на КСПУ проводилось повторяющимися импульсами длительностью 0,25 мс и плотностью энергии до 2,5 МДж/м^2. В гофрированной многопробочной ловушке ГОЛ-3 взаимодействующая с материалами плазма нагревалась до температуры 2…4 кэВ мощным релятивистским электронным пучком (0.8 МэВ, ~30 кА, ~12 мкс, ~120 кДж). Анализируется морфология поверхности мишеней, облученных на КСПУ и ГОЛ-3. Обсуждается развитие трещин и капельная эрозия вольфрама.

ВЗАЄМОДІЯ ПЛАЗМИ З ПОВЕРХНЕЮ У ПЕРЕХІДНИХ РЕЖИМАХ ІТЕРу: МОДЕЛЬНІ ЕКСПЕРИМЕНТИ НА УСТАНОВКАХ КСПП Х-50 ТА ГОЛ-3

І.Є. Гаркуша, О.В. Бурдаков, І.О. Іванов, Э.П. Кругляков, К.М. Куклін, І.С. Ландман, В.О. Махлай, С.В. Полосаткін, А.А. Шошин, В.І. Терешин, М.М. Аксьонов

Представлені результати досліджень взаємодії плазми з поверхнею й поведінки матеріалів при плазмових навантаженнях, відповідних граничним локалізованим модам в ІТЕРі. Експерименти проводились на установках КСПП Х-50 (Харків) й ГОЛ-3 (Новосибірськ). Опромінення на КСПП проводилось повторюваними імпульсами тривалістю 0,25 мс та густиною енергії до 2,5 МДж/м^2. У гофрованій багатопробочній пастці ГОЛ-3 плазма, яка взаємодіє з матеріалами, нагрівалась до температури 2…4 кеВ потужним релятивістським електронним пучком (0.8 МеВ, ~30 кА, ~12 мкс, ~120 кДж). Аналізується морфологія поверхні мішеней, що опромінені на КСПП та ГОЛ-3. Обговорюється розвиток тріщин й крапельна ерозія вольфраму.