Experimental studies of cyclical plasma effects on tungsten

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Plasma-surface interaction is an important issue of creating protective materials for ITER divertor. Its main function is absorption of heat flow out of the edge plasma and extraction of helium which is a product of burning in the reaction of thermonuclear fusion. It is assumed that the walls of the divertor will be irradiated with a flow of helium ions 10^{22}-10^{24} He m^{-2} s^{-1} (<500 eV), as well thermal stresses as a result of ELM-events will be occurred. Existing tokamaks can not generate heat flow needed for the reactor. Currently the most adequate interaction of the plasma with the wall of ITER can be experimentally studied and modeled in real tokamaks equipped with samples previously irradiated (damaged) using alternative high power heat sources. Such experiments focus on study of the properties of materials and the behavior of the parameters of the tokamak plasma. This work aims at an experimental study of cyclic heat flow on tungsten produced by plasmas of a coaxial gun [1] and the tokamak Globus-M [2]. Experimental results on the interaction of tungsten tiles with hydrogen, deuterium and helium plasma are presented.

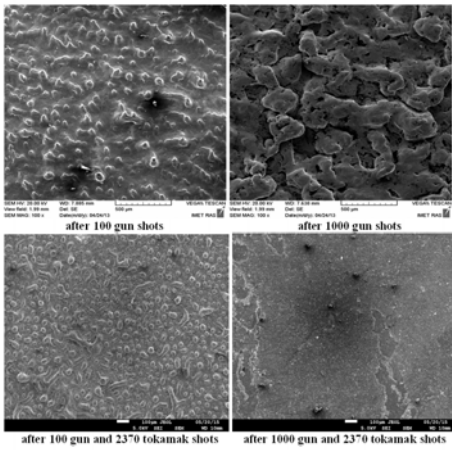
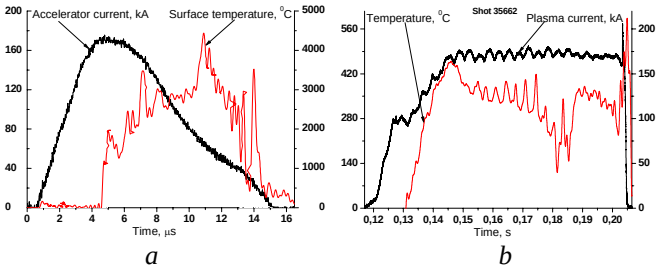


Fig. 1: SEM images of surface of Plansee tungsten samples after cyclic irradiation by a hydrogen plasma jet and deuterium plasma of Globus-M. The plasma jet parameters: pulse duration 15 μs; power density ≤100 GW/m^2; heat flux factor ≤230 MJ m^{-2}c$^{-1/2}$. The Globus-M plasma parameters: pulse duration~70 ms; power density ≤2.5 MW/m^2; heat flux factor ≤1 MJ m^{-2} c$^{-1/2}$

Investigation of tungsten irradiated by the plasma of the coaxial gun. We have already presented some results of cyclic irradiation of tungsten with a hydrogen plasma jet simulating transient heat loads (ELM-events) [3,4]. Significant changes in the morphology of the surface layer were found with the help of scanning electron microscopy (SEM) (JEOL JSM-7001F) (Fig. 1a). After 100 cycles of irradiation columnar structure

perpendicular to the irradiated surface was formed. After 1000-fold cycles the failure mechanism was changed - the columns melted to form a droplet-shape structure. The surface became rough forming recrystallized layer with depth of approximately 100 μm and a friable layer under the irradiated surface. Two-color high-speed pyrometer developed by IoffeLED Ltd allowed measurements of the surface temperature of tungsten during irradiation by the plasma jet. (Fig. 2a) [5]. One can see that the surface temperature was heated up to 4000 ^{0}C and quickly cooled. The whole process lasted ~ 10 μs.



a *b*

Fig. 2: Dependences of the plasma current and the surface temperature on time. Tungsten irradiated by: a) jet of plasma gun (pulse duration 15 μs; power density ≤100 GW/m^2; heat flux factor ≤230 MJm^{-2}c$^{-1/2}$); b) plasma of Globus-M (pulse duration~70 ms; power density ≤2.5 MW/m^2; heat flux factor ≤1 MJm^{-2}c$^{-1/2}$)

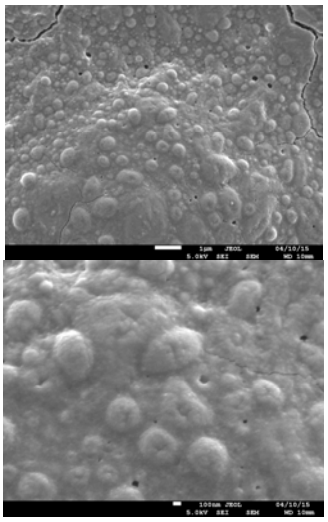


Fig. 3: SEM images of surface of JSC POLEMA tungsten samples after cyclic irradiation by helium plasma jet (number of pulses 1000; pulse duration 15 μs; distance between the gun and the sample 250 mm; fluence 10^{23} – 10^{24} He/m^2; power density ≤20 GW/m^2; heat flux factor ≤50 MJm^{-2}c$^{1/2}$)

Multiple irradiation of tungsten with a helium plasma jet simulating helium ash divertor condition was conducted. In this case the temperature did not reach the melting point of tungsten and was about 1000 ^{0}C (Fig. 3). It is evident that multiple plasma gun irradiations created bubbles and pores. In large areas of blocks a structural transmutation associated with the accumulation of energy was occurred. Recrystallized processes at submicron level of tungsten were happened. The helium damaged samples were installed in the Globus –M tokamak for further investigation. The studies have shown that the jet of the plasma gun allows us to simulate the impact of ELM-events and helium ions on the material in conditions similar to the ITER divertor ones.

Investigation of tungsten irradiated by tokamak plasma of Globus-M. The tungsten samples a priory irradiated by the plasma gun were installed near the outer strike point region of the Globus-M lower divertor. Specific power load to the divertor tiles reached ~ 2.5 MW/m^2. The first results of the interaction of deuterium tokamak plasma with the surface of the tiles damaged by ELM-events have been reported in [2, 6]. IR camera measuring the temperature field of the tungsten surface showed that shortly after discharge termination the temperature was much higher on the tiles damaged by the hydrogen plasma jet. The heat removal from the bulk of the tiles damaged with cyclic loading equivalent to 1000 ITER ELM events by the plasma jet

was obstructed by formation of a loose layer. Two color pyrometer with spatial resolution about 1 cm registered surface temperature of low divertor region (Fig.2b). One can see that the temperature of the tile could reach the value ≥ 400^0C.

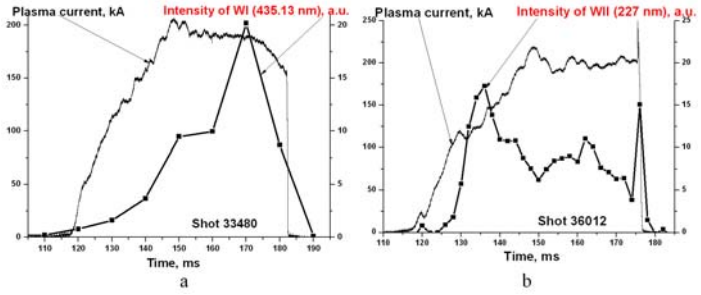


Fig. 4: Dependences of plasma current and line radiation of tungsten on time in Globus-M

Radial displacement of the outer branch of the separartrix could cause a variation of the temperature on time. Tungsten shielded divertor did not change total radiation losses noticeable. But spectroscopy detected some neutral and ionized tungsten in plasma of the Globus-M (Fig.4). Figure 4a shows that amount of the neutral tungsten increased by the end of the discharge. The total plasma radiation losses had similar behavior. Ionized tungsten partially burned out at the current rise and recombined at discharge termination (Fig.4b).

After 2370 shots (total duration ~ 200 s) the Plansee double forged tungsten samples were taken out for analysis. Structure of tungsten surface layers irradiated by the hydrogen plasma jet and their subsequent exposure in deuterium plasma of the tokamak Globus-M was modified (Fig.1b). Investigation of morphology showed that the columnar and droplet-shape structures were smoothed. An in-depth distribution of D, H and other elements in tungsten was determined by SIMS CAMECA IMS 7f (Fig.5). One can see that characteristic depth of the layer accumulating impurities was more than 0.5 μm. The sample irradiated with 1000 gun and 2370 tokamak pulses had the greatest depth and quantity of the impurity (c). Mainly the layer accumulated impurity of boron (boronization of the tokamak chamber was conducted regularly in order to improve the discharge reproducibility). The amount of other elements in the layer was not more than a few percents.

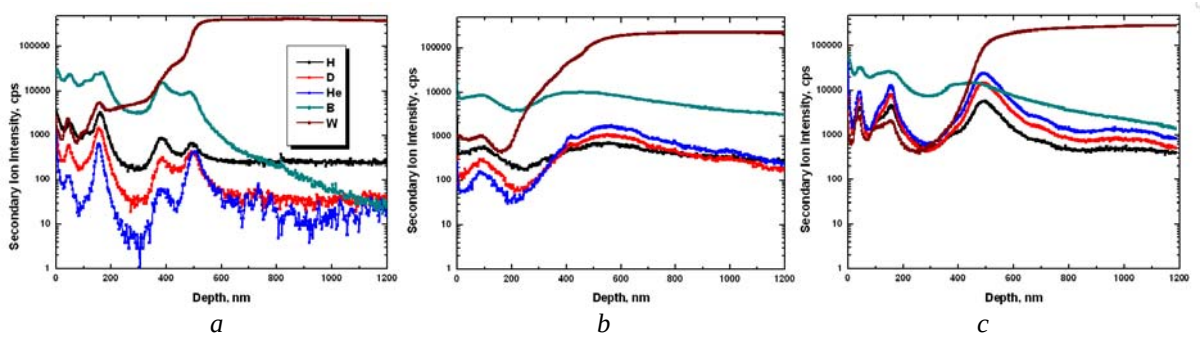


Fig. 5: SIMS in-depth profiles of elements in Plansee double forged tungsten after irradiation by: a) 2370 shots of the Globus-M; b) 100 shots of plasma gun and (a); c) 1000 shots of plasma gun and (a). Hydrogen plasma jet parameters: pulse duration 15 μs; power density ≤100 GW/m^2; heat flux factor ≤230 MJ m^{-2} c$^{-1/2}$. Deuterium Globus-M plasma parameters: pulse duration~70 ms; power density ≤2.5 MW/m^2; heat flux factor ≤1 MJ m^{-2} c$^{-1/2}$

Conclusions

Multiple irradiations of tungsten by pulse flows of hydrogen, deuterium and helium plasma were conducted. The surface temperature during irradiation by the plasma jet (up to 4000 ^{0}C) and the tokamak plasma (~400 ^{0}C) with spatial and time resolution was measured. Investigations of morphology of the surface layer of tungsten after multiple plasma irradiations under various conditions were performed. The helium jet of the plasma gun allows simulation of the impact of helium ions in the ITER divertor materials - creating bubbles. It was shown that the structure of tungsten surface layers irradiated by the hydrogen plasma jet and their subsequent exposure in deuterium plasma of the tokamak Globus-M was modified - structure gets smoothed. The tiles did not increase total radiation losses appreciable, but spectroscopy detected some neutral and ionized tungsten in Globus-M. The characteristic depth of the layer accumulating impurities reached more than 0.5 μm. The samples irradiated with the gun and the tokamak had the greatest damaged depth and quantity of the impurity. Mainly the layer accumulated the boron impurity. The amount of other elements in the layer was not exceeded a few percents. The results of successively plasma irradiation of tungsten with the help of the plasma gun and the tokamak confirmed a possibility of modeling of plasma-wall interaction in the ITER divertor.

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