# HIGH HEAT FLUX PLASMA TESTING OF ITER DIVERTOR MATERIALS UNDER ELM RELEVANT CONDITIONS IN QSPA Kh-50

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Performed studies of plasma-surface interaction include measurements of plasma energy deposited to the material surface and determination of tungsten cracking threshold during repetitive ITER ELM-like plasma exposures in QSPA Kh-50 with plasma pulses of energy density up to 2.5 MJ/m$^2$ and duration of 0.25 ms. The energy threshold for tungsten cracking development is found to be ~0,3 MJ/m$^2$. The Ductile-to-Brittle Transition Temperature (DBTT) is experimentally estimated for ITER relevant tungsten grade. Major crack network (cells size up to 1.3 mm) forms only in cases of initial target temperatures below DBTT. Intergranular micro-cracks network (size of cells corresponds to the grain size) appears under heat loads after melting threshold.

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## 1. INTRODUCTION

Divertor armor response to the repetitive plasma impacts during the transient events in ITER and DEMO remains to be one of the most important issues that determine the tokamak performance. Erosion of plasma-facing components (PFCs) restricts the divertor lifetime, leads to contamination of the hot plasma by impurities and can produce a substantial amount of the material dust [1]. The present-day experimental investigations of plasma-surface interaction under conditions simulating ITER transient events are aimed at determination of erosion mechanisms of plasma facing materials, dynamics of erosion products, the impurities transport in the plasma, the vapor shield effects and its influence on plasma energy transfer to the material surface [2-8].

This paper presents recent results of ELM-simulation experiments with the quasi-stationary plasma accelerator QSPA Kh-50. The experiments include study of plasma-surface interaction under inclined plasma impact, the cracks analysis and the results of residual stress measurements for tungsten targets with elongated grains, which is ITER reference W grade.

## 2. EXPERIMENTAL SETUP AND DIAGNOSTICS

Experimental simulations of ITER ELMs (Edge Localized Modes) impacts were performed with quasi-steady-state plasma accelerator QSPA Kh-50 that is largest and most powerful device of this kind [2, 5-8]. The main parameters of QSPA Kh-50 hydrogen plasma streams were as follows: ion impact energy about 0.4 keV, maximum plasma pressure 3.2 bar, and the plasma stream diameter 18 cm. The plasma pulse shape is approximately triangular, pulse duration 0.25 ms and the heat loads varied in the range (0.2…2.5) MJ/m$^2$.

A deformed W grade sample delivered from Plansee AG, was used for the plasma load tests. Cylindrical shaped specimens had been a diameter of 12 mm and a height of 5 mm [4]. An electric heater was installed at target's back-side to keep the target temperature in the range $T_0$ = (200…600) °C before plasma pulse. For temperature monitoring a calibrated thermocouple and an infrared pyrometer were used. All targets were exposed to perpendicular plasma stream. The energy density in plasma stream and surface heat load measured with a calorimeter.

Surface analysis was carried out with an optical microscope MMR-4 equipped with a CCD camera and Scanning Electron Microscopy (SEM) JEOL JSM-6390. The so called '$\vartheta$-2$\vartheta$ scans' with X-ray diffraction technique (XRD) of exposed targets were performed using a monochromatic $K_\alpha$ line of Cu anode radiation [7]. Diffraction peaks intensity, their profiles, and their angular positions were analyzed for estimation the macrostrain and the lattice parameters.

## 3. EXPERIMENTAL RESULTS

### 3.1. FEATURES PLASMA-SURFACE INTERACTION IN QSPA Kh-50

In our previous experiments it was demonstrated that tungsten melting threshold under QSPA Kh-50 exposures is (0.56…0.6) MJ/m$^2$. The evaporation onset is estimated as 1.1 MJ/m$^2$ [2]. For combined W-C targets the melting and evaporation was not achieved under the plasma exposures with fixed energy density. Enhanced evaporation of carbon (carbon evaporation threshold (0.4…0.45) MJ/m$^2$) results in additional shielding of tungsten surface by C cloud. It protects W surface from the evaporation even for essentially increased energy density of impacting plasma [6].

Calorimetric measurements demonstrate that even for plasma exposures, which not result in the tungsten melting, the absorbed heat load is not more 60% of the impact plasma energy. The stopped plasma layer, formed from the head of the plasma stream, ceases to be completely transparent for subsequently impacting plasma ions [2, 6]. This layer of cold plasma is responsible for decreasing part of incident plasma energy which is delivered to the surface. In recent studies for inclined exposure of the different targets, diminution of energy density delivered to surface has been observed with decrease of incidence angle (Fig. 1).

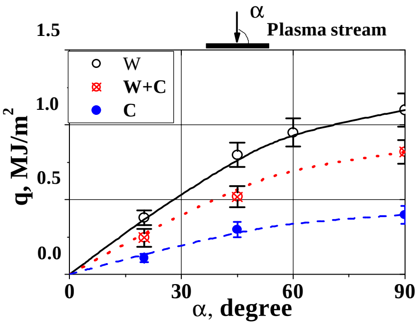

*Fig.1. Heat load to the target surface vs. incidence angle of impacting plasma stream. Plasma stream energy density is 2.4 MJ/m$^2$*

### 3.2. CRACKING THRESHOLDS ANALYSIS

Cracking development is characterized by measured threshold load and threshold target temperature, which determine the existing region of W performance without cracks. The energy threshold for tungsten cracking development is found to be ~0.3 MJ/m$^2$ for QSPA Kh-50 pulse. The Ductile Brittle Transition Temperature (DBTT) is experimentally estimated. The Ductile Brittle Transition (DBT) occurs in the temperature range of 200 °C $\le T_{DBTT} <$ 300 °C. For initial temperature $T_0 >$ 300 °C no major cracks are formed on the exposed surface.

Major cracks network forms only in cases of initial target temperatures below DBTT. Mesh of cells of major crack network is achieved (0.8…1.3) mm for near the center of the spot (Fig. 2).

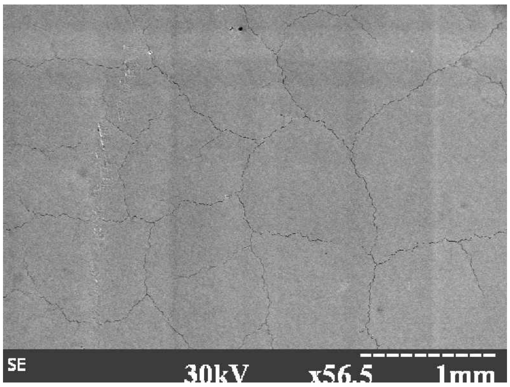

*Fig. 2. SEM image of major crack network on tungsten surface after 5 pulses of 0.45 MJ/m$^2$, $T_0$ = 200 °C*

Intergranular micro-cracks appear after plasma exposition with heat load above melting threshold. Typical cell sizes of intergranular micro-cracks network are 10 to 80 μm. Most of cells are within (10…40) μm, which corresponds to the grain size of this W grade (Fig. 3). The micro-cracks propagate along the grain boundaries completely surrounding the grains. The typical width of intergranular cracks is not exceeded 1 μm. Fine cracks are developed in rather thin surface layer ~ (5…10) μm. Major cracks are much deeper (Fig. 4). Appearance of pores in some regions of surface layer can be caused by expansion of macro-cracks mesh and losses of tungsten grains in result of plasma impacts.

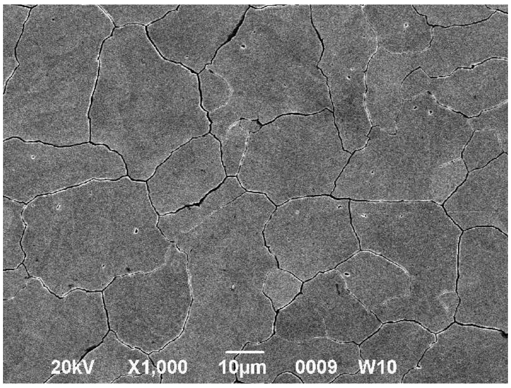

*Fig. 3. SEM image of micro cracks network on tungsten surface after 5 plasma pulses of 0.75 MJ/m$^2$, $T_0$ = 600 °C*

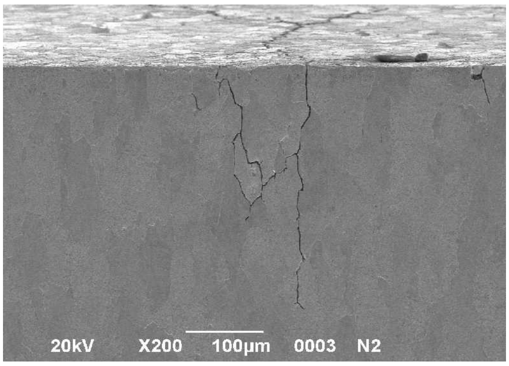

*Fig. 4. Cross-section of tungsten target preheated at $T_0$ = 200 °C and exposed with 10 pulses of 0.75 MJ/m$^2$*

### 3.3. RESIDUAL STRESSES IN TUNGSTEN AFFECTED BY PLASMA STREAMS

The XRD diffraction analysis has confirmed absence of material phases built of impurities. Only W lines on the surface and in deeper layers were observed. This is important indication of plasma and target purity.

Plasma irradiation results in a symmetrical tensile stress in thin subsurface layer. Rather weak dependencies of residual stresses on the initial temperature and the irradiation dose were obtained for plasma exposures with heat load of 0.2 MJ/m$^2$. The values of residual stresses ≈ 160…180) MPa.

The residual stress of 314 MPa appears in the surface preheated to $T_0$ = 200 °C and exposed by single plasma pulse of 0.45 MJ/m$^2$. If $T_0$ overcomes the DBTT point the stress drops down to 250 MPa. Increasing the number of plasma pulses leads to some saturation of residual stress which does not depend on $T_0$ (Fig. 5).

Single pulse irradiation of W surface preheated at 200 $^0$C with the heat load above the melting threshold 0.75 MJ/m$^2$ led to the absolute maximal residual stress 390 MPa. Preheating of tungsten at the temperature larger than 400 $^0$C causes the saturation of the residual stress in tungsten on the level of 300 MPa. In the course of 5 plasma pulses the residual stress linearly decreases from

362 MPa down to 200 MPa with rising of initial surface temperature from 200 up to 600 $^0$C (see Fig. 5).

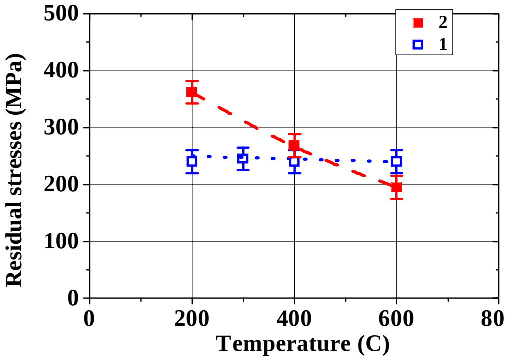

*Fig.5. Residual stresses in tungsten targets exposed with five QSPA plasma pulses of 0.45 MJ/m$^2$ (1) and 0.75 MJ/m$^2$(2) versus the initial bulk temperature*

## 4. CONCLUSIONS

1. Features of tungsten erosion under repetitive plasma heat loads up to 1.1 MJ/m$^2$ lasting 0.25 ms, which are relevant to ITER Type I ELMs, has been investigated.
2. Influence of target inclination and neighborhood W and C as divertor components on the material response to the repetitive plasma heat loads was analyzed.
3. The energy threshold for cracking development is found to be ~0.3 MJ/m$^2$ for plasma pulse of 0.25 ms duration with triangular pulse shape.
4. The Ductile-to-Brittle Transition occurs in the temperature range of 200 °C $\le T_{DBTT} <$ 300 °C. For initial target temperature $T_0 > 300$ C no major cracks are formed on the exposed surface.
5. Major cracks network forms only if initial target temperature is below DBTT. The intergranular micro-cracks network appears under heat loads above the melting threshold.
6. Performed measurements demonstrate that the residual stress does not depend practically on initial target temperature and it significantly grows with increasing thermal loads.

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## ТЕСТИРОВАНИЕ МОЩНЫМИ ПОТОКАМИ ПЛАЗМЫ МАТЕРИАЛОВ ДИВЕРТОРА ITER В УСЛОВИЯХ, СООТВЕТСТВУЮЩИХ ELM, НА КСПУ Х-50

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Выполненные исследования плазменно-поверхностного взаимодействия включали измерения плазменной энергии, достигающей поверхности материалов, и определение порога хрупкого разрушения вольфрама при периодически повторяющихся плазменных нагрузках, подобных ELM в ITERе, на КСПУ Х-50 плазменными импульсами с плотностью энергии в потоке до 2,5 МДж/м$^2$ и длительностью 0,25 мс. Энергетический порог хрупкого разрушения вольфрама составляет ~0,3 МДж/м$^2$. Температура вязкохрупкого перехода (ТВХП) экспериментально оценена для сорта вольфрама, выбранного для ITERа. Сетка макротрещин (размер ячейки до 1,3 мм) формируется только в случаях, когда начальная температура мишени ниже ТВХП. Сетка межгранульных микротрещин (размер ячеек соответствует размеру зерна) появляется при тепловых нагрузках выше порога плавления.

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## ТЕСТУВАННЯ ПОТУЖНИМИ ПОТОКАМИ ПЛАЗМИ МАТЕРІАЛІВ ДИВЕРТОРА ІТЕР В УМОВАХ, ЩО ВІДПОВІДАЮТЬ ELM, НА КСПП Х-50

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Виконані дослідження плазмово-поверхневої взаємодії включали вимірювання енергії плазми, що досягає поверхні матеріалів, і визначення порогу крихкого руйнування вольфраму при плазмових навантаженнях подібних ELM в ІТЕРі, що періодично повторюються, на КСПП Х-50 плазмовими іпульсами з густиною енергії в потоці до 2,5 МДж/м$^2$ і тривалістю 0,25 мс. Енергетичний поріг крихкого руйнування вольфраму складає ~0,3 МДж/м$^2$. Температура в'язкокрихкого переходу (ТВХП) експериментально оцінена для сорту вольфраму, вибраного для ІТЕRу. Сітка макротріщин (розмір осередку до 1,3 мм) формується тільки у випадках, коли початкова температура мішені нижче ТВХП. Сітка міжгранульних мікротріщин (розмір осередків відповідає розміру зерна) з'являється при теплових навантаженнях вище порогу плавлення.