Properties of Tungsten Vapor Plasma Formed at Conditions Relevant to Transient Events in ITER at Plasma Gun Facility MK-200UG

Poznyak I.M.[1, 2, a)], Toporkov D.A.[1, b)], Karelov S.V.[1, c)],
Safronov V.M.[1, 2, 3, d)], Arkhipov N.I.[1, 3, e)]

[1]*State Research Center of Russian Federation "Troitsk Institute for Fusion and Innovation Research",*
Russia, Moscow, Troitsk, Pushkovih str., 12.
[2]*Moscow Institute of Physics and Technology, Russia, Moscow reg., Dolgoprudny, Institutskiy per., 9.*
[3]*Project Center ITER, Russia, Moscow, pl. Akademika Kurchatova, 1.*

[a)]Corresponding author: teufida@gmail.com
[b)]toporkov@triniti.ru
[c)]karscer1@mail.ru
[d)]v.safronov@iterrf.ru
[e)]n.arkhipov@iterrf.ru

Abstract. This paper presents experimental results obtained at pulsed plasma gun facility MK-200UG. Tungsten targets were irradiated by hot magnetized hydrogen plasma streams. Experimental conditions (heat loads, magnetic field, impact ions energy) were relevant to Edge Localized Modes (ELM) and mitigated disruptions in ITER. Primary attention has been focused on investigation of tungsten plasma formation, its properties and transport along the magnetic field lines. GGG At the plasma pulse duration of $\tau = 50$ us, EUV radiation of the tungsten plasma is detected at the plasma heat load $q = 0.3$ MJ/m^2. An effective thickness of the near-surface plasma layer, which emits in the EUV spectral band, is about $\Delta x = 4 – 5$ cm. Weak EUV radiation of tungsten is detected up to the distance of $x \approx 20$ cm. The target plasma contains mainly tungsten ions of ionization state W^{+7} and above. It was found that the tungsten plasma velocity is about $v \approx 2 \cdot 10^6$ cm/s for a wide range of the plasma heat loads.

INTRODUCTION

Tungsten is foreseen presently as the main candidate armour material for the divertor targets in ITER. During the transient processes, such as ELMs and disruptions, the divertor armour will be exposed to the high plasma loads [1], which can cause a severe erosion of the armour materials. Erosion reduces lifetime of the divertor components and leads to production of impurities, which can penetrate into the hot fusion plasma causing its radiative cooling. Properties of the eroded materials are critically important for understanding of plasma-wall interaction processes, which occurs during transient events in ITER.

The plasma heat loads expected in the ITER transient events are not achieved in the existing tokamak machines. Therefore, behavior of candidate armour materials is studied by use of powerful plasma guns [2-4] and e-beam facilities [5,6], which are capable to simulate, at least in part, the loading condition of interest. The present work refers to experimental study of tungsten armour. The tungsten targets have been tested by intense hydrogen plasma streams at the pulsed plasma gun MK-200UG [2]. The plasma heat fluxes were relevant to ITER ELMs and mitigated disruptions. Primary attention has been focused at investigation of impurity formation due to tungsten evaporation, properties of tungsten plasma and its transport along the magnetic field lines.

EXPERIMENTAL TECHNIQUE

MK-200UG Facility

MK-200UG facility consists of a pulsed plasma gun, 9.5 m length drift tube and a target chamber (“Fig. 1”). The tungsten sample is placed in the target chamber of 30 cm diameter and 50 cm length. The chamber is filled with a longitudinal magnetic field varying in the range of B = 0.5 – 1.6 T.

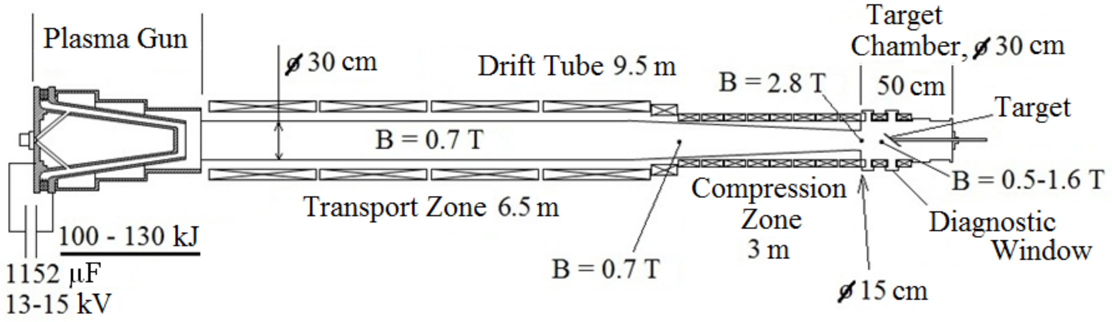


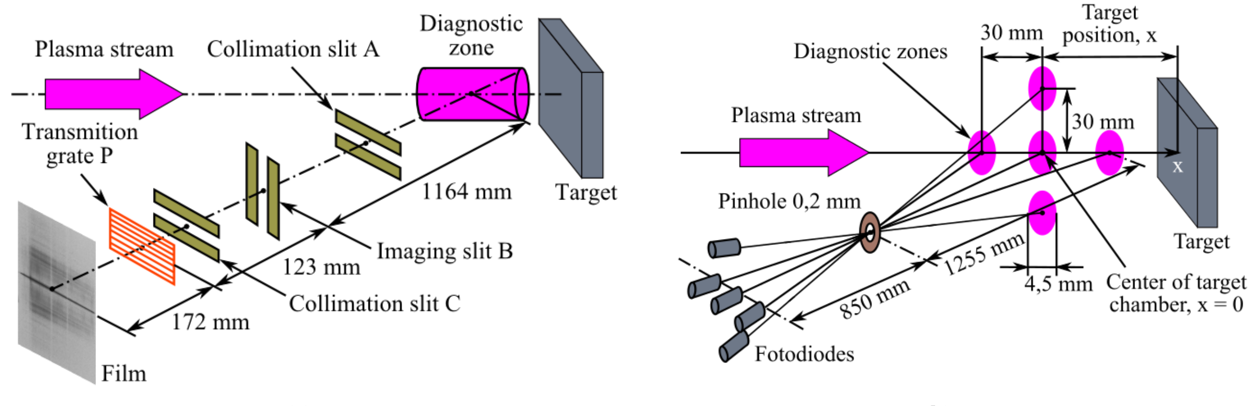
FIGURE 1. Scheme of MK200-UG facility

The targets are tested by magnetized hydrogen plasma streams with heat load Q = 0.2 – 1.2 MJ/m^2 and pulse duration τ = 50 μs. The plasma heat load Q varies by changing the plasma density in the range n = (0.1 – 2)×10^{20} m^{-3} while the impact ion energy remains practically unaltered E_i = 2 – 3 keV. Plasma pressure varies in the range p = 0.02 – 0.5 bar, diameter of the plasma stream – d = 0.06 – 0.1 m.

Plasma stream parameters such as heat flux w = Q/τ, impact ion energy Ei, density n, pressure P, and negligible percentage of impurities (<1%) are close to the expected ones in ITER during the transient processes. The disadvantage of MK-200UG facility is short duration τ of the plasma pulse. Because of the short pulse duration, the facility is not suited for longevity test of the divertor materials. Nevertheless, it is quite suitable to simulate the initial stage of the ITER transient events under rather realistic plasma parameters. These experimental data need for development and validation of appropriate numerical models [7-9].

Diagnostics

Three tungsten targets were used in the experiment. The first one is a cylinder of 1 cm thickness and 2 cm diameter. Plasma stream can flow around this target. The second and third targets are “large” tungsten plates (145x80 mm and 120x60 mm), which fully overlap the plasma stream. One of the “large” targets was made of tungsten produced by POLEMA JSC (Russia, Tula), specially for ITER divertor armour.



(a)

(b)

FIGURE 2. TGIS (a) and pinhole camera (b) measurements schemes

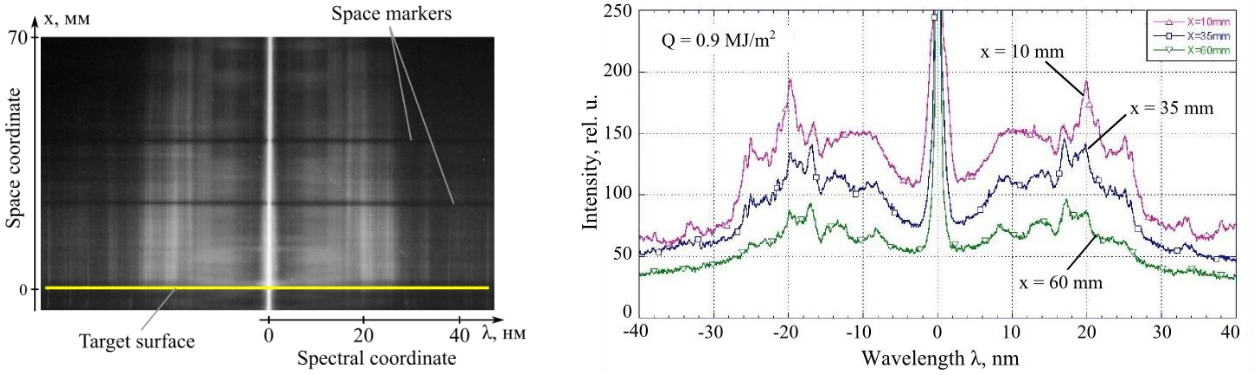
All targets are equipped by the thermocouples. Energy absorbed by the material Q_{abs} is determined from the measured target heating ΔT, known mass m of the target and it's specific heat c: $Q_{abs} = cm\Delta T$. Full plasma stream energy is measured using a “small” cylindrical calorimeter of 2 cm diameter and 7 cm length. The calorimeter is equipped by the thermocouples, which allows to measure increase of the wall temperature after the plasma exposure.

EUV transmission grating imaging spectrograph (TGIS, “Fig. 2a”) is used to investigate the tungsten plasma radiation in spectral interval $\Delta\lambda = 1 – 40$ nm. In the present experiment, spectral dispersion was 1.8 nm/mm, spectral resolution 0.2 nm and spatial resolution about 2 mm.

A pinhole camera equipped with AXUV-photodiodes (“Fig. 2b”) is used to study the tungsten plasma formation and dynamics. These photodiodes are sensitive in a wide spectral range $\Delta\lambda = 0.02 – 1100$ nm. Full energy of near surface plasma radiation was measured by means of a bolometer.

EXPERIMENTAL RESULTS

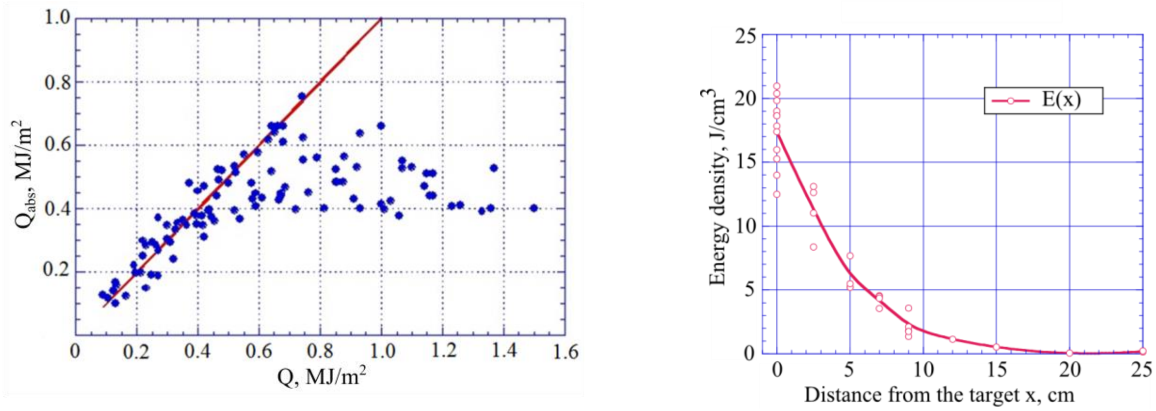
According to the performed spectral measurements the tungsten spectral lines are not detected at plasma loads $Q < 0.35$ MJ/m^2. Increase of the load to $Q = 0.5$ MJ/m^2 results in abrupt intensification of the EUV radiation and essential change of the spectrum shape. It means that at such a plasma load the intense evaporation of tungsten begins. Typical EUV spectrogram of tungsten plasma is shown in “Fig. 3a” (heat load $Q = 0.9$ MJ/m^2).



(a) (b)

FIGURE 3. Typical near-surface plasma spectrogram (a) and spectra at various distances from the target (b)

Radiation of vapor plasma lies in the spectral range $\lambda < 30$ nm with a maximum at $\lambda = 16 – 20$ nm (“Fig. 3b”). Comparison of the measured tungsten spectra with the calculated one shows that the near-surface plasma contains the tungsten ions ionized up to W^{+7} and above [10].



(a) (b)

FIGURE 4. Results of calorimetric measurements (a), spatial distribution of tungsten plasma radiation (b)

Figure 4a shows the results of calorimetric measurements. At heat loads $Q > 0.4$ MJ/m^2 the absorbed energy Q_{abs} is smaller than the energy of the incoming plasma stream. It means that under such heat loads, an intense evaporation of the target material starts up and the shielding layer is formed in front of the exposed target surface.

An expansion velocity V of the tungsten plasma is evaluated by means of time-of-flight method, by measuring the time delay between t AXUV's signals located at various distances from the target. In the present experiment the velocity was about $V \approx 2 \cdot 10^6$ cm/s. It does not depend on plasma heat load Q in the investigated range of Q.

According to the performed pinhole measurements, EUV radiation from the near surface zone is not detected at plasma heat loads $Q < 0.3$ MJ/m^2. Radiation was detected at $Q = 0.35$ MJ/m^2 and higher. Radiation intensity I(x) at varying distance x from the target is shown in "Fig. 4b". I(x) reduces quickly with the distance: it falls tenfold at $x \approx 10$ cm. Nevertheless, the tungsten radiation is reliably detected by AXUV diodes up to the distances 15 – 20 cm.

SUMMARY

Tungsten targets were tested by intense plasma streams at plasma gun facility MK-200UG under the plasma heat fluxes relevant to ELMs and mitigated disruptions in ITER. Tungsten impurity formation and dynamics have been studied. It's shown that at the plasma pulse duration of $\tau = 50$ us, EUV radiation of the tungsten plasma is detected reliably at the plasma heat load $q = 0.3$ MJ/m^2. The EUV intensity of the target plasma radiation has a maximum close to the surface and reduces with a distance. An effective thickness of the near-surface plasma layer, which emits in the EUV spectral band, is about $\Delta x = 4 – 5$ cm. However a weak EUV radiation of tungsten is detected up to the distance of $x \approx 20$ cm. Comparison of the measured tungsten spectra with the calculated spectral data shows that the target plasma contains mainly tungsten ions of ionization state W^{+7} and above. It was found that the tungsten plasma velocity is about $v \approx 2 \cdot 10^6$ cm/s for a wide range of the plasma heat loads. Based on the obtained experimental data it would be too early to conclude that the tungsten impurities in ITER will be localized near the divertor plates and they can't penetrate into the main tokamak chamber. Additional investigation should be carried on.

ACKNOWLEDGMENTS

We are grateful Dmitry Glazunov, Nikolay Litunovsky and Alexey Makhankov from Efremov Institute (Russia, St. Petersburg), Laboratory of Plasma Facing (high heat flux) components, STC "Sintez", who provided us ITER-like tungsten for one of the targets.

REFERENCES

[1]. G. Federici et al., Plasma Phys. Control. Fusion **41**, 1523 (2003).
[2]. N. I. Arkhipov et al., J. Nucl. Mater. **233-237**, 686 (1996).
[3]. V. I. Tereshin et al., J. Nucl. Mater. **313-316**, 767 (2003).
[4]. V. Belan et al., J. Nucl. Mater. **233-237**, 763 (1996).
[5]. V. T. Astrelin et al., Nucl. Fusion **37**, 1541 (1997).
[6]. J. Linke et al., J. Nucl. Mater. **212-215**, 1195 (1994).
[7]. I. S. Landman et al., J. Nucl. Mater. **337-339**, 761 (2005).
[8]. S. Pestchanyi and I. Landman, Fusion Eng. Design. **81**, 275 (2006).
[9]. B. Bazylev et al., Physica Scripta **T111**, 213 (2004).
[10]. S. Pestchanyi et al., J. Nucl. Mater. **438**, S459 (2013).