EXPERIMENTAL STUDY OF TUNGSTEN IMPURITY FORMATION AND DYNAMICS AT PLASMA GUN FACILITY MK-200 UNDER CONDITION RELEVANT TO TRANSIENT EVENTS IN ITER

I.M. Poznyak, N.I. Arkhipov, S.V. Karelov, V.M. Safronov , D.A. Toporkov

State Research Center of Russian Federation Troitsk Institute for Innovation and Fusion Research, 142190 Troitsk, Moscow, Russia

Tungsten targets were irradiated by intense plasma streams at plasma gun facility MK-200UG. The targets were tested by plasma loads relevant to Edge Localised Modes (ELM) and mitigated disruptions in ITER. Primary attention has been focused on investigation of impurity formation due to tungsten evaporation and on investigation of impurity transport along the magnetic field lines.

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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. The properties of the eroded materials are critically important to analysis of tokamak-reactor.

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 plasma streams at the pulsed plasma gun MK-200UG. The targets were examined by plasma heat fluxes relevant to ITER ELMs and mitigated disruptions. Primary attention has been focused at investigation of impurity formation due to tungsten evaporation and on investigation of impurity transport along the magnetic field lines.

1. EXPERIMENTAL TECHNIQUE

1.1. MK-200UG FACILITY

At MK-200UG facility, the targets are tested by magnetized hydrogen plasma streams with heat load $Q = 0.2 \ldots 1.2$ MJ/m^2 and pulse duration $\tau = 0.05$ ms. The plasma heat load Q varies by changing the plasma density in the range $n = (0.1 \ldots 2) \times 10^{20}$ m^{-3} while the impact ion energy remains practically unaltered $E_i = 2 \ldots 3$ keV. Plasma pressure varies in the range $P = 0.03 \ldots 0.5$ bar. Diameter of the plasma stream – $d = 0.06 \ldots 0.1$ m. Plasma/target interaction occurs in the magnetic field $B = 0.5 \ldots 2$ T.

Plasma stream parameters such as heat flux $w = Q/\tau$, impact ion energy E_i, 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 small duration τ of the plasma pulse. Because of the small 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].

1.2. DIAGNOSTICS

The targets to be tested are equipped by the thermocouples. Energy absorbed by the target q_{abs} is determined from the measured target heating ΔT, known mass m of the target and it's specific heat c: $q_{abs} = cm\Delta T$.

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

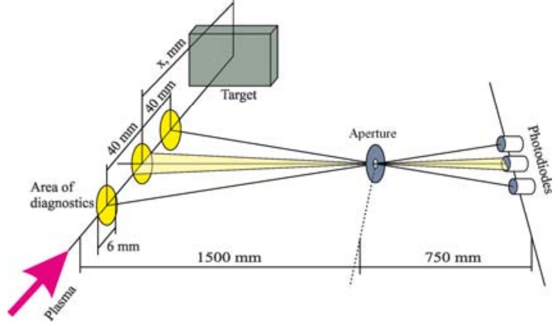

Fig. 1. Pinhole camera equipped AXUV photodiodes

A pinhole camera equipped AXUV-photodiodes used to study the tungsten impurity formation and dynamics (Fig. 1). Photodiodes are sensitive in range $\Delta\lambda = 0.02 \ldots 1100$ nm. A part of experiments were carried out with a filter – a thin aluminum foil. The foil has a transparency window $\Delta\lambda = 17 \ldots 80$ nm.

2. EXPERIMENTAL RESULTS

2.1. EUV SPECTROSCOPY

At low plasma loads $Q < 0.35$ MJ/m^2 tungsten spectral lines are absent on spectrograms. Increase of the load to $Q = 0.5$ MJ/m^2 results in the abrupt intensification of the EUV radiation and in the essential change of the spectrum shape. It means that at such plasma load the intense evaporation of tungsten begins.

Typical EUV spectra of tungsten plasma is shown on Fig. 2. Radiation lies in the spectral range $\lambda < 30$ nm with a maximum amplitude at $\lambda = 16 \ldots 20$ nm. A comparison of the measured tungsten spectra with the calculated spectral data shows that the target plasma contains tungsten ions ionized up to W^{+7} and above [10].

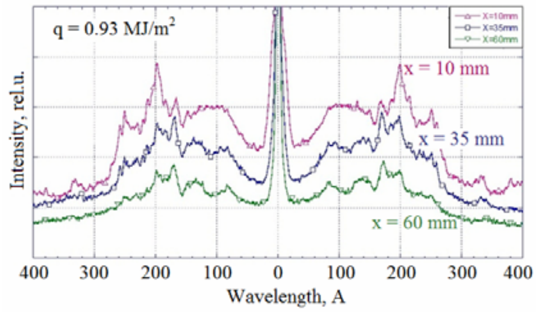

Fig. 2. EUV spectra of tungsten plasma

Fig. 3 shows the intensity I(x) of tungsten plasma radiation at varying distance x from the target. The intensity I(x) was determined by integration of EUV radiation over the spectral interval λ = 5…30 nm.

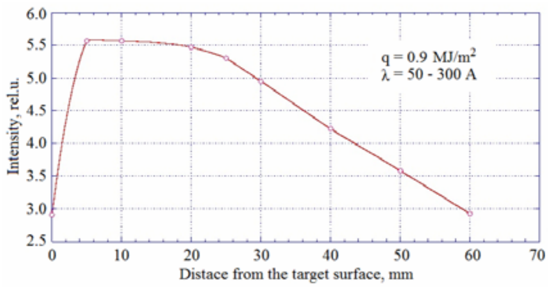

Fig. 3. Spatial distribution of EUV radiation of tungsten plasma

An effective thickness of the emitting layer is about Δx ≈ 5 cm. The intensity of the tungsten radiation I(x) reduces quickly with the distance x. Meanwhile the impurity radiation is reliably detected at the distances larger than x = 10 cm from the target surface.

2.2. IMPURITY DYNAMICS

The pinhole camera equipped by AXUV diodes (see Fig. 1) enable to investigate the tungsten plasma dynamics.

The expansion velocity V of the tungsten impurities is evaluated by means of time-of-flight method, by measuring the time delay between the rising edges of the AXUV's signals (Fig. 4). In the present experiment the velocity is about $V \approx 2 \cdot 10^6$ cm/c. It does not depend on plasma heat load in the investigated range of the loads.

The AXUV-diodes diagnostic is more sensitive than TGIS-spectrograph. Therefore the diodes allow to detect the tungsten radiation at smaller plasma loads. Thus it was found that the energy threshold of tungsten evaporation is Q = 0.35 MJ/m^2 rather than Q = 0.5 MJ/m^2 according to the EUV spectroscopy.

Fig. 5 shows the spatial distribution of the tungsten plasma radiation. One can see that the radiation reduces monotonically with a distance from the surface. At the distances x ≈ 0…10 cm the impurity radiation falls tenfold. Due to a high sensitivity the applied diagnostic makes possible to detect the tungsten radiation up to x ≈ 15…20 cm.

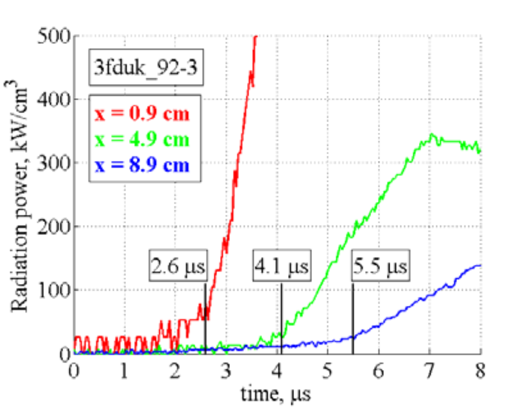

Fig. 4. Rising fronts of AXUV's signals at various distances from the target surface

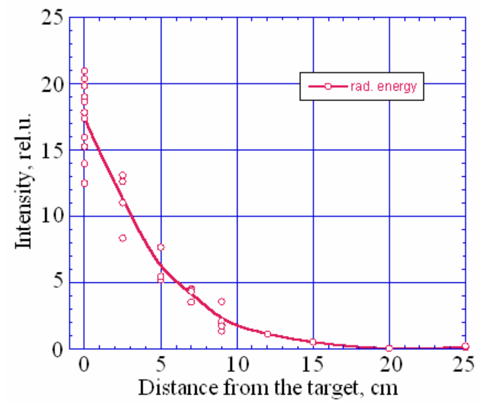

Fig. 5. Spatial distribution of tungsten plasma radiation, AXUV

Fig. 6 and Fig. 7 show the spatial distribution of the tungsten plasma radiation which is obtained by use of the open pinhole and by the pinhole with a filter. A thin Al foil of 0.65 μm thickness was applied as filter. Such foil have transparency window in the wavelength range Δλ = 17…80 nm.

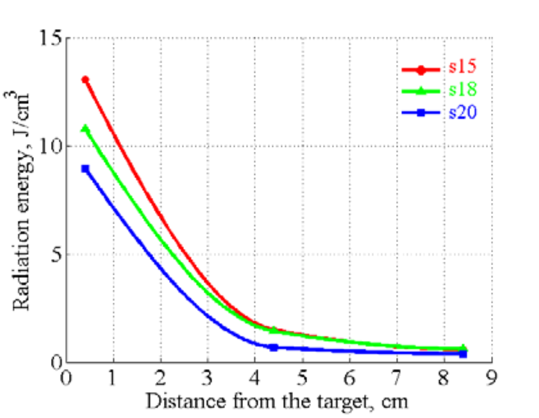

Fig. 6. Spatial distribution of tungsten plasma radiation, open pinhole

In both cases the intensity of impurity radiation decreases monotonically and rapidly from the target surface. At a distance of x ≈ 5 cm it falls by one order of magnitude.

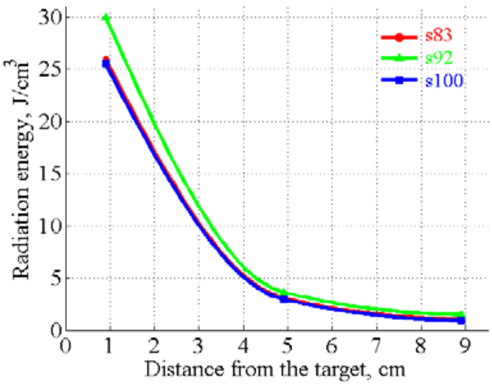

Fig. 7. Spatial distribution of tungsten plasma radiation, Al foil used as filter

Comparing the obtained data one can conclud that the basic spatial features of the radiation distribution are defined by the radiation of the spectral range λ = 17…80 nm. The radiation of the range λ = 5…17 nm belongs to the tungsten ions which have greater ionization stage than the ions at λ = 17…80 nm and do not change the typical character of the spatial dependences.

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 τ = 0.05 ms, EUV radiation of the tungsten plasma was reliably detected 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 Δx = 4…5 cm. However a weak EUV radiation of tungsten is detected up to the distance of x ≈ 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 ≈ 2·10^6 cm/s for a wide range of the incoming plasma heat loads.

The basic spatial features of the radiation distribution are defined by the radiation in the spectral range λ = 17…80 nm.

Based on the obtained experimental data it would be too early to conclude that the tungsten impurities will be localized near the divertor plates and they can't penetrate into the main tokamak chamber. Additional investigation should be carried on.

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ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ФОРМИРОВАНИЯ И ДИНАМИКИ ПРИМЕСЕЙ ВОЛЬФРАМА НА ПЛАЗМЕННОЙ УСТАНОВКЕ МК-200UG В УСЛОВИЯХ, ХАРАКТЕРНЫХ ДЛЯ ПЕРЕХОДНЫХ ПРОЦЕССОВ В ITER

И.М. Позняк, Н.И. Архипов, С.В. Карелов, В.М. Сафронов, Д.А. Топорков

Мишени из вольфрама были подвергнуты воздействию интенсивных потоков плазмы на плазменном ускорителе МК-200UG. Испытания проводились при плазменных нагрузках, характерных для ELM'ов и ослабленных срывов в ITER. Исследованы процессы формирования примесей вольфрама за счет испарения материала мишени и их распространения вдоль силовых линий магнитного поля.

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ФОРМУВАННЯ І ДИНАМІКИ ДОМІШОК ВОЛЬФРАМУ НА ПЛАЗМОВІЙ УСТАНОВЦІ МК-200UG В УМОВАХ, ХАРАКТЕРНИХ ДЛЯ ПЕРЕХІДНИХ ПРОЦЕСІВ В ITER

І.М. Позняк, Н.І. Архіпов, С.В. Карелов, В.М. Сафронов, Д.А. Топорков

Мішені з вольфраму були піддані впливу інтенсивних потоків плазми на плазмовому прискорювачі МК-200UG. Випробування проводилися при плазмових навантаженнях, характерних для ELM'ів і послаблених зривів в ITER. Досліджено процеси формування домішок вольфраму за рахунок випаровування матеріалу мішені і їх поширення уздовж силових ліній магнітного поля.