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Heat load to a tantalum–tungsten twin-test-limiter and the effect to high-Z core plasma concentration of TEXTOR-94

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Abstract

The high-Z impurity concentration of tungsten (W) and tantalum (Ta) released from a twin-test-limiter half made of W and the other half made of Ta was investigated by inserting the twin-test-limiter into the edge plasmas of the TEXTOR-94 tokamak. To study the spectra of W and Ta in the extreme ultraviolet (XUV) range, these high-Z materials were introduced into the plasma by a laser blow-off technique. The quasi-continuum spectrum near 5 nm by pure Ta shifted about 0.2 nm to the longer wavelength side than that by pure W. The intensities were about the same for both material for the identical discharge parameters. The increment in temperature for the Ta limiter facing the ion drift side was about 1.4 times higher than that of W for identical plasma exposure conditions. The larger increase in temperature can be quantitatively explained by a smaller thermal conductivity of Ta. In the test-limiter experiment, the position of the peak in the XUV spectrum was unaffected by the orientation of the limiter, which corresponded to an equal influence of the particle emissions from both sides of the limiter.

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1. Introduction

High-Z materials like tungsten (W) and molybdenum (Mo) are candidate materials for plasma facing materials (PFMs) in future fusion devices because of their low erosion rate and high melting point [1,2]. The impacts upon the plasma performance due to impurity particles as the PFM have been investigated at ALCATOR-C-mod, ASDEX-U, and TEXTOR-94 [3–9], and it was shown that high-Z accumulation due to sputtering by deuterium and impurity ions was not serious. The relatively smaller impacts upon the plasma performance by the high-Z material usage can be partly due to the impurity screening effects arising from the prompt-redeposition originating from the large Larmor radius and smaller ionization mean free path of the released particles.

Though it was found that the impacts were not as serious as originally anticipated, the disadvantage of high-Z materials causing high power radiation losses from the plasma core occasionally caused the instability leading to disruptions. The spectroscopic investigation of the extreme ultraviolet (XUV) region were found very important in estimating the radiation power loss arising from the high-Z impurity. The spectrum also yielded the

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identification of the concentrations for the charge states of high-Z ions [10,11]. Especially, quasi-continuum spectra of W around 5 nm have been extensively investigated in tokamaks [12–16]. Many other high-Z metals were also observed and identified except for Ta.

Tantalum (Ta) has one atomic number less than W and has similar particle reflection properties. However, its work function is lower than W and the thermal conductivity substantially lower than that of W; hence, it can be a good sample material to study the influence of the particle release upon these physical parameters. In this study, a Ta/W twin-test-limiter has been exposed to the edge plasma in TEXTOR-94 to study the impurity concentrations of these high-Z impurities in the plasma core. The spectra in the XUV region of the radiation were investigated with a grazing incidence spectrometer. In order to distinguish Ta quasi-continuum spectra from that of W, laser blow-off experiments have been also carried out.

2. Experimental setup

The TEXTOR-94 tokamak has a 175 cm major radius. In normal operation its minor radius is determined at 46 cm with an ALT-II toroidal belt limiter made of graphite. Discharge parameters were set to the usual TEXTOR operation conditions. The toroidal magnetic field was 2.25 T and the plasma current was adjusted from 334 to 491 kA. The plasma can be heated with simultaneous neutral beam injection with 1.4 MW of power.

A twin-test-limiter, half made of W and the other half made of Ta, was put into the plasma edge from the top of the torus at a position of 46.5 cm away the plasma center. The dimensions of the test limiter are 120 and 80 mm in toroidal and poloidal directions, respectively, and it has a 70 mm spherical radius at the top surface facing the plasma. The temperature distribution of the limiter surface was observed by a CCD camera attached with an IR transmission filter (850–1100 nm). A laser blow-off system was used to inject Ta and W into the plasma to observe the spectra of each material in the XUV wavelength region. The system can provide about 4–5 × 10^{16} atoms per laser shot.

The grazing incidence XUV spectrometer installed in TEXTOR-94 can detect the XUV radiation at wavelength ranges from 0.7 to 8 nm. The optical axis of the spectrometer was aligned to observe the center of the plasma from the outer side of the torus, and the distance between the entrance slit of the spectrometer and the center of the plasma was about 3 m. The width of the 10-mm-height entrance slit was set to 80 μm, and the XUV image of the spectrum was directly formed on the surface of a two-stage multi-channel-plate (MCP) placed at the focal plane of the flat field grating, which had a 50 mm × 30 mm effective area with 2400 grooves/mm. In this series of experiments, the position of the MCP was adjusted so as to measure the XUV spectrum from 1 to 7 nm, and the signals were integrated every 100 ms.

3. Results and discussion

3.1. Confirmation of tantalum spectrum by laser blow-off experiment

When W ions penetrate a plasma with electron temperature near 1 keV, it is known that quasi-continuum spectrum around 4–7 nm are observed, which consists of mainly silver-, palladium- and rhodium-like ions [17–19]. Wavelengths of the line emitted from highly ionized Ta ions with the same isoelectronic sequences are predicted in Refs. [17–19] to be longer than the W ion lines of the same sequences by about 0.15 nm in wavelength. But quasi-continuum spectra from highly ionized Ta ions have not been observed yet. In order to confirm quasi-continuum emitted by pure Ta, XUV spectra of pure Ta and W were observed by laser blow-off thin-film target (1 μm in thickness) in the TEXTOR-94 tokamak. In Fig. 1 the temporal change of the line averaged central electron density (n_e), electron temperature (T_e) and total radiated power (P_{rad}) are shown at pure Ta injection shot with 10 Hz injection rate from $t = 3.5$ to 5.0 s of the discharge. During the laser blow-off injection, the P_{rad} signal increased rapidly after injecting Ta and then decayed with a decaying time. A pure W spectrum was also obtained in the same experimental condition except the repetition rate of the laser blow-off was reduced to 5 Hz and the starting time of the injection was set to $t = 3.3$ s. Although T_e and n_e were slightly reduced by the injection, the plasma parameters were nearly constant at $n_e = 2.5 \times 10^{13}$ cm^{-3} and $T_e = 0.75$ keV from

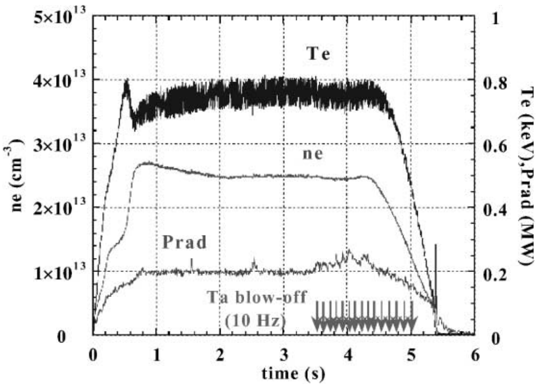

Fig. 1. Temporal evolution of line averaged central electron density (n_e; cm^{-3}), electron temperature (T_e; keV) and total radiated power (P_{rad}; MW) in the laser blow-off experiment.

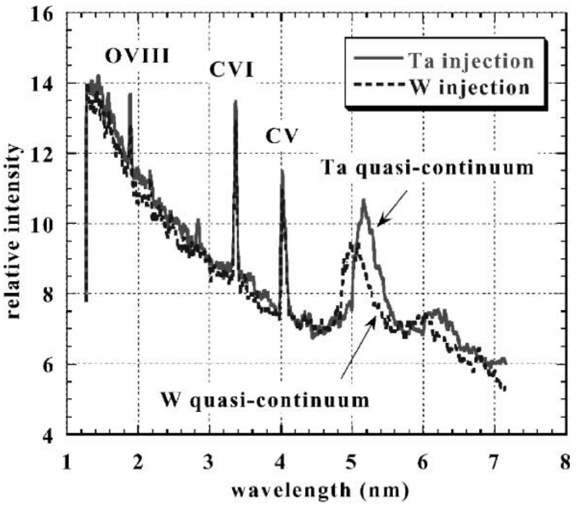

Fig. 2. XUV spectra after Ta and W injection integrated from 3.5 to 4.2 s with spectral lines emitted from highly ionized O and C.

3.5 to 4.2 s. In Fig. 2, Ta and W spectra in the XUV region integrated from 3.5 to 4.2 s are shown. Though quasi-continuum spectra of Ta and W showed two peaks at around 5 and 6 nm, the peaks of pure Ta shifted about 0.2 nm toward the longer wavelength than that of pure W. The quasi-continuum intensity of Ta integrated from 4.6 to 7 nm was about 1.14 times larger than that of W. During $t = 3.5$–4.2 s Ta and W were injected seven pulses and four pulses into the plasma, respectively. The signal after subtracting the back ground in the P_{rad} data was regarded as the contribution due to the injected high-Z particles. Decay times of Ta and W were estimated from the signals in each experiment to be 60 ms for Ta and 85 ms for W on the average. The effect of the particle confinement time, τ, on the spectrum intensity by laser blow-off can be estimated by

$$I = n\tau\left[N - \sum_{i=1}^{N} \exp\left(-i\frac{\Delta t}{\tau}\right)\right], \qquad (1)$$

where I is the intensity of quasi-continuum, n is the number of injected atoms per pulse, N is the number of laser pulses, and Δt is the interval time of the laser pulses. Assuming that the volume of the Ta on the glass plate injected by one laser pulse is the same as that of W, the number of injected Ta atoms per pulse, n(Ta), is 1.15 times larger than n(W). The calculated radiation loss rate of Ta at $T_e = 0.75$ keV is 1.05 times larger than that of W according to the reported value of the cooling rate [20]. All these considerations suggest that the quasi-continuum intensity of Ta is about to 1.10 times larger than that of W, which is in agreement with the measured value obtained in experiments. This fact indicates that when a Ta particle of the same quantity as W is introduced into the plasma, it will cause nearly the same intensity of the quasi-continuum radiation as that of W.

3.2. Heat load to a Ta–W twin-test-limiter

In order to realize a high-heat-load to the twin-test-limiter, the electron density increased up to 6×10^{13} cm^{-3}. In Fig. 3 typical plasma parameters in high-heat-load experiments are shown. The twin-test-limiter was inserted at a position of 46.5 cm from the plasma center in these discharges. Temporal behavior of the surface temperature of the limiter measured by pyrometer in three discharges is shown in Fig. 4. The pyrometer was observing the position 2 cm toward the ion drift side from the boundary between the tantalum and tungsten part of the limiter. The twin-test-limiter was warmed up to 800 K before discharge. The surface temperature of Ta reached up to 2450 K at shot #86795, and it reached up to 1450 K at shot #86792. In the other shot, where W faced the ion drift side, the surface temperature of the W limiter went up to 1450 K. The local n_e and T_e were identical to these shots, and the increment of the surface temperature of W was 40% of that of Ta for the identical discharge condition, which can be explained by the smaller thermal conductivity of Ta. In Fig. 5 temperature distributions along the toroidal direction at $t = 2.5$ s obtained by thermograph measurement are shown. It was found that the temperature of the Ta side was substantially higher than W irrespective of the direction which the limiter faced.

3.3. Quasi-continuum spectra emitted from Ta and W

XUV spectra in ohmic discharges observed by the grazing incidence spectrometer are shown in Fig. 5. Two

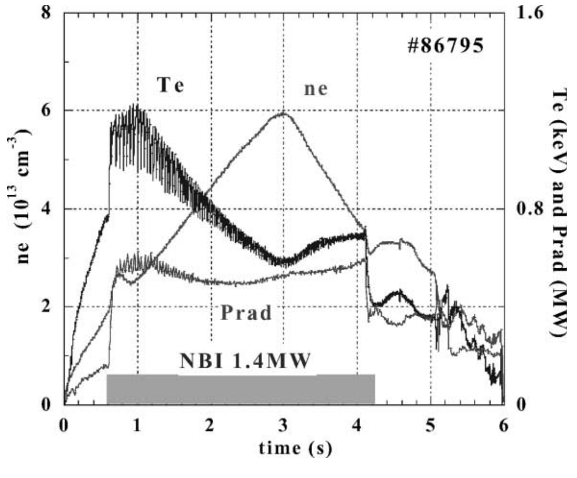

Fig. 3. Typical plasma parameters in high-heat-load discharge of a Ta–W twin-test-limiter experiment.

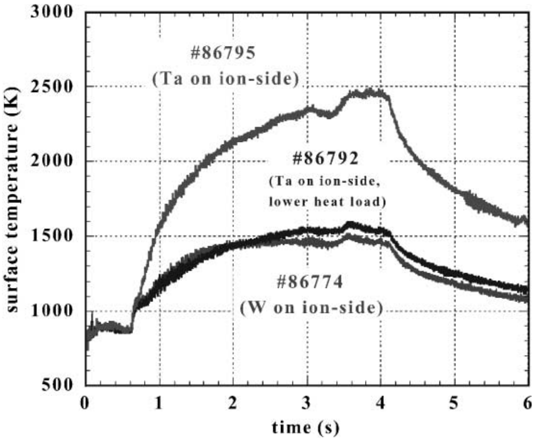

Fig. 4. Temporal behaviors of surface temperature of the limiter measured by the pyrometer in three discharges. In shots #86774 and #86795 heat flux were higher than that in shot #86792.

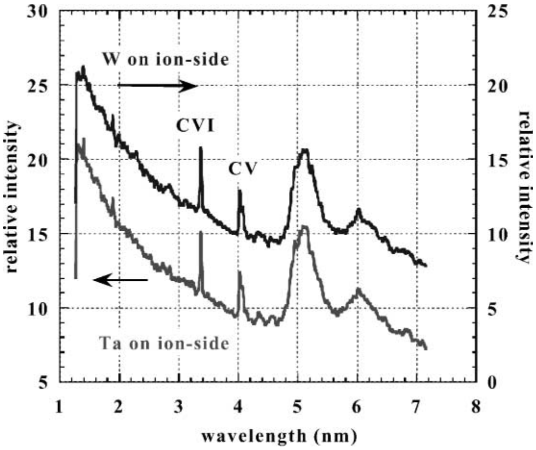

Fig. 5. The XUV spectra in ohmic discharge observed by the grazing incidence spectrometer. Two discharges of Ta and W faced on ion-side were operated under the same condition of n_e and T_e with the laser blow-off experiment (Fig. 1).

discharges of Ta and W faced on the ion-drift-side were operated under the same condition as the laser blow-off experiment. Quasi-continuum spectra could be observed around 5 and 6 nm together with the hydrogen- and helium-like C ion lines. At both discharges of Ta and W facing the ion-drift-side of the limiter, the XUV spectra were almost identical. Quasi-continuum intensities of both discharges are the same and the wavelengths of the peak intensity near 5 nm were 5.1 nm. The quasi-continuum peaks near 5 nm emitted from laser-injected pure Ta and W are 5.0 and 5.2 nm, respectively. Namely, these spectra have the peak wavelength halfway between the wavelengths of the two peaks of pure Ta and pure W. This indicated that the spectra is composed of the contributions from both Ta and W.

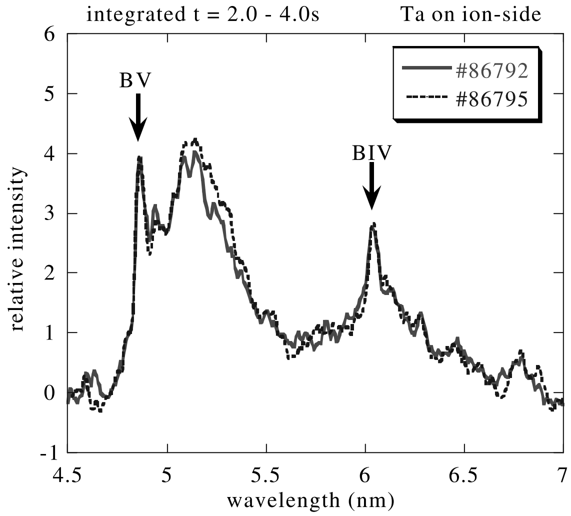

Fig. 6. Quasi-continuum spectra emitted from Ta and W integrated from $t = 2.0$ to 4.0 s in shots #86792 and #86795.

The concentrations of high-Z materials in the plasma core among shots of different heat loads to the limiter were compared with the intensities of XUV spectra for shots indicated in Fig. 3. In Fig. 6, quasi-continuum spectra emitted from Ta and W integrated from $t = 2.0$ to 4.0 s of shots #86792 and #86795 are shown with hydrogen- and helium-like boron ion line intensities subtracted as back ground noise. The two spectra have almost the same shapes and intensities. Intensities of the quasi-continuum after subtracting boron lines in shot #86795 of higher heat flux to the limiter is estimated to be 125% larger than that in shot #86792. The heat flux into each limiter facing the ion drift side can be estimated by fitting the pyrometer signal to a heat transfer calculation by the 3D finite element method. According to the calculation, the heat fluxes about 31 and 13 MW/cm^2 were striking the Ta limiter in shot #86795 and shot #86792, respectively. Although the estimated heat flux to the Ta limiter in shot #86795 was about 2.4 times larger than that of shot #86792, the intensity of the quasi-continuum remained only 1.25 times larger. Namely, the high-Z flux did not increase in proportion to the heat load, which may be attributable to the reduced physical sputtering at a higher heat load due to a reduction in floating potential of the test limiter.

Electrons are emitted from the limiter surface following the Richardson–Dushman equation as a function of the surface temperature. When the temperature of the W side of the limiter is heated to 1500 K, the current density due to thermionic electron emission is estimated to be 4.6×10^{-7} A/cm^2, while the Ta side of the limiter heated up to 2500 K reach a current density of 3.9A/cm^2. According to the edge plasma parameters, $n_e = 9 \times 10^{12}$ cm^{-3} and $T_e = 30$ eV at $r = 46.5$ cm and at $t = 2.5$ s in shot #86795. By using these parameters the floating potential of the limiter can be estimated by a current balance equation. In a point model, the floating potential is estimated to be about −120 V, while at a limiter temperature of 2500 K, it can be reduced to −90 V. This estimation indicated that the floating potential of the limiter could be closer to the plasma potential by about 30 V, which can reduce the physical sputtering.

4. Summary

In order to investigate the thermal response against high-heat-flux, a Ta and W twin-test-limiter experiment was carried out in TEXTOR-94. To distinguish a Ta spectrum from W in the XUV wavelength region, a laser blow-off experiment was conducted. XUV spectra of pure Ta in the wavelength region from 1 to 7 nm were observed. It was confirmed that Ta XUV spectra had a quasi-continuum structure like W, and the wavelength of the peak of quasi-continuum spectrum of Ta shifted to longer wavelength by about 0.2 nm compared to W. From the signal of the total radiated power of Ta and W after the injection, the decay time of high-Z impurities could be estimated. It was found that the decay time of Ta was 60 ms and was faster than 85 ms for W. By taking these decay times into account, it was found that the same quantity of Ta as W caused nearly the same intensity of the quasi-continuum spectrum.

In the twin-test-limiter experiment the surface temperature of the Ta side reached 2450 K, which was about 40% higher than that of W for the identical discharge condition. It was also found that the temperature of the Ta side was always higher than W irrespective of the direction of the limiter. These can be explained by smaller thermal conductivity of Ta than that of W. In discharges of Ta and W facing the ion-drift-side of the limiter, the intensities of the observed XUV spectra were almost identical. The wavelengths at the peak of the quasi-continuum spectrum were unaffected by the orientation of the limiter, which corresponded to an equal influence of particle emissions from both sides of the limiter.

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