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Effect upon the core plasma radiation due to high power laser injection onto C, W and Ta test-limiters in TEXTOR

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Abstract

To investigate the effect due to localized high heat flux pulses onto plasma facing components, light pulses from a ruby laser (15 J in maximum energy, 0.3 ms in duration) were injected onto test-limiter (C, W, and Ta) surfaces immersed in TEXTOR edge plasmas. When the laser pulses irradiated the C limiter surface, the CVI signal from the plasma core increased slightly. In laser injection onto high-Z limiters, the increment of the quasi-continuum around 5 nm of the Ta signal was larger than that of the W signal. With the laser focusing down to 2 mm in diameter, small high-Z particles were found to be ejected from the limiter surfaces which penetrated into the plasma beyond the LCFS. However, the plasma withstood the core cooling due to the radiation loss of high-Z impurity. The amounts of impurities in the core were also estimated by a laser blow-off experiment.

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1. Introduction

Localized high heat flux can cause severe damage to the first wall in a fusion plasma apparatus, and the particle emission due to the damage can trigger a major change in the edge and core plasma parameters. The intense emission of impurity particles lasts for only a short duration [1,2], and the effect to the plasma by a pulsed impurity injection is different from a continuous emission of impurity from the wall. In most Tokamaks diverter plates are exposed to high heat flux for a short time, typically less than 1 ms, triggered by a minor disruption and/or the edge-localized-modes (ELMs) under H-mode discharge conditions [3]. Under exposure to pulsed localized high heat flux, diverter plates made of high-Z materials release impurities into the plasma which may cause intense radiation loss from the core. Therefore it is important to study the impurity release and the successive plasma behavior caused by a pulsed localized high heat flux to a plasma facing component (PFC). To investigate the effect of the localized high heat

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flux pulse onto a high-Z PFC, a system capable of injecting focused laser light onto a test limiter surface immersed in the TEXTOR edge plasmas was assembled and tested.

2. Experimental setup

The minor radius of TEXTOR plasmas was fixed to 46 cm by the main ALT-II toroidal belt-limiter made of graphite. The toroidal magnetic field was 2.2 T, and the discharge current was 340 kA. During the 6s discharge, neutral beam injection (NBI) heated the plasma with a power of 1.8 MW for some operations.

The experiments were conducted with two types of twin-test-limiter. The one was a carbon (C)/tungsten (W) twin limiter, and the other was a tungsten (W)/tantalum (Ta) twin limiter. The limiters were inserted from the top of the torus into the edge plasma at the minor radius position less than 46 cm by the LIM-LOCK system of TEXTOR [4]. The twin-limiters were 12 cm long in the toroidal direction and 8 cm long in the poloidal direction. They have spherical surfaces facing against the plasma with a radius of 7 cm. The limiter could be rotated, and the direction of the twin-limiter was adjusted to keep each material facing either the ion-drift-side or the electron-drift-side. The experimental setup is schematically illustrated in Fig. 1.

In order to provide a localized high-heat-flux pulse onto the surface of the limiter a ruby laser with the maximum energy of 15 J and the pulse length of 0.3 ms was used. The power density of the laser was varied by changing the diameter of the laser light at the surface of the limiter. The laser was directed onto C, W, and Ta in the ion-drift-side of the limiter. Two-dimensional (2D) intensity distributions of line spectra from atoms and ions were observed by CCD cameras equipped with interference filters of 1.5 nm bandwidth at the wavelengths of CII (514.6 nm) and WI (400.8 nm) lines, viewing the limiter from the direction tangential to the top limiter surface. Distributions of spectral line intensities of atoms and ions along the direction of the minor radius were measured by another CCD camera attached to a monochromator. The penetration of the high-Z impurities into the plasma core was monitored by a grazing incidence spectrometer covering the extreme ultraviolet wavelength (XUV) from 1 to 7 nm, where the quasi-continuum spectra of Ta and W together with the line spectra of CV (He-like) and CVI (H-like) were observed.

To investigate the decay times of quasi-continuum spectra of W and Ta after pulsed injections of these impurities, and to correlate the XUV spectrometer signal to the density of high-Z impurity ions in the plasma core, laser blow-off experiments were conducted for both ohmic and NBI heating discharges. The decay times of W and Ta were estimated from those of the total

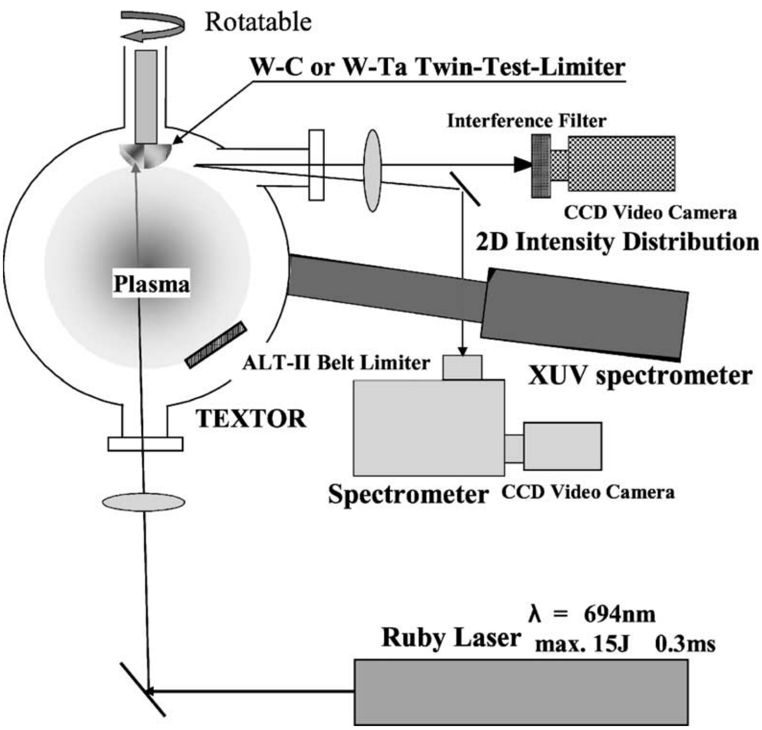

Fig. 1. Schematic view of the experimental set up.

radiated power measured by bolometer arrays. The laser blow-off system can provide about 5×10^{16} atoms per one laser shot.

3. Results and discussion

3.1. Laser injection onto C and W twin limiter surface

The C–W twin limiter surface was irradiated by the ruby laser light of 8 mm-diameter with an energy of 15 J by changing the distance of the limiter from the plasma center shot by shot. The laser injection on the carbon side increased the CII line intensity observed by the monochromator for about 20 ms. The intensity returned to the original value when the limiter was placed 46.5 and 47 cm from the plasma center. However, when the limiter was positioned at $r = 46$ cm the CII intensity kept a higher value after the laser injection at $t = 2.06$ s, as shown in Fig. 2. The 2-D measurement with the band pass filter at the CII line also showed the clear enhancement of CII signal after the laser injection. The formation of a hot spot triggered by the laser pulse is speculated, but it has not been confirmed yet. Meanwhile, the CVI intensity from the plasma core showed little enhancement at any position of the limiter. Carbon atoms should penetrate into the plasma core after the laser injection, but they could have been transported out of the core plasma with a very short confinement time. When the laser of this beam size was injected onto the W side, neither a significant change on the WI line intensity nor W quasi-continuum intensity in the plasma core was observed.

3.2. Laser injection onto W and Ta twin limiter surface

When the laser beams of 12.5 J were focused to a 3 mm diameter spot on the W–Ta twin limiter in ohmic discharges, intensities of quasi-continuum spectra in XUV region increased substantially. Typical results are shown for both sides of the limiter in Fig. 3(a) and (b). It

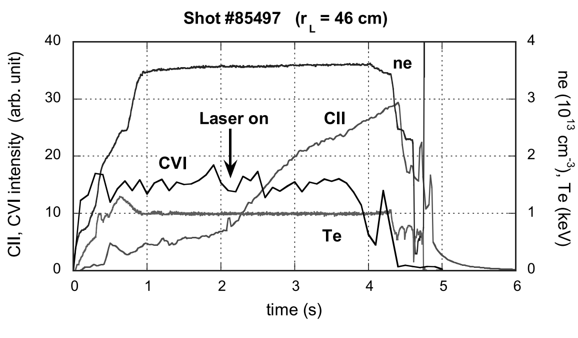

Fig. 2. Temporal changes of CII and CVI intensities with ne and Te under the limiter position of $r_L = 46$ cm.

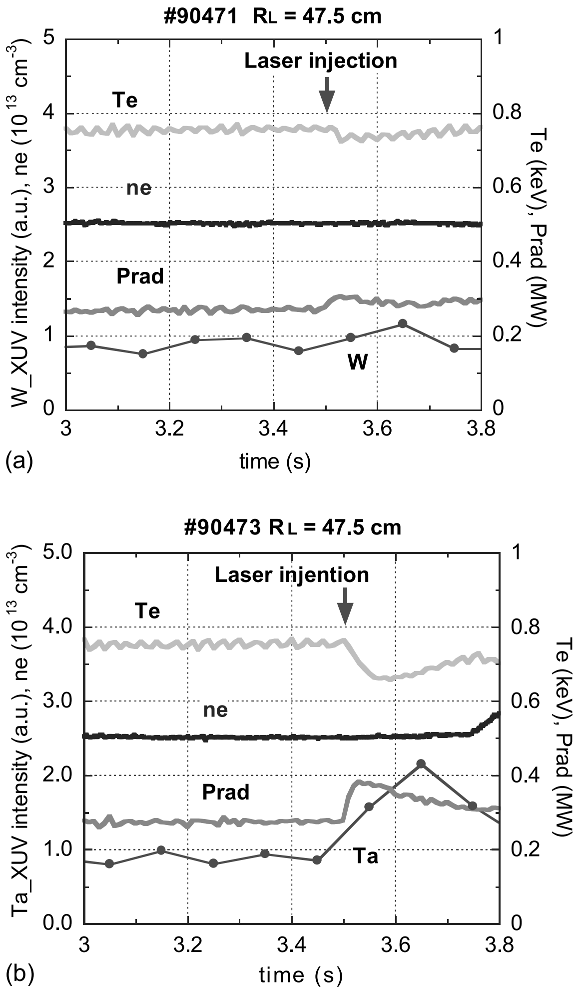

Fig. 3. Temporal change of the quasi-continuum intensities by laser injection onto W (a) and onto Ta (b).

is found that the increment due to laser injection onto the Ta side was larger than that onto the W side. Time behavior of Prad (total radiated power), Te and ne are also shown in Fig. 3. After laser injection onto the Ta surface Prad increased about 0.1 MW, and Te decreased by 70 eV. The changes of Prad and Te were smaller for the case when the laser beam irradiates the W surface than the Ta surface. The amount of released atoms by the laser irradiation could be larger for Ta than for W.

Differences in the XUV spectra before and after the laser injection for the same shot as Fig. 3(b) are shown in Fig. 4 together with an XUV spectrum obtained by pure Ta in the previous experiment [8]. In the previous experiments [5–8], it was confirmed that the wavelength of maximum intensity of Ta quasi-continuum was longer by about 0.2 nm than that of W. Since the two spectra obtained in the present experiments were similar in

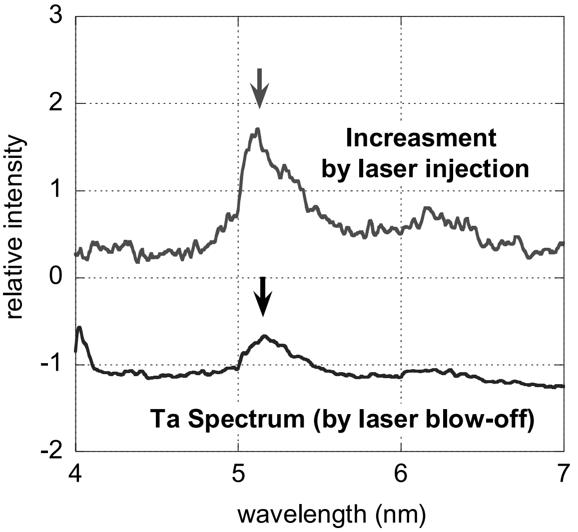

Fig. 4. Increment in spectrum intensity by laser injection onto Ta (upper) obtained by subtracting the spectrum before the laser injection from that after the laser injection. The lower spectrum was obtained by injecting Ta into the plasma by means of the laser blow-off method [8]. The upper spectrum shows the peak at the same wavelength as that of the peak in the lower spectrum.

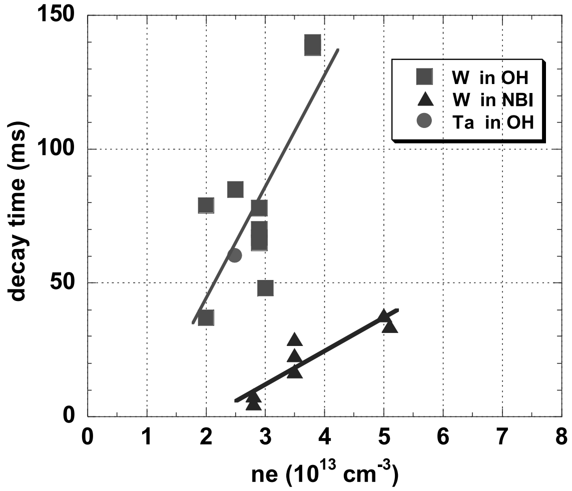

Fig. 5. The dependence of the decay times of W and that of Ta upon electron density. Electron temperature Te varied from 0.6 to 0.8 keV in ohmic, and from 0.7 to 1.1 keV in NBI discharges for different values of ne.

shape, the increment due to laser injection onto the Ta side should be mainly due to Ta.

In NBI discharges with the W–Ta twin limiter, penetration of neither W nor Ta into the plasma core was not observed. Intensity of WI near the limiter increased at the time of the laser injection for a short duration after the laser injection, but no change in Prad and Te was observed. When the laser was focused down to 2 mm in diameter, small high-Z particles were found ejected from the surfaces and penetrated beyond the LCFS. The quasi-continuum signal increased after the penetration of these particles, but the plasma withstood the core cooling due to enhanced radiation from the plasma.

3.3. Decay time measurement by laser blow-off

To investigate the decay times of W and Ta ions in the core plasma, W and Ta thin films (1 μm in thickness) deposited on glass plates were blown off by a pulse Nd-YAG laser. At the moment that W or Ta was injected into the plasma, the Prad signal instantly increased and then exponentially decreased. During the corresponding interval, the intensity of quasi-continuum spectrum of W or Ta increased. The increment of Prad showed the same temporal behavior as that of W or Ta quasi-continuum signal. It can be assumed that the increment of the Prad signals was mainly due to the emission from high charge state ions of injected W or Ta. The decay time was estimated by fitting the temporal evolution of the Prad signal to an exponential function. Because W or Ta was injected for a short duration, the decay time can be assumed equal to the particle confinement time. In Fig. 5, the dependence upon the electron density of the decay times of W and Ta are shown. In both ohmic and NBI discharges decay times are nearly proportional to ne. The decay times in ohmic discharges are about six times longer than those in NBI discharges. This difference in the confinement time explains the stronger penetration of W or Ta for ohmic discharges than NBI discharges. Tungsten decay times have been measured in NBI discharges at various electron densities by Rapp et al. [9]. Their results are in good agreement with ours for NBI discharges.

3.4. Estimation of W and Ta atoms released from the limiter by the laser injection

Under the condition that coronal ionization equilibrium for W ions is valid, calibration of the quasi-continuum of W (47 nm) can be useful to determine the W concentration [10]. Total radiation power, P_w, emitted from W ions can be written by $P_w = n_w \cdot n_e \cdot L_z$, where n_w is the density of W ion, n_e is the electron density and L_z is the calculated radiation loss factor [11]. The quasi-continuum intensity, I_c, observed by the grazing incident spectrometer can be written as $I_c = S \cdot L \cdot n_w \cdot n_e = S \cdot L \cdot P_w/L_z$, where S is a calibration factor, and L is an effective observation length of W ions along the line of sight. When n_w can be deduced from the localized radiation power in the laser blow-off experiment, the calibration factor S can be determined.

Consequently, the tungsten ion density, N_w, in the plasma core is given by

$$N_w = \frac{L_0 \cdot P_{w0}}{I_{c0}} \frac{I_c}{n_e \cdot L},$$

where L_0, P_{w0} and I_{c0} were obtained by the laser blow-off experiment. Assuming L is nearly constant at L_0, N_w can be determined by I_c and n_e. From the laser blow-off experiment, values of $L_0 = 40$ cm, $I_{c0} = 20$ count-pixel, $L_z = 6.0 \times 10^{-25}$ Wcm^3 and $P_{w0} = 1.5 \times 10^{-2}$ W/cm^3 were obtained.

In an ohmic discharge with high power laser injection, N_w is estimated to be about 8×10^8 cm^{-3}, and N_{Ta} is estimated to be about 2×10^9 cm^{-3}. The volume of the torus with the minor radius of 40 cm is about 7×10^5 cm^3. The number of W ions in the plasma center is estimated to be about 6×10^{14} and the number of Ta ions is estimated to be about 1×10^{15}.

4. Summary

When the diameter of the ruby laser light was as large as 8 mm, neither a significant change on the WI line intensity nor the W quasi-continuum intensity by laser injection to the W limiter was observed. In an ohmic discharge the increment of the quasi-continuum of Ta appeared higher than that of W. The decay times of W and Ta in the plasma core were measured by observing the Prad signal in both of ohmic and NBI discharges. The decay times in ohmic discharges were about six times longer than those in NBI discharges. The amounts of W and Ta atoms which penetrated into the plasma by laser injection were estimated from the calibration of the XUV grazing incident spectrometer to be about 6×10^{14} and 1×10^{15} ions for W and Ta, respectively.

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