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Impurity release from high Z test limiters immersed in TEXTOR-94 edge plasmas

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Abstract

A W test limiter has been inserted into the plasma edge of TEXTOR beyond the magnetic surface of the main ALT graphite limiter, and the release of neutral W as well as carbon and oxygen are examined spectroscopically. The penetration depth of neutral W has decreased significantly with increasing plasma density and it is as small as 1.2 mm when the local plasma density at the magnetic surface of the limiter increases up to 1.5×10^{19} m^{-3}. The flux of neutral W decreases as the local density increases, while the C and D fluxes increase. Radial intensity distributions of CII line spectrum emission have indicated larger penetrations of C ions emitted from a W limiter than those from a C limiter. The penetration length of OII emission from a W limiter is similar to that from a C limiter and much smaller than that of CII.

Keywords: TEXTOR; High Z wall material; Limiter; Impurity source; Line emission diagnostics

1. Introduction

High Z metals have several advantages over graphite or other low Z elements as a plasma facing material [1]. To investigate the performance of high Z materials under an intense plasma radiation, high Z test limiter experiments have been being conducted in TEXTOR-94 under various plasma heating conditions. Using a Mo test limiter we have shown the rise in surface temperature was smaller than a C limiter for similar heat load conditions [2]. The accumulation of Mo at the plasma center became appreciable for Ohmic discharges of density higher than 3×10^{19} m^{-3}, but the impact on the plasma performance by the Mo test limiter was negligible as the plasma was heated by neutral beam injection (NBI) [3]. When the plasma was heated with NBI, the ionization length of Mo near the limiter measured from the intensity distribution of MoI light was smaller than those for OH conditions and was as small as about 1 mm at the highest line averaged density of 5×10^{19} m^{-3} [4].

We continue our work using W limiters [5] as W has some properties superior to Mo, like a higher melting point, lower sputtering yield and higher thermal conductivity [6]. It is also meaningful to perform experiments with a W limiter and compare the results with those obtained in the programs investigating W as a divertor plate material [7]. In this paper we report the result of the study on the penetration of neutral W as well as D, C and O ions into the plasma by a spectroscopic method.

2. Experimental setup

The W and the C test limiters were immersed in the TEXTOR edge plasma through a limiter-lock manifold as shown in Fig. 1 [8]. The plasma minor radius is determined by graphite-made ALT-II limiter to be 46 cm and the effect of the W test limiter upon the plasma performance

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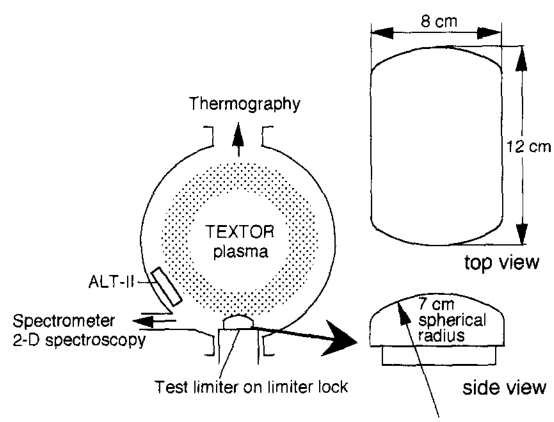

Fig. 1. Schematic view of the experimental setup.

becomes apparent as the limiter surface is positioned deeper than the last closed flux surface determined by ALT-II limiter. In this experiment, the W limiter was usually positioned at 45 cm from the plasma center. TEXTOR was operated at 340 kA plasma current, 2.25 T toroidal magnetic field and 6 s discharge duration. The plasma can be heated by NBI at the power of 1.3 MW for 3 s.

The boundary plasma conditions were changed by changing the line averaged density for both Ohmic and NBI conditions. Radiation power from the plasma was measured by the bolometer array, while the highly ionized W ions in the central region of the plasma was monitored by detecting the W band emission around 5 nm. Local electron temperatures and densities at the position of the same radial distance but of different toroidal and poloidal angles were obtained by a He atomic beam method [9].

Radial distributions of spectral line intensities of emissions from ions and neutrals around test limiters were measured by an image intensified CCD-camera coupled to a monochromator. The spectrum was recorded in the wavelength range from 409 to 435 nm, where we observed CII (426.7 nm), WI (429.5 nm), Dγ (434.0 nm) and OII (434.6 nm). The 2D intensity distribution of the WI line emission was observed by another CCD-camera through an interference filter at 400.8 nm with 1.5 nm band width from the direction tangential to the limiter surface. The third CCD-camera viewed the limiter surface from the top through an infrared transmission filter to construct the temperature distribution of the limiter surface. Thermocouples were installed in the electron and the ion drift sides of the limiter and located 0.7 cm from the limiter surface.

3. Results

3.1. Edge plasma parameters and radiation characteristics

For both Ohmic and NBI discharges the electron temperature at the position corresponding with the limiter surface decreased with an increasing density. The temperature was usually higher for a NBI discharge than for an Ohmic discharge by about 10 eV. The plasma density at the limiter was higher for a NBI discharge than for an Ohmic discharge and changed almost linearly with the line averaged density. Gradients of electron density and temperature at the limiter edge were of the order 10^{18} m^{-3}/cm and 10 eV/cm, respectively.

In Fig. 2, the radiation power from the plasma and the W band intensity are plotted as functions of the line averaged density. The radiation from the plasma increased with increasing plasma density for Ohmic and NBI heated plasmas and it was higher for a NBI heated plasma than an Ohmic plasma. The surface temperature of the W limiter measured by the IR camera showed an increase as a plasma was heated with NBI from an Ohmic heating condition. Under the NBI heating, the increment of the surface temperature had shown a decrease by the increase in plasma density, which was also confirmed from the thermocouple signals.

To make the contribution of the limiter insertion clear against the relatively large plasma noise, the W band signals of discharges with W limiter positioned at 45 cm are subtracted by those with W limiter at 47.5 cm. The signal after the subtraction increased almost in proportion to the plasma density for Ohmic discharges, while it did not show a noticeable change for almost all cases for NBI discharges. When the line averaged density of the Ohmic plasma was increased up to 3.7×10^{19} m^{-3}, abrupt increases in the W band signal and in radiation were observed.

3.2. Intensity distribution of WI line emission

As more light emission was observed at the ion drift side in the 2D WI line emission measurement, the spectrometer was adjusted to observe line emissions from the

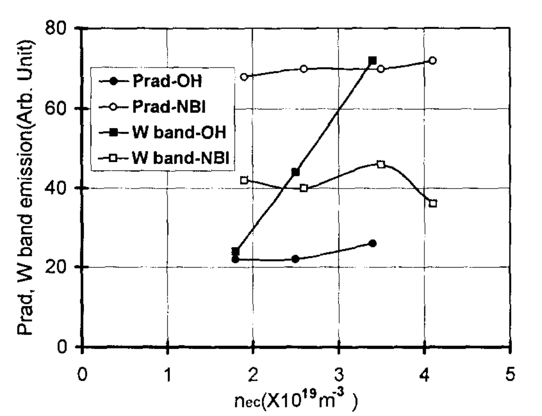

Fig. 2. Radiation power from the plasma, P_{rad} and intensity of the W band emission plotted as functions of the line averaged electron density, n_{ec}.

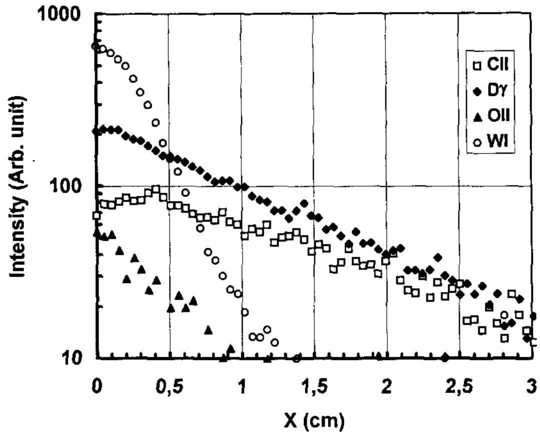

Fig. 3. Intensities of line spectra of WI, Dγ, CII and OII plotted as functions of distance from the surface of the limiter into the plasma, x.

plasma of the ion drift side of the limiter. Radial intensity distributions for CII, WI, Dγ and OII observed for a local plasma of 60 eV electron temperature and 4.5×10^{18} m^{-3} electron density with a NBI heating are plotted in Fig. 3. The intensity distribution of the WI line emission decayed almost exponentially to the center, and when the e-folding length for the decay was plotted as a function of the local electron density, it showed a decrease against increasing density.

3.3. Intensity distributions of Dγ, CII and OII line emissions

The measured local electron temperatures at the position of the limiter surface were usually lower for a W limiter than a C limiter. To compare Dγ and CII intensity distributions under similar plasma conditions, data for a W limiter at the position 45 cm from the plasma center was compared with those for a C limiter at 46 cm. In Fig. 4 the radial distributions of emissions of CII and Dγ from a W limiter are compared with those from a C limiter. The local electron densities were nearly the same for these two conditions at 3.0×10^{18} m^{-3}, while the electron temperatures were 52 eV and 42 eV for discharges with a C limiter and a W limiter, respectively. The penetrations of Dγ and CII line emissions were larger than those shown in Fig. 2, as the local electron density was 50% smaller than in the case of Fig. 2.

The spatial distribution of the OII line intensity showed a much smaller penetration length than that of CII as shown in Fig. 3. It did not change much with the change of the local plasma density but the e-folding length for the intensity of the OII line emission was usually constant at about 0.5 cm. The flux ratio of O to C was nearly the same between C and W limiters.

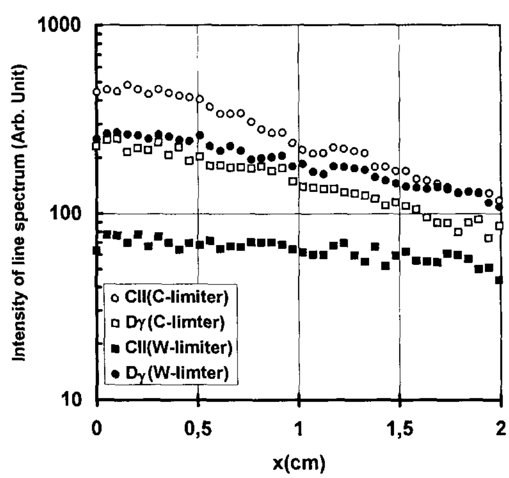

Fig. 4. Comparison in the dependence of the line intensity emission upon the distance from the limiter surface, x, between W and C limiters.

4. Discussion

4.1. Release of W into the plasma

The density distribution and the flux of neutral W are estimated by integrating the emission intensity in the radial direction [10]. In Fig. 5, the ionization mean free path and the neutral W flux calculated from the WI line emission are plotted as functions of the local electron density. The mean free path of the neutral W is a little larger than the penetration lengths of the WI light emission and is 1.2 mm at a local plasma density of 1.5×10^{19} m^{-3}. When the average velocity of W neutrals estimated from the Thompson distribution for C^{4+} impact is used, the Lamor radius of singly ionized W is calculated to be 2.5 mm. The

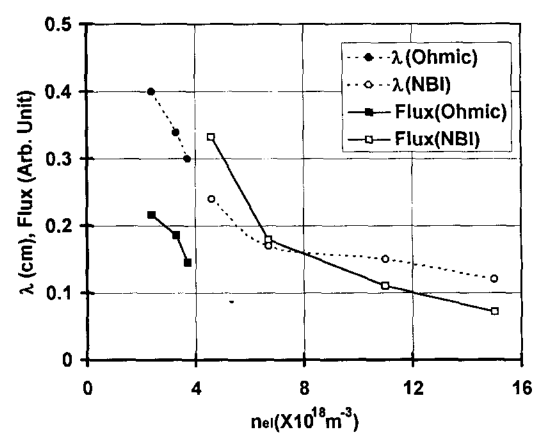

Fig. 5. Ionization mean free path, λ, and flux of neutral W plotted as functions of local plasma density, n_{el}.

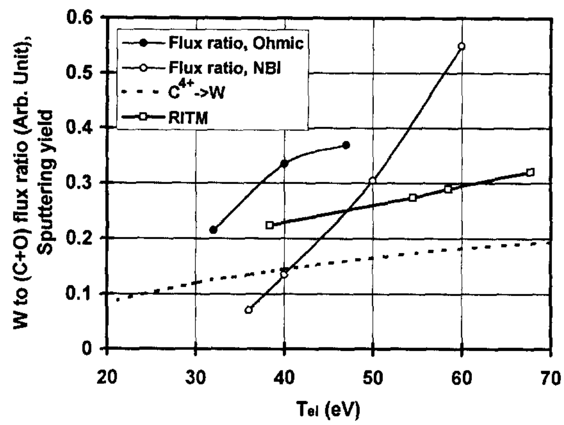

Fig. 6. Experimentally obtained flux ratio of W to sum of C and O and that computed from RITM plotted as functions of local plasma temperature, T_{el}. Sputtering yield of W by C^{4+} is also plotted for reference.

fraction of prompt redeposition can then be estimated from the analytical result by Fussmann et al. [7] to be about 81%. Thus, a large part of the sputtered W atoms do not leave the surface of the limiter and the effective sputtering yield should be reduced.

The neutral W flux showed a decreasing dependence with increasing density. The trend was the same for both Ohmic and NBI discharges, but the amount of W efflux was much smaller for an Ohmic discharge when the plasma parameters were similar at the position corresponding to the limiter surface. This dependence of the W efflux from the limiter upon the density appears contradictory to the signal of W band emission in the plasma center. However, a larger release of W into the edge plasma does not directly correspond to a higher concentration of W ions in the plasma core, unless the W in the edge plasma are transported into the core. The observed contradictory relation between the W efflux and the W band intensity indicates that the transport process plays more important role than the amount of W efflux for the accumulation of W in the plasma core.

To obtain the correlation between the W efflux to the incident plasma ions, the ratio of the flux of neutral W to the sum of the C and O fluxes is plotted as the function of the local electron temperature in Fig. 6. The contribution of deuterons to sputtering of W was assumed negligible and Fig. 6 can be compared with sputtering yields of W due to C and O. The sputtering yield of W by C^{4+} ions calculated from a formula in Ref. [11] is drawn in Fig. 6 for reference, but the theoretical sputtering yield does not increase as steeply as the experimental result at this energy range.

Because the mean charge state of the incident ions may become larger at higher electron temperature, a model was developed to calculate the mean charge state and the W flux due to sputtering. The transport code RITM [12] has been run to calculate self-consistently the densities and temperatures of electrons, deuterons and all charge states of C and O near the test limiter. As an input the plasma mean density, current, power of additional heating and the influxes of impurities through the last closed magnetic surface touching the ALT-II limiter were used [13]. As a result the fluxes of D^+ and C and O ions of all charges to the limiter surface were found and the outflow of sputtered W atoms was calculated according to the formulas of Ref. [14]. A plot in Fig. 6 shows the effective yield of W defined as the ratio of the sputtered flux to the sum of fluxes of carbon and oxygen ions to the limiter. A steeper increase for increasing local plasma temperature than a simple sputtering yield is seen, but the experimental result shows much steeper increase against the electron temperature. The mean charge states which we here define by a simple sum of flux multiplied by the charge number divided by the sum of the fluxes, was relatively constant or slightly increasing against density and it changed from 4.1 to 4.6 for C and from 5.2 to 6.0 for O.

4.2. Release of C and O from a W limiter

Fig. 4 shows that the penetration of the CII line emission into the plasma is larger for a W limiter than a C limiter. Carbon atoms produced from molecules due to chemical sputtering on the surface of a C limiter should have a substantially smaller penetration length into the plasma than the atoms backscattered or sputtered at the surface [15]. In the case of a W limiter most of the C atoms leaving the surface should be produced either by backscattering or sputtering. The particle reflection coefficient of C^{3+} ions for W calculated by Kawata and Ohya for conditions similar to the TEXTOR edge plasma is about 40 times higher than that for C [16]. The calculated energy distributions of C atoms backscattered from W show the mean velocity much higher than those from C. Incident C atoms not promptly reflected should be deposited on the surface and may stay on the surface forming some carbide like the case of Mo [17]. Part of them are then sputtered back into the plasma with a mean velocity higher than that of species produced by chemical sputtering. Thus, the average velocity of C atoms should be larger for a W limiter than a C limiter and the effective ionization-mean-free-path should become greater for W.

The penetration depth of the OII line emission was not very much different from W to C limiter and was substantially smaller than those of Dγ and CII. As the mass ratio of O to W is similar to that of C to W, we would expect the sputtering and backscattering characteristics of O similar to C. The substantially smaller penetration length into the discharge, corresponding with smaller velocity, can be explained by the particle emission due to chemical sputtering (CO). Smaller penetration length of O than C should mean that the chemical sputtering is the dominating process for O emission, while it takes only some part for C emission [18].

5. Conclusions

The measured ionization mean free path of W into the plasma appeared to be proportional to the inverse of the electron density. The ionization mean free path became less than half the radius of a singly ionized W at a high local density and the corresponding fraction of the prompt redeposition is calculated to be more than 80%. The flux of neutral W decreased as the electron density increased. The decrease can be explained neither by a simple argument based on the energy dependence of the sputtering yield nor by the result from a model calculation to estimate the high Z efflux from the test limiter and some more work is necessary to explain the dependence of W flux upon the edge plasma parameters. The experimentally observed characteristics of the mean free path and efflux of neutral W versus the local density should result in the reduction of W source into the edge plasma at a high local plasma density.

The penetration of singly ionized C shows that carbon atoms leave the surface of a W limiter with a mean energy higher than they leave the surface of a C limiter. This can be the indication of a higher energy reflection coefficient of W for C reflection. Meanwhile, singly ionized O seem to have lower velocity than C and the release of O from W surface by a chemical sputtering is the possible explanation for this observation.

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