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Journal of Nuclear Materials 249 (1997) 116–120

journal of nuclear materials

Impact of molybdenum and tungsten test limiters on ion fluxes in the plasma edge of TEXTOR

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Received 18 March 1997; accepted 10 July 1997

Abstract

Ion fluxes in the scrape-off layer (SOL) of the TEXTOR tokamak were traced by means of the collector probe technique during tests of tungsten and molybdenum limiters. Graphite probes were exposed under different operation conditions: limiter position, plasma density, neon edge cooling and heating mode. Following the exposures, the surfaces were examined with ion beam analysis techniques (RBS, NRA) in order to determine deposition rates of metals, deuterium and other species. Under the same experimental conditions deposition rates of tungsten are found to be 6.5–7.5 times lower than those for molybdenum. The results for both the metals are compared and discussed in terms of processes governing the erosion rate of high-Z metals in tokamaks: physical sputtering and re-deposition of sputtered species. Moreover, the results of the collector probe measurements of fluxes in the SOL are compared with the spectroscopic observations of high-Z impurity atoms in the plasma. © 1997 Elsevier Science B.V.

1. Introduction

For a few recent years heavy metals of high melting point have been reconsidered as plasma facing materials in controlled fusion devices [1]. As summarized by Noda et al. [2], experiments in tokamaks (for instance at TEXTOR, ASDEX Upgrade, FTU, DIII-D) and in simulators of plasma–surface interactions are under way in order to recognize the behavior of high-Z elements under different plasma conditions and to assess the feasibility of those elements for plasma facing components in controlled fusion devices. Tests performed at the TEXTOR tokamak with W and Mo have indicated satisfactory behavior of high-Z impurities in the plasma core during discharges auxiliary heated with neutral beams [3]. The result has encouraged further investigation and recent efforts have been focused especially on experiments with high power NBI heating combined with the plasma edge cooling by neon injection.

This contribution describes the collector probe measurements of ion fluxes in the TEXTOR scrape-off layer evolved in the presence of molybdenum or tungsten test limiters. The aim is to compare the impact of Mo and W limiters on the impurity production and the ability of high-Z atoms to escape the limiter surface and penetrate to the SOL plasma. The influence of several parameters (heating mode, plasma density and the limiter radial position in the torus) on the impurity release are addressed.

2. Experimental

The experiments were carried out during deuterium fueled discharges in the TEXTOR tokamak operated with

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PII S0022-3115(97)00234-1

molybdenum or tungsten test limiters. The plasma radius was defined by the graphite blades of a toroidal pump limiter ALT II at $a = 46$ cm, whereas the test limiters were inserted from the bottom of the torus: from $r = 44$ cm (i.e., 2 cm immersed in the plasma) to $r = 56$ cm (limiter fully withdrawn). The surface area of the test limiters was about 60 cm^2 in comparison to the area of graphite blades of the main limiter (ALT II) being about 4 m^2. Experimental set-up, shape and the position of the high-Z test limiters in the torus have been described in detail elsewhere [4].

In addition to many diagnostic techniques employed during the high-Z limiter tests, the surface collector probe was in use in order to trace impurity ion fluxes in the SOL. The probe was installed 90° poloidally and 90° toroidally apart from the test limiters. Several tens of probe exposures were done under various conditions: line-averaged electron density from 1.5 to 5.5×10^{19} m^{-3}, radial position of the test limiters, neon edge cooling, ohmically and auxiliary (NBI) heated discharges. The tests of the Mo limiter were done approx. 1050 discharges after a siliconization of TEXTOR, whereas the W limiter tests took place approx. 600 discharges after a boronization. A single probe was exposed to maximum two discharges performed under very similar operation conditions.

After the exposure, the probes were examined by means of ion beam analysis techniques to determine the amount of species deposited. Nuclear reaction analysis (NRA) was used to determine the amount of deuterium [^{3}He(d, p)^{4}He] and boron [^{11}B(p, α)^{8}Be], whereas Rutherford backscattering spectroscopy (RBS) was applied to quantify the amount of oxygen, silicon and metals (Mo, W and Inconel components: Ni + Cr + Fe originating from the machine liner). The liner material contains also Mo, as a minor constituent, and the corresponding background flux of molybdenum (at $r = 47.5$) was found to be $2\text{–}5 \times 10^{13}$ cm^{-2} s^{-1}, dependent on the discharge conditions. This background value is subtracted from the fluxes determined during the Mo limiter test. No background fluxes of tungsten could be detected prior to the operation with the W limiter. The results concerning oxygen measurements will be omitted in the following, as it has been proven that the oxygen content on surfaces exposed in the presence of boronized walls is decided not only by the incident oxygen impurity flux, but also by the uptake of atmospheric oxygen when the probe is transferred from the torus to the surface analysis station [5].

3. Results and discussion

Fig. 1 shows the Rutherford backscattering spectra recorded following the probes' exposures to ohmically and NBI heated discharges with the W limiter at $r = 45$ cm, i.e., immersed 1 cm deep into the plasma. One may perceive that the deposition of various species, which is related to ion fluxes in the SOL, is greater for the NBI heated discharge. The effect is mostly attributed to the increased fluxes because of the decreased particle confinement, during the NBI phase, which results in the enhanced sputtering. In addition to the species indicated in the spectra, deuterium, boron (both measured separately with NRA) and carbon atoms were also deposited. Using the graphite probes, the deposition of carbon could not be determined directly, but according to the previous findings [6,7] it has been known that carbon atoms are the major species deposited on the probes exposed at TEXTOR operated with graphite toroidal limiters. The ratio of carbon to hydrogen fluxes to the limiter surface measured by spectroscopy methods amount to approximately 0.015–0.025 of the hydrogen flux [8].

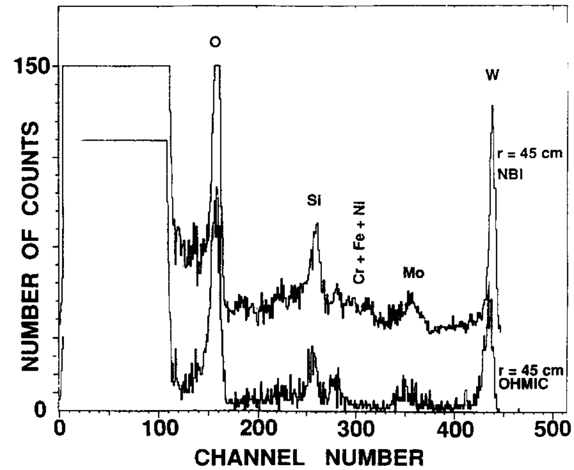

Fig. 1. Rutherford backscattering spectra of deposits collected on the probes during ohmically (lower) and NBI heated (upper) pulses in the presence of the tungsten limiter at $r = 45$ cm.

Fig. 2 presents a comparison of the deposition rates, at $r = 47.5$ cm, of various species on the probes exposed to ohmic discharges ($n_e = 2.6 \times 10^{19}$ m^{-3}) with the tungsten (Fig. 2a) and molybdenum (Fig. 2b) test limiters at different radial positions. The deposition rates for metal atoms correspond closely to the fluxes of those species because the sticking probility of heavy ions impinging on light substrates approaches unity [9]. Two important features can be noticed: (i) comparing the W and Mo fluxes recorded for a given radial position ($r = 44$ or 45 cm) one observes that the W flux is 6.5–7.5 times lower than the Mo flux; (ii) the deposition rates of other species remain nearly constant in the presence and after the withdrawal of the high-Z limiter ($r = 55$ cm) indicating that the release of heavy atoms do not influence significantly the release of these elements from other wall components. This can be understood by the fact that the fluxes of high-Z atoms measured at $r = 47.4$ cm (i.e., 14 mm from the LCFS) are generally low: $8\text{–}17 \times 10^{12}$ cm^{-2} s^{-1} for tungsten and $4\text{–}10 \times 10^{13}$ cm − 2 s − 1 for molybdenum dependent on the limiter radial position. Therefore, their contribution to

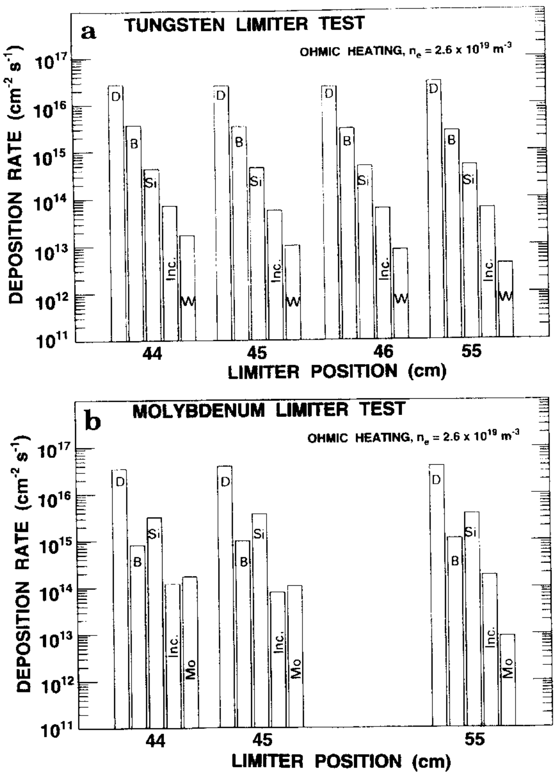

Fig. 2. Deposition rates of deuterium and plasma impurity atoms for different radial positions of W and Mo limiters in the torus. (Term 'Inc.' in the histograms denotes Inconel components: Ni + Cr + Fe.)

the overall erosion rate of wall components is small. The measurements of high-Z fluxes with the limiters at $r = 55$ cm were performed immediately after the operation with the test limiters and one may notice that the limiters' withdrawal resulted in the decrease of high-Z fluxes, but not in their disappearance.

As mentioned above (see Section 2), the experiments were carried out under different wall conditions. This is reflected in the histograms: the ratio of the B/Si deposition rates is 6.9 and 0.26 for the measurements performed with tungsten and molybdenum limiters, respectively.

The results obtained for NBI auxiliary heated discharges are summarized in Fig. 3a and b where the soft X-ray spectroscopy data (for Mo, L shell emission around 2.4 keV) or total concentration of W atoms in the plasma are compared with the deposition rates measured with the collector probe. The number of W atoms in the plasma was calculated from the total radiation power — background subtracted — on the basis of corona equilibrium using the data on radiation potential [10]. Results in Fig. 3 clearly indicate that the plasma contamination decreases significantly with the density increase. This is because of the plasma shielding effect, i.e., decreased net erosion of limiters at higher densities — as explained below.

Another important result is that for a given density the deposition rates of W are approximately seven times lower than those of Mo. Though the measured fluxes of Mo and W in the SOL under the NBI heating are greater than those observed in ohmic pulses, the major finding is consistent in all the cases: the flux ratio (Φ_{Mo}/Φ_W) is between 6.5 and 7.5 for similar operation conditions, both in ohmically and NBI heated discharges.

To explain that flux ratio, the influence of two factors will be considered: physical sputtering and prompt re-deposition of sputtered high-Z atoms on the limiter surface. Threshold energies for sputtering (according to the semiempirical formula proposed by Bohdansky and modified by Garcia-Rosales et al. [11].) of molybdenum and tungsten by deuterium ions are 84 eV and 216 eV, respectively. Therefore, under the operation conditions, with the edge temperature of either 20 (representative for ohmic cases) or 40 eV (NBI) and assuming Maxwellian distribution of ions accelerated in the sheath potential equal to $3kT_e/e$, the physical sputtering of tungsten by deuterium ions can generally be neglected and the erosion by carbon impurity fluxes ($E_{th} = 45$ eV) should mostly be considered, whereas for molybdenum, especially in the NBI

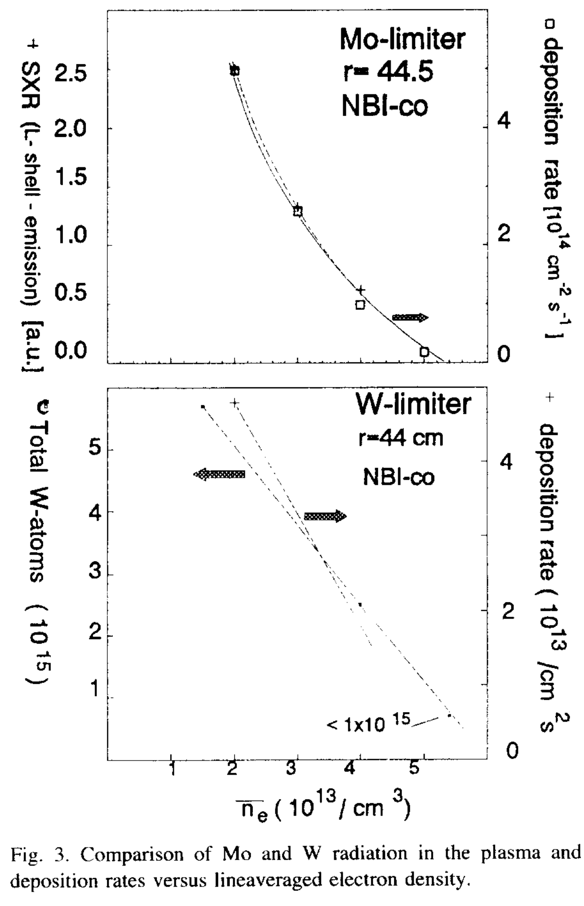

Fig. 3. Comparison of Mo and W radiation in the plasma and deposition rates versus lineaveraged electron density.

heated pulses, both deuterium and carbon — induced erosion must be taken into account. For the limiters immersed into the plasma by 1 or 2 cm, carbon is assumed to ionized to the +4 state and the corresponding ion energy is equivalent to approx. 250 eV for ohmic and approx. 500 eV for NBI heated discharges. In Table 1 there are shown calculated sputtering yields of molybdenum and tungsten by deuterium and carbon ions. Self sputtering is also included, but the fluxes of high-Z metals are so small (in comparison to D and C fluxes) that their influence on the total erosion of limiters is negligible. As mentioned above, according to the spectroscopic measurements by Pospieszczyk et al. [8] the ratio of carbon to hydrogen flux to the limiter amounts to approximately 2%. Since the fluxes of other impurities are distinctly smaller, it can be assumed that the flux interacting with the limiter consists of 98 o of D and 2% of C ions. Therefore, the ratio R_S of sputter erosion of molybdenum and tungsten can be written as

$$R_s = (0.98 Y_{Mo}^{D} + 0.02 Y_{Mo}^{C})/(0.98 Y_{W}^{D} + 0.02 Y_{W}^{C}), \quad (1)$$

where Y_{MO}^{D} and Y_{W}^{D} are sputtering yields of metals by deuterium ions, Y_{Mo}^{C} and Y_{W}^{C} are sputtering yields by carbon ions.

For tungsten the term Y_{W}^{D} can be neglected. The values of R_s are 3.67 and 3.94 for the electron temperature equal to 20 eV and 40 eV, respectively.

The second process to be compared, is the prompt re-deposition of sputtered species, as proposed by Naujoks and Behrisch [12]. The efficiency of re-deposition depends on the ionization lengths of sputtered atoms and the Larmor radii when the atoms become ionized. Therefore, species ionized and subsequently gyrating in the vicinity of the limiter can hit its surface and become promptly re-deposited. While the Larmor radius increases with the ion mass, the ionization length — for a given electron density — decreases with the increasing mass. Thus, the molybdenum ions have a greater ability to escape from the vicinity of the limiter than the heavier tungsten species. Fig. 4 shows the plots representing the Larmor radii and the ionization lengths versus the energy of sputtered particles (calculated for the edge electron density of 2.5×10^{18} m^{-3} — value measured at TEXTOR). Most of the sputtered particles are released as atoms with kinetic energy being one half of the surface binding energy (enthalpy of

Table 1
Sputtering yields of molybdenum and tungsten by plasma ions calculated for edge electron temperature of 20 eV and 40 eV

Plasma ion	Molybdenum		Tungsten	
	$T_e = 20$ eV	$T_e = 40$ eV	$T_e = 20$ eV	$T_e = 40$ eV
D^+	1.05×10^{-3}	7.06×10^{-3}	–	–
C^{4+}	0.163	0.247	0.0879	0.151
X_{self}^{6+}	0.638	1.13	0.584	1.12

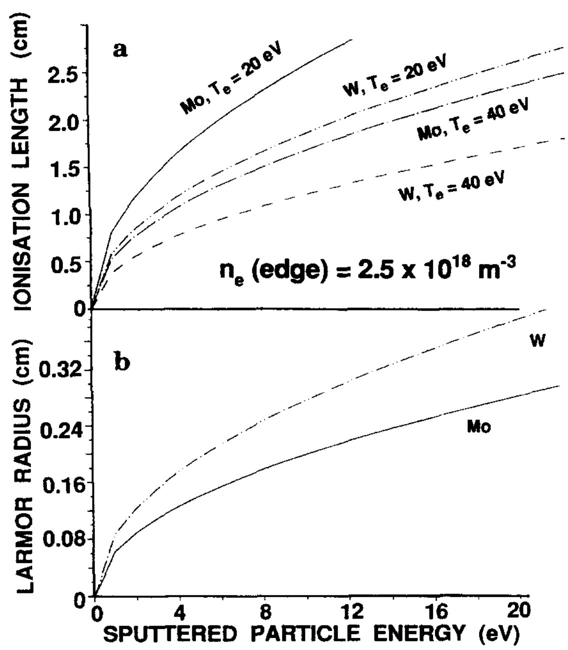

Fig. 4. Ionization length (calculated for the edge density 2.5×10^{18} m^{-3}) for two edge temperatures and Larmor radii of W and Mo versus the energy of atoms sputtered from the test limiters.

sublimation): 3.4 eV for Mo and 4.45 eV for W. The relation of the ionization lengths and the Larmor radii (λ/ρ) for Mo and W can be determined as the ratio R_e — the escape coefficient:

$$R_e = \lambda_{Mo}/\rho_{Mo} : \lambda_W/\rho_W. \quad (2)$$

For edge temperatures of 20 eV and 40 eV the values of R_e are 2.0 and 1.77, respectively. Multiplying the coefficients $R_s \times R_e$ one finds the value $T_{Mo/W}$ representing the relation between effective transfer factors of high — Z species to the scrape-off layer. $T_{Mo/W}$ equals 7.3 and 7.0 for the electron temperatures discussed. These values are very clone to those found experimentally (6.5 to 7.5). Therefore, one can conclude on a good agreement between the modelling and experiment.

4. Summary

A comparison of molybdenum and tungsten ion fluxes in the scrape-off layer during the high-Z limiter tests shows that under similar operation conditions, both under ohmically and NBI heated conditions, the net erosion of tungsten is distinctly (approximately seven times) lower than that of molybdenum. The erosion of both metals decreases with increasing density: this is due to reduced sputtering of the limiter surface and more efficient ionization (shorter λ) of sputtered atoms. As a result, the re-deposition of sputtered species becomes enhanced (so called improved edge screening effect). In general, the best performance of the test limiters, i.e., the smaller release of high-Z impurities to the plasma boundary, occurs during high density operation.

Acknowledgements

The authors are very grateful to the TEXTOR Team for kind and fruitful co-operation. The work was partly supported by NFR Contracts F/AC - FF - 06571-307 and 312, and a Grant-in-aid for scientific research by the Ministry of Education, Culture and Science of Japan.

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