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Comparison of impurity production and recycling on carbon and tungsten limiters in TEXTOR–94

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1. Introduction

Carbon and tungsten are considered to be favourable candidates for low- and high Z plasma facing materials in fusion devices. It is important to determine the interaction of the plasma with both materials in detail. In order to directly compare the impurity production and recycling at carbon and tungsten surfaces, a C–W twin test limiter half made of tungsten and another half made of carbon was inserted into the edge plasma of TEXTOR–94. The release of impurities (W,C,O,Cr) from different surfaces (C and W) is examined spectroscopically for identical plasma and observation conditions.

2. Experimental setup

The experiments have been performed in the tokamak TEXTOR–94 with a major radius R=1.75m and a minor radius a=0.46m. TEXTOR-94 was operated at $B_T = 2.25\ T$ and $I_p = 350\ kA$. The line average central electron density was varied between $\overline{n}_e = 1 \times 10^{19}$ m^{-3} and $\overline{n}_e = 6 \times 10^{19}\ m^{-3}$. Additional heating was provided by a neutral beam injector (NBI) injecting tangentially in the co–direction with a power of 1.3MW.

A C–W twin test limiter with dimensions of 12cm x 8cm and a spherical shape with a radius of 7cm was inserted into the edge plasma through a limiter-lock [1] to the position of the LCFS at the top of the torus . The entire limiter could be rotated in–between shots, making it possible to face the C- or the W-side of the twin limiter either to the ion drift or the electron drift direction.

The radial distributions of spectral line intensities of emissions from ions and neutrals in front of the test limiter were measured by an image intensified CCD-camera coupled to a spectrometer, the entrance slit of which was focussed at a toroidal position 20mm from the center at the ion drift side. The rotation of the twin limiter between the discharges allowed to perform investigations on different materials (C and W) under identical plasma conditions. The 2D intensity distribution of impurity line emissions (W,C) was observed by another CCD-camera coupled to interference filters with 1.5nm bandwidth. The power deposition on the limiter surface was measured by a pyrometer and a third CCD-camera with an infrared filter (transmission wavelength from 850nm to 1100nm). Additionally the bulk temperature of each half limiter side was monitored with thermocouples. Edge electron temperature and density profiles were measured by means of an atomic beam diagnostics (He and Li–beams) [2].

3. Results and Discussion

Fig.1 shows typical spectra of the plasma in front of the carbon and the tungsten section of the twin limiter in the wavelength range between 409nm and 436nm. These spectra are recorded in discharges with additional NBI–heating with a power of 1.3MW and a line–averaged electron density of $3 \times 10^{19} m^{-3}$.

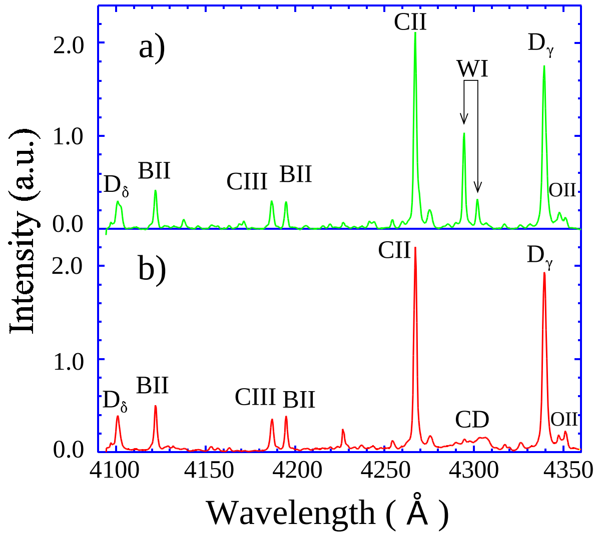

Fig. 1. *Typical spectra of plasma in front of W (a) and C (b) limiters*

The spectrometer allows the simultaneous observation of several emission lines of chromium, boron, carbon, tungsten, oxygen, hydrogen and molecular CD–bands. When the limiter material was changed from graphite to tungsten, a strong emission of WI (429.5nm) was observed. This is accompanied by a strong reduction of emission band of the CD-radical (430.7nm).

Fig. 2 shows a comparison of the measured CII-profiles with one simulated by ERO–TEXTOR code [3] for carbon and tungsten limiters. A very good agreement between experiment and simulation is achieved for the following conditions: chemical erosion yield for CD_4 of 3%, reflection coefficients for hydrocarbons R_{ion}=0.2 and $R_{neutral}$=1.0. The simulation for the tungsten limiter were performed under the assumption that the W surface is covered with carbon and chemical erosion can be neglected. The limiter heads were investigated postmortem with ion beam analysis to determine the spatial distribution and quantity of species deposited on the limiter surface [5]. Although no significant carbon layer (<1 monolayer) was found in the erosion region on tungsten, the maximum intensity of the CII flux from carbon is only ≈20% larger than that from tungsten. CII carbon lines in front of the tungsten limiter result from carbon, which is implanted in the near surface layer and sputtered by particle impact. The number of carbon sticking on areas of net erosion is equal to number of re–sputtered carbon neutrals. Under this assumtion we can roughly estimate the relative carbon surface concentration n_c

$$\Gamma_c(1 - R_c^c \cdot n_c - R_w^c \cdot n_w) = \Gamma_d \cdot Y_{dc} \cdot n_c + \Gamma_c \cdot Y_{cc} \cdot n_c + \Gamma_o \cdot Y_{oc} \cdot n_c \quad (1)$$

$$n_c = \frac{1 - R_w^c}{\Gamma_d/\Gamma_c \cdot Y_{dc} + Y_{cc} + \Gamma_o/\Gamma_c \cdot Y_{oc} + R_c^c - R_w^c} \quad (2)$$

where Γ_d, Γ_c, Γ_o are the fluxes of deuterium, carbon and oxygen onto the limiter, respectively. Y_{dc}, Y_{cc}, Y_{oc} are the sputtering yields of carbon on a W surface by deuterium, carbon and oxygen ions. $R_c^c \approx 0.25$ and $R_w^c \approx 0.65$ (angle 60^0, charge Z=4, T_e=T_i) [4] are the reflection coefficients of C particles on C and W surfaces, respectively. Impact energies for deuterium, carbon and oxygen are used according to E_d=5kT_e and $E_{c,o}$=(2+3Z)kT_e assuming an impurity charge state of Z=4 for carbon and oxygen. The C/D flux ratio are obtained from a CII line at 426.7nm and D_γ using a ratio for the ionization to photon rates S/XB(CII) : S/XB(D_γ) of 28. The O/D flux ratio is evaluated using ratio S/XB(OII λ=424.6nm) : S/XB(D_γ) of 10. For $\overline{n}_e = 3.0 \cdot 10^{19} \mathrm{m}^{-3}$ the measured C/D and O/D flux

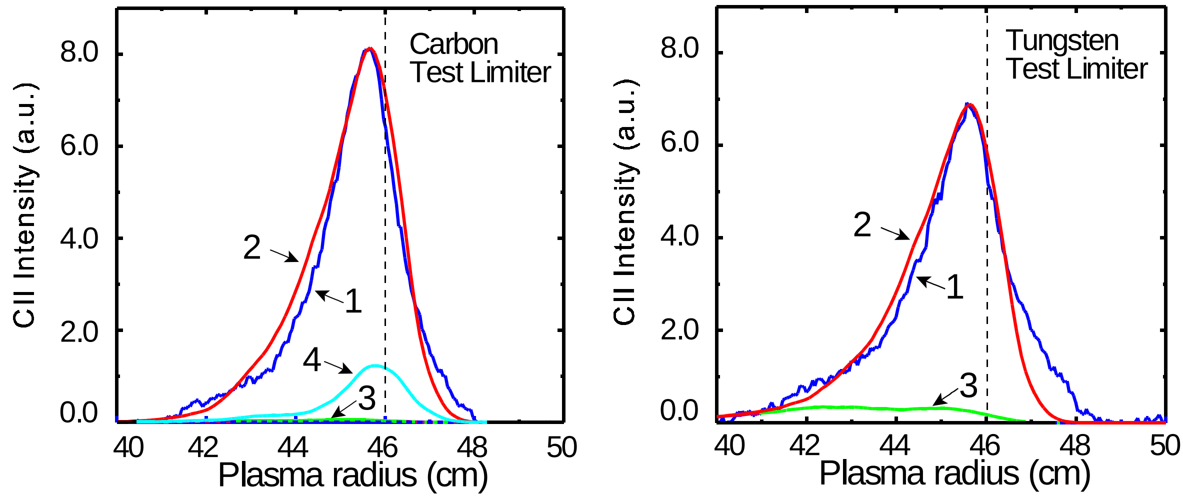

Fig. 2. *Comparison of experimental (1) and simulated (2) CII-emission profiles in radial direction from carbon (left) and tungsten (right) limiters. The simulated profile has a contribution due to background reflected C particles (3), chemical (4) (only for C limiter) and physical sputtering*

ratios are about 3.5% and 2% respectively. The local electron density and temperature are $3.5 \cdot 10^{18}\mathrm{m}^{-3}$ and ≈50eV. For this condition n_c is calculated to be about 0.5. The transient layer of C ($n_c = 0.5$) on W would reduce the reflection coefficient for C on W from R^c_w=0.65 to $R^c_{(w+layer)}$=0.45.

Because the observation range was limited 40 cm and 50cm plasma radius , we observe only a very small part (< 10%) of directly reflected particles within the observed volume. When we correct the measured C– and D–fluxes with respect to the estimated reflection coefficients, we obtain

$$\frac{CII}{D_\gamma} \cdot \frac{S/XB(CII)}{S/XB(D_\gamma)} \cdot \frac{1 - R^d_{(w+layer,c)}}{1 - R^c_{(w+layer,c)}}$$

equal to 2.3% and 2.4% on W and C surfaces respectivelly. Only the difference of 0.1% has to be attributed to carbon being eroded from the substrate material and contributing to the net–erosion. Thus, under the present conditions, the net–erosion is below 10% of the gross–erosion and hardly to identify within the accuracy of the experimental data.

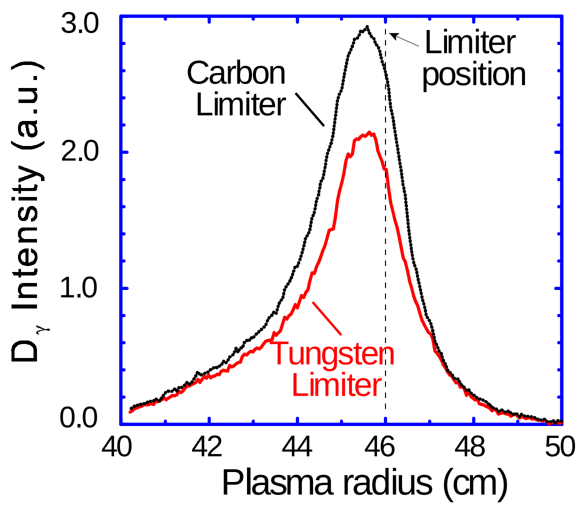

Fig. 3. *Radial distributions of D_γ from tungsten and carbon limiters*

In. Fig. 3 the radial distributions of the D_γ emission from the tungsten limiter are compared to those from the carbon limiter. The intensity of the D_γ is about 20%-30% larger on carbon than on tungsten.

The particle reflection coefficient for D on W and C is about 75% and 40% (angle 60^0, charge Z=4, $T_e = T_i$) correspondingly, where the projectiles loose 55% and 20% of their energy. The transient layer of C ($n_c = 0.5$) on W would reduce the reflection coefficient for D on W from R^d_w=0.7 to $R^d_{(w+layer)}$=0.57. Due to the limited observation range the emission of reflected D atoms do not contribute to the measured emissions. Thus we expect to observe the emission of the remaining 43% and 60% of incoming D^+ on W and C respectively. The ratio between the integral emissions of D_γ on W and C correlate very well with the ratio ≈43%/60%=1:1.4.

In Fig. 4 the e–folding lengths of the intensity profiles for D_γ, CII and WI(400.8nm) from W and C limiters are plotted as a function of local electron density.

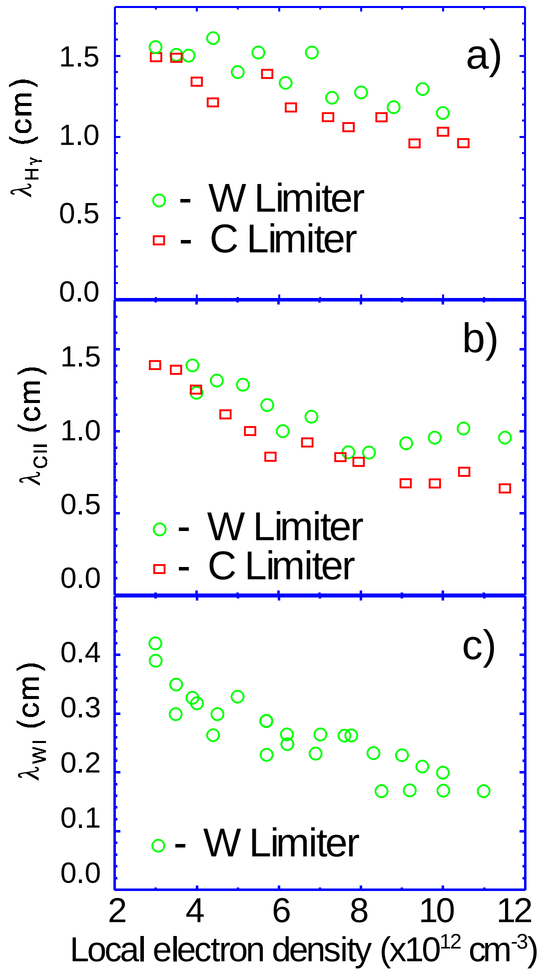

Fig. 4. *e–folding lengths of D_γ (a), CII (b) and WI (c) emission lines at C and W limiters plotted as functions of local electron density*

The intensity distibution of D_γ on C and W surfaces showed practically the same decay length. We can estimate the velocity of the released D atoms $v = \lambda \cdot n_e \cdot < \sigma v >_{ion} < 5 \cdot 10^3 m/s$. This is much smaller than the velocity of reflected D particles $\approx 1 \cdot 10^5 m/s$. The e-folding length of the CII emission varied between ≈15mm at lowest densities and ≈10mm at highest densities. The e-folding lengths are hardly different (≈ 15% more at W limiter) on C and W surfaces. This can be explained as follows: The amount of carbon , which is released in form of hydrocarbons from the tungsten surface is small compared to a graphite surface (see CD-emission in Fig.1). The penetration depth of CII-emissions contributing from hydrocarbons is shorter than from physical sputtering. Additionaly the CII-emission due to reflected C particles on a W surface is larger than on C. The emission from reflected C atoms leads to the broadening of the radial distribution.It can be seen that the e–folding length of the WI emission is very small and comparable to the Larmor radius (ρ_L ≈0.2cm) at the highest density. Thus the redeposition of W^+ at the surface within the first gyromotion is important. The fraction of prompt redeposited W particles can be estimated from an analytical formula [6]. It increases from 45% at lowest densities to 70% at the highest densities.

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