Sputtered Tungsten Atoms Investigated in a Linear Plasma Generator

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Introduction

High Z materials are currently tested as an alternative to carbon as a plasma facing material [1]. Parts of the ITER divertor for instance are planned to be covered with tungsten. These activities call for reliable measurements of eroded fluxes. Most easily these fluxes can be determined by passive spectroscopy, provided the crucial atomic data, i.e. S/XB values, are available. In order to determine this important coefficient, that links the particle flux Γ to the photon flux I by

$$\Gamma = 4\pi \frac{S}{XB} I, \tag{1}$$

particular experiments have been performed in the plasma generator PSI-1.

The use of formula (1) is restricted to an experimental situation where the ionisation length λ_{ion} is small compared to the characteristic scale length of the plasma (for more details see [2]). In the experiment with $\lambda_{ion} = 2\,\text{cm} - 4\,\text{cm}$ this condition was only marginally met. For this reason it was necessary to model measured intensity profiles in front of a tungsten target to obtain the ionisation S and the excitation rate coefficient X separately. Since the branching ratio of the considered line is known ($B \approx 1$ taken from [3]), the S/XB-value can be calculated.

Experiment

A negatively biased tungsten target (1cm × 1cm) was exposed to the cylindrical plasma (radius ≈ 5cm) in the target chamber of the PSI-1 generator. The electron temperature T_e ranged from 2 eV to 20 eV and the electron densities n_e from $6 \cdot 10^{11}\text{cm}^3$ to $7 \cdot 10^{12}\text{cm}^3$, measured by a fast reciprocating Langmuir probe. The radial profile of the electron temperature tends to have a maximum at the plasma rim. By placing the target at this temperature peak of the plasma (see figure 1), we were able to measure the radiation of the eroded tungsten atoms up to electron temperatures of 17 eV. Different plasmas (D, He and Ar) were used to sputter the target. The target was biased negatively (U ranging from -35V to -330V) to give the plasma ions a kinetic energy (above threshold) to produce sufficiently high sputtering rates.

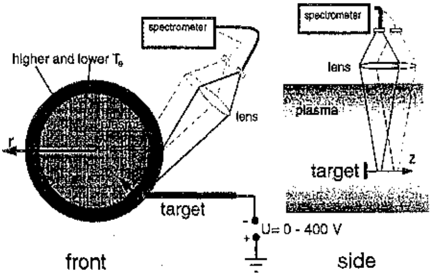

Figure 1: *A negatively biased tungsten target was exposed to the stationary plasma of the PSI-1 linear generator. To obtain intensity profiles spatial scans parallel to the y- and the z-axis with the line of sight were made.*

To determine the S/XB value, the tungsten flux Γ_W into the plasma has to be known. This flux was determined by the loss of weight of the target and dividing by the exposure time ($\approx$ 1h). The reduction of target mass was typically 0.5 to 2 % of the total target mass ($\approx 2\,$g) and could be weighed to an accuracy of 50μg.

By measuring the ion flux Γ_{ion} to the target one can determine the sputtering yield $Y = \frac{\Gamma_W}{\Gamma_{ion}}$. For the different plasmas used the measured sputtering yields are compared to results obtained with ion beam experiments [4] in figure 2.

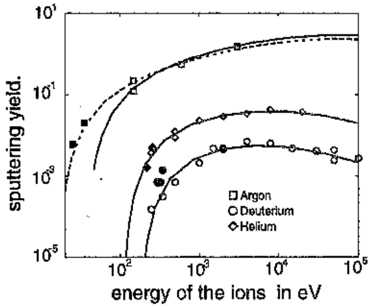

Figure 2: *The obtained sputtering yields (filled black) compared with results from ion beam experiments (open grey) [4]. All fits were obtained using the revised Bohdansky-formula [4].*

With a Czerny-Turner spectrometer and an attached multi-channel analyzer, spectra from 350 to 550nm were measured in front of the target. We observed 28 neutral tungsten lines including the most intense line at $\lambda = 400.9\,$nm. The lines of sight were scanned perpendicular (z-axis) and parallel (y-axis) to the target surface. The intensities were calibrated with an integrating sphere.

An example for an intensity profile perpendicular to the target surface (z-axis) is presented in figure 3. Most of the tungsten atoms leave the target in the ground state and are excited in the plasma. Within the electric sheath which can - depending on the bias voltage of the target - reach up to 2mm into the plasma, the electron density is very low. Consequently, the excitation is weak and the intensity rather small in front of the target. The decrease of intensity further away from the target is dominated by the ionisation of the neutral tungsten atoms and by the divergence of the neutral flux. Therefore, the decrease of the intensity includes information about the ionisation length λ_{ion} and the absolute intensity information about the excitation rate coefficient. The intensity profiles parallel to the target surface (y-axis) strongly depend on the angular distribution of the tungsten atoms. Due to the radial dependence of electron temperature, however, the determination of this distribution is not straight forward.

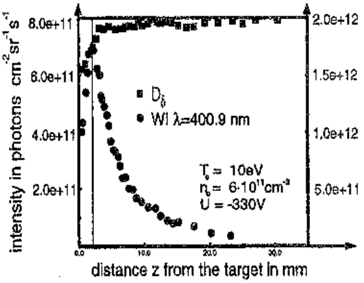

Figure 3: *Intensity profiles perpendicular to the target. The decrease close to the target ($z = 0$) is due to the poor excitation in the electric sheath. The reduction of the WI intensity away from the target is due to ionisation of neutrals and the divergence of the flux.*

Model

If we use a simple three-dimensional model to describe the intensity profiles, we can determine the ionisation rate coefficient S and the excitation rate coefficient X by fitting to the measured profiles. In the model the following assumptions are made:

- The atoms leave the target with an under-cosine (kidney-shaped) angular distribution f_θ. For such a distribution we achieved the best fit to the measured profiles. We choose a fitting function of the type $f_\theta = K\cos\theta\exp\left(\theta\tan\left(\theta_{max}\right)\right)$, were K is the normalization factor and θ_{max} the angle under which the flux is maximal.
- Within the electric sheath ($z < z_0$) the electron density is taken to be zero, whereas $n_e = \text{const}$ is assumed within the observed plasma region ($z > z_0$).

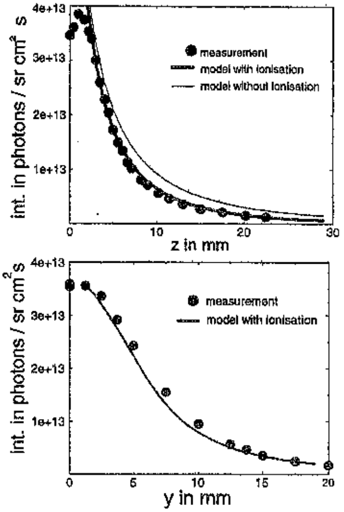

Figure 4: *The modeled intensity profile fits the measured values (here for an argon plasma $n_e = 3 \cdot 10^{12} cm^3$ and $T_e = 4eV$) very good.*

- The atoms leave the target with the average velocity v on a straight line (with coordinates r,θ). The reduction of the neutral density n along the line $\theta = \text{const}$ is described by the equation $\frac{\partial n}{\partial r} = \frac{n_e S}{v} n = \frac{n}{\lambda_{ion}}$ where v is calculated by averaging over the Thompson velocity distribution using the results from [5] to scale to the needed parameter for tungsten.
- After the atoms have entered the plasma, the density n_j of all excited levels is stationary.

The above assumptions lead to the following integral

$$I(z) = W_{ex} \int\int dF dl \frac{f_\theta}{r^2} \exp\left(-\frac{r - r_0}{\lambda_{ion}}\right) \tag{2}$$

for an intensity profile. The pathlength of the atoms in the electric sheath is $r_0 = \frac{z_0}{\cos(\theta)}$. The integration is carried out over the target surface (dF) and the line of sight (dl) considering the given geometric situation. The factor in front of the integral is given by

$$W_{ex} = \frac{1}{4\pi} X B n_e \frac{\Gamma}{v}; \tag{3}$$

it can be obtained by comparing the absolute values of the measurement with the calculated ones. The parameters θ_{max} and λ_{ion} are varied over a large range and the squared difference between model and measured profile is calculated . We find one single minimum for the squared difference as a function of the parameters for all results presented. An example for a fit is shown in figure 4. Using this method the coefficients of interest (S,X and $\frac{S}{XB}$) are given by

$$S = \frac{v}{n_e \lambda_{Ion}}, \quad XB = W_{ex} 4\pi \frac{v}{n_e \Gamma} \quad \text{and} \quad \frac{S}{XB} = \frac{\Gamma}{4\pi \lambda_{Ion} W_{ex}}. \tag{4}$$

The maximum error of these coefficients is dominated by the uncertainty in measuring the electron density ±30% and by the uncertainty with respect to the angular distribution of the neutral atoms. The latter case produces a maximum error for the ionisation length λ_{ion} of ±20%.

Results

The experimental S/XB-values for the WI-line $\lambda = 400.9\,\mathrm{nm}$ and the ionisation rate coefficients S are presented in figures 5 and 6. S/XB has a maximum value of 24 ± 8 in the given range of the electron temperature. Note that the measured ionisation rate coefficient S, is substantially smaller (up to a factor of eight) than predicted by the Lotz-formula . Our values are about twice as large as the ionisation rates for WII measured by Montague et al. [6].

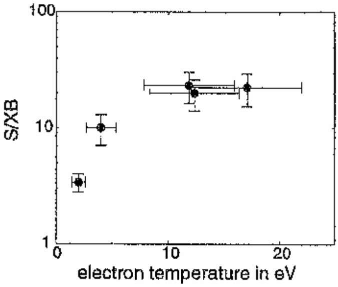

Figure 5: *S/XB is determined with a maximum value of* 24 ± 8.

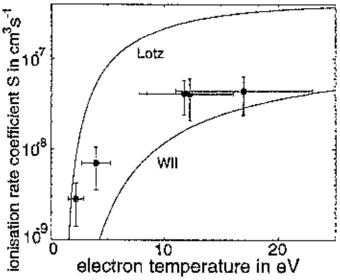

Figure 6: *The ionisation rate coefficient is substantially smaller than predicted by the Lotz-formula and a factor of two above the measured rate coefficient for WII (taken from [6]).*

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