Ground state population of sputtered tungsten atoms by peak emission analysis in PSI-2 argon plasmas

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Introduction

Tungsten (W) is foreseen as plasma-facing components (PFCs) in future fusion reactor [1]. The lifetime of W divertor PFCs will finally be determined physical sputtering. Therefore the initial level population of sputtered W atoms from PFCs is important for the interpretation of spectroscopic data used for the estimation of gross erosion rates. Monoenergetic ion beam bombardment of different metals (e.g. Fe) suggest a release of atoms predominantly in the electronic ground state of more than 95 % [2].

Sputtering experiments in the tokamak TEXTOR with W PFCs exposed to a fully ionizing edge plasma ($T_e > 30\,\mathrm{eV}$) lead to the assumption of a local thermal equilibrium in the fivefold ground term ^{5}D and the $^7S_3$ level with an effective temperature T_W of 0.1 to 0.3 eV of physically sputtered W atoms by energetic plasma impurity ions at surface temperatures (T_surf) of more than 720 K [3]. We show by analysis of the WI peak emission in the low temperature Ar plasma of about 2 eV in the linear plasma device PSI-2 [4], and for mono-energetic ions at the order of 80 eV only the ground level $^5D_0$ is strongly populated.

Theory

In PSI-2, where the experiments have been carried out, the corona equilibrium is valid. This means that particles in the plasma get excited mainly by electron impact and relax by spontaneous emission. The population of excited electronic level N_i is determined by the rate equation:

$$\frac{dN_\mathrm{i}}{dt} = N_0 n_\mathrm{e} \langle v_\mathrm{e} \sigma_\mathrm{X} \rangle_{0\rightarrow \mathrm{i}} - N_\mathrm{i} \sum_{\mathrm{j<i}} A_\mathrm{ij}. \qquad (1)$$

The population is given by the product of the ground level population N_0, the electron density n_e, and the excitation rate $\langle v_\mathrm{e} \sigma_\mathrm{X} \rangle_{0\rightarrow \mathrm{i}}$. The depopulation is driven by the product of N_i times the sum of the Einstein coefficients A_ij for all levels that are energetic lower than i, the excited level. For sputtered particles the axial distance d_x of the peak of emission from target surface is approximately proportional to the velocity of the sputtered atoms v_atom times the lifetime of the upper energy level τ, if the lower level of the transition is strongly populated [5]. Ionization processes are neglected due to the low electron temperature of the plasma.Thus, in this case is the lifetime equal to the reciprocal sum of the Einstein coefficients of the upper level. The kinetic energy of the sputtered atoms is transfered due to the ion collisions during sputtering. This

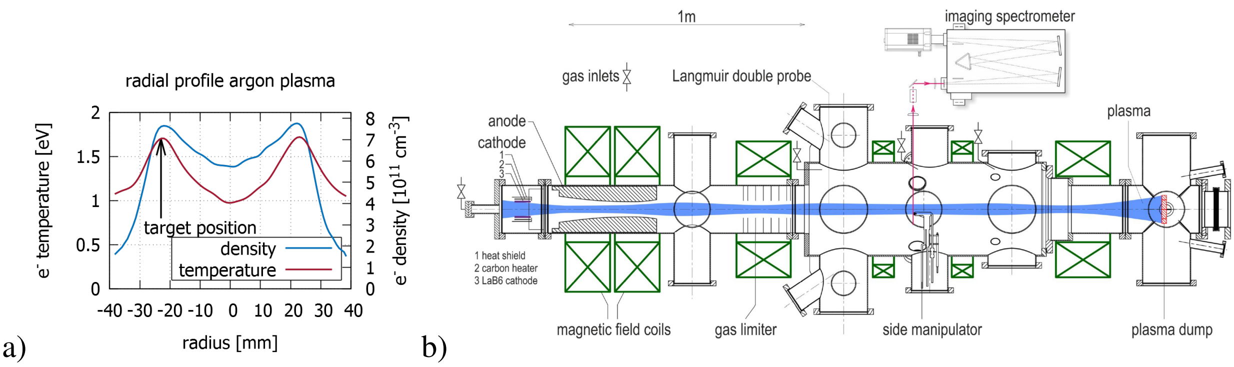


Figure 1: a) *shows the electron temperature and density profile of the argon plasma in PSI-2 and* b) *the experimental setup.*

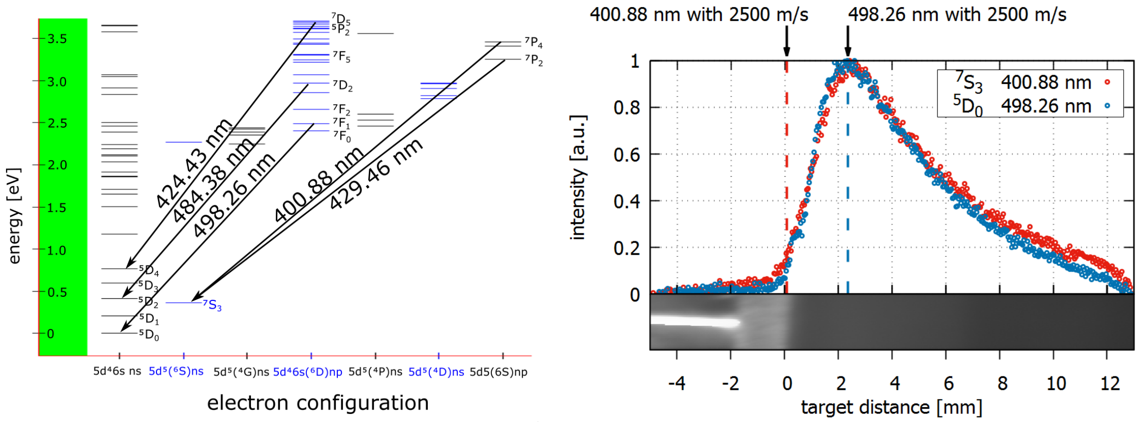
energy can be assumed as constant for a optical thin plasma, like in PSI-2, where ion impacts with the sputtered atoms are negligible. The W atoms leave the target surface with an angular distribution that has to be taken into account for determining the position of the maximum of WI emission. For argon ions (Ar^+) with an impact energy of 80 eV, W is expected to be sputtered with a cosine-like distribution [6]. This reduces the emission peak distance to the target approximately by a factor of two. The position of the light maximum is given by:

$$d_x \approx \frac{v_{\text{atom}} \times \tau}{2} = \frac{v_{\text{atom}}}{2A}. \tag{2}$$

However, due to geometrical losses caused by the dimension of the plasma, the angular distribution, and ionization of the sputtered atoms, the amount of observed W particles is reduced with increasing distance to the target. The intensity of the observed transition is decreasing with the distance to the source and is does not stay constant, like for an infinite target in a non-ionizing plasma as assumed in the theory..

Experimental setup

A small W target ($1.3 \times 1.3\,\text{cm}^2$, $T_{\text{surf}} = 300\,\text{K}$) has been exposed to to the peak temperature and density of the Ar plasma PSI-2 ($T_e = 2\,\text{eV}$, $n_e = 7 \times 10^{11}\,\text{cm}^{-3}$). The measured density and temperature profiles are shown in figure 1 a) and were measured with a Langmuir probe. Under these conditions ionization is almost negligible and the losses are purely dominated by geometrical effects. The experimental setup is shown in figure 1 b). The tungsten target was mounted on the side manipulator and biased with $U_{\text{bias}} = -100\,\text{V}$. The plasma potential of $U_{\text{potential}} = -20\,\text{V}$ reduces the impact energy of the single ionized Ar to 80 eV. The horizontal direction in front of the target was observed with an imaging spectrometer. The spatial evolution in horizontal axis amounts to $50\,\mu\text{m/pixel}$. The spatial development of different W I lines has been observed.



a) b)

Figure 2: a) *is the reduced Grotrian diagram of W I, adopted from [7]* . b) *shows the behavior of two lines and the position where the lines should peak, if they are populated in the moment they enter the plasma. The dashed lines show the expected point for the WI emission peak with a velocity of* 2500 m/s *determined by eq.* (2). *The picture on the bottom shows the target recorded with the spectrometer in the zeroth order and open slit.*

Results

In figure 2 a) a reduced Grotrian diagram of W I with the investigated transitions is shown. In-between the fivefold ground state the energy gap between the lowest level $^5D_0$ and the $^5D_4$ is about 0.8 eV. The $^7S_3$ level is 0.4 eV higher than $^5D_0$. These transitions were chosen because the branching ratio of the upper level for this transition is favorable and so the equilibrium between excitation and relaxation is dominated by this transition.
The mean velocity v_{mean} for sputtered W in an argon ion beam with impact energy of 80 eV is approximately 2500 m/s [8]. This v_{mean} is taken in first approximation as starting velocity v_{atom}. The graph in figure 2 b) shows an exemplary behavior of two WI lines in axial direction in front of the W target. The transition at 400.88 nm is the most prominent for tungsten and the 498.26 nm is a ground state transition with high intensity and high branching ratio. These lines have a very similar behavior even though the lifetime of the upper level of the 400.88 nm line is a factor of 30 lower than the lifetime of the 498.26 nm line. The expected peaks of the maximum are marked by the arrows. The ground term transition is in a good agreement with this position whereas the other line peaks further away from the target. Transitions of other levels are documented in table 1. The velocity v_{atom} that results out of the position of the emission maximum is given.

Conclusion

This data shows, that for a target at room temperature bombarded with mono-energetic ions at impact energy of 80 eV W is sputtered primarily in the lowest ground level $^5D_0$. In this case of a

lower Level	Wavelength [nm]	Position maximum d_x [mm]	Einstein coefficient upper level A [10^5 s^{-1}]	Derived velocity v_{atom} [m/s]
$^5D_0$	498.26	2.34	5.3	2485
$^5D_2$	484.38	1.80	33.7	12132
$^5D_4$	424.43	4.05	14.4	11664
$^7S_3$	400.88	2.43	164.7	80190
$^7S_3$	429.46	2.20	131.5	58212

Table 1: *The velocity of the sputtered particles results out of the measured position of emission maximum, and the Einstein coefficient of the upper level are taken from [7].*

low ionizing plasma, all other levels are most likely populated subsequently in the plasma. The maximum of emission would apparently be reduced if ionization of the plasma would become stronger. Figure 3 provides an overview for the deviation of the investigated lines to the position of their emission maximum. The ground level transition is in a good agreement, all other lines peak at positions too far away from the target compared to their Einstein coefficient and velocity. The consequence is, that these levels are not populated during sputtering. They are obviously populated later in the plasma, which takes some time.

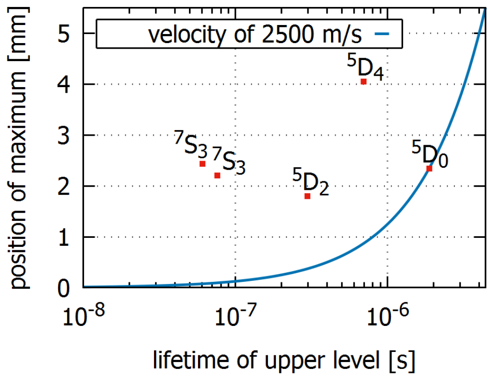


Figure 3: *Shows the the lower level of the investigated transition at the position of where the emission maximum is detected, the blue curve is the theoretical value for a velocity of* 2500 m/s.

Acknowledgment

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