An analytical model for the electric field and particle tracing at surface vicinity in plasma-surface interaction experiments

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1. Introduction

The study of plasma–surface interaction processes is important for a successful realization of the international ITER project. It is necessary to determine the inflow and outflow of fuel and impurity particles along the wall, to predict hydrogen isotope retention, which should be avoided, and plasma–facing components (PFC) erosion determining their life time.

It has been shown [1] that increasing of the magnetic field inclination angle causes a negligible influence on the floating potential, however both the length of the magnetic presheath and the potential drop there are increasing. The angle and energy distributions of the plasma species impinging on the PFC surface have a strong influence on the physical sputtering. The movement of species just before impact is strongly determined by the local electric and magnetic fields in the surface sheath. A useful analytical approximation for the electric potential profile is suggested (AP-model) which is simpler than the integral equations in [1-2]. Using this AP-model the influence of the magnetic field inclination angle on the angle and energy distributions of particles reaching the wall and thus on the effective sputtering is analyzed for various first wall materials. This AP-model can be used for refining the modeling of the plasma-surface interaction experiments by the ERO code, for instance, at JET ITER-like wall [2] or at linear device PSI-2 [6]. In the Monte-Carlo 3D local plasma impurity transport ERO code a purely numerical approach was used for calculating of the traced particle trajectories. We have developed an analytical solution (APA-model) for the very last part of the trajectory just before the surface impact, including the varying sheath E-field.

2. An approximation for the sheath potential profile in case of oblique magnetic field

For a potential profile description in a magnetic presheath (mps) we have made two assumptions. Firstly, as the magnetic presheath is quasineutral, the ion and electron density difference related to the electric field potential is small. This allows assuming a linear dependence as a first order approximation:

$$n_i - n_e = \Delta n_{\mathrm{mps}} \frac{\lambda}{\lambda_{mps}} \tag{1}$$

where n_e and n_i are the electron and ion densities normalized by plasma density, $\lambda = e(\varphi - \varphi_0)/(kT_e)$ – represents the normalized potential, φ_0 is the potential at the sheath/presheath boundary, $\lambda_{mps} = \ln \cos\alpha$ is the normalized potential drop in the magnetic presheath as derived in [1], α is an angle between the magnetic field and the surface normal, Δn_{mps} is the ion and electron density difference at the magnetic presheath/the Debye sheath boundary, where $\lambda = \lambda_{mps}$.

Secondly, we assume the electric field is equal to the value of average electric field in the magnetic presheath at $\lambda = \lambda_{mps}/2$:

$$\left.\frac{d\lambda}{d\xi}\right|_{\frac{\lambda mps}{2}} = \frac{\lambda_{mps}}{L_{mps}} \tag{2}$$

where ξ is the distance from the surface in units of the Debye length, $L_{mps} = 2 \cdot \rho_{iCs}/r_D \cdot \sin\alpha$ is the magnetic presheath length, ρ_{iCs} is the Larmour radius for ion acoustic velocity.

Solving the Poisson equation $\Delta\lambda = n_e - n_i$ and taking into account that the potential drop λ and electric field in plasma are zero we obtain the following dimensionless approximation for the potential distribution in the magnetic presheath:

$$\lambda = \lambda_{mps} \cdot \exp(-\sqrt{-\frac{\Delta n_{\mathrm{mps}}}{\lambda_{\mathrm{mps}}}} \cdot (\xi - \xi_{mps})) \tag{3}$$

where $\Delta n_{\mathrm{mps}} = -\frac{\ln(\cos\alpha)}{((\rho_{iCs}/r_d)\cdot\sin\alpha)^2}$ and ξ_{mps} is the magnetic presheath/the Debye sheath boundary.

In the Debye sheath the solution of the Poisson's equation was found as following:

$$\lambda(\xi) = \lambda_w + Q - Q \cdot \exp(-a \cdot \xi) \tag{4}$$

where λ_w is the value of the floating potential and parameters a and Q depend on the plasma parameters and magnetic field strength and angle:

$$\lambda_w = \frac{e\cdot(\varphi_w - \varphi_0)}{k \cdot T_e} = \frac{1}{2}\cdot \ln\left(2\pi \frac{m_e}{M_i} \cdot \frac{T_e + T_i}{T_e}\right) \tag{5}$$

$$a = \frac{\sqrt{-\Delta n_{mps}\cdot\lambda_{mps}} - \sqrt{2\exp(\lambda_w) + 4\cdot\cos\alpha\cdot\sqrt{1-(\lambda_w - \lambda_{mps})} + C_1}}{\lambda_w - \lambda_{mps}}$$

$$Q = \frac{1}{a}\cdot\sqrt{2\exp(\lambda_w) + 4\cdot\cos\alpha\cdot\sqrt{1-(\lambda_w-\lambda_{mps})} + C_1} \tag{6}$$

$$C_1 = -\Delta n_{mps}\cdot\lambda_{mps} - 6\cdot\cos\alpha$$

The coordinate ξ_{mps} of the magnetic presheath/the Debye sheath boundary was obtained from (4):

$$\xi_{mps} = \frac{-1}{a}\ln\left(\frac{\lambda_w - \lambda_{mps} + Q}{Q}\right) \tag{7}$$

Figure 1 presents the good agreement of the potential profiles calculated using the approximated potential model (AP-model) given by (3) and (4), the Chodura and Stangeby potential distributions [1, 3] and respective particle-in-cell (PIC) simulations performed with the SPICE2 code [4] ($T_e = T_i = 30$ eV, $B = 3$ T, $n=10^{14}$ cm^{-3}, $\alpha = 80°$).

Using the AP-model the magnetic field angle influence on the angular distribution of impinging on the surface ions was investigated. It was found that plasma density and magnetic field strength practically do not affect the most probable incident ion angle (figure 2). As the most of the potential drop in a strong oblique magnetic field occurs in the magnetic presheath, the increase of the E-field with the plasma density in the Debye sheath practically doesn't affect ion incident angles. The magnetic field strength variation doesn't change the character of ions movement in the magnetic presheath.

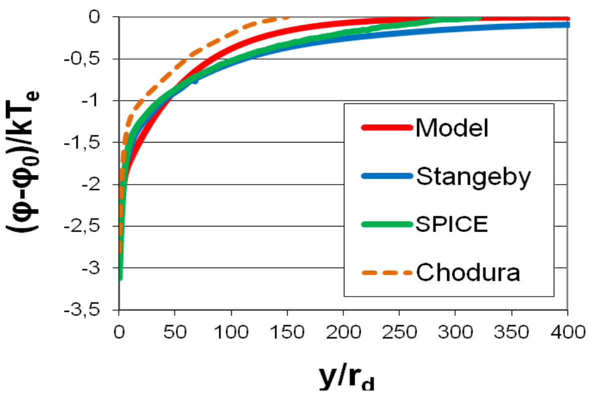

Fig.1. The potential profiles obtained from [2], AP-model, code SPICE2 and [3] (T_e=T_i=30eV, n=10^{14}cm^{-3}, B=3.2 T)

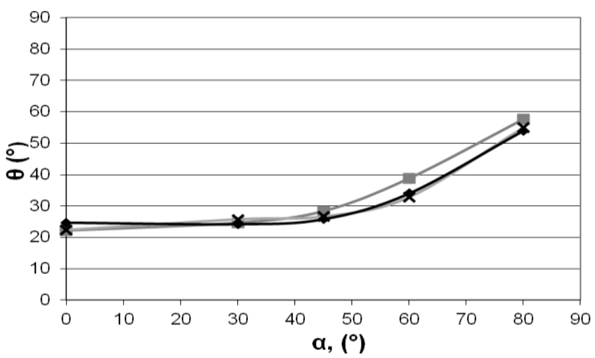

Fig.2 The most probable incident ion angle dependence on the magnetic field angle for different plasma density: n=10^{12}cm^{-3}-(■), 10^{14}cm^{-3}-(▲), 10^{16}cm^{-3}-(**X**) (T_e=T_i=30eV, B=3.2 T)

3. The analytical model for the ion motion in the Debye sheath

For calculation of the angular and energy distribution of incident ions the AP-model was extended with an **A**nalytical solution for the particle motion just before the impact with surface (APA-model). Dividing the last part of the trajectory by several sub-layers we assume in each sub-layer the constant E-field taken from the AP-model. The equations of motion in the electric and magnetic fields and equation for y coordinate (normal to the surface) are integrated in each sub-layer successively. The resulting expressions for the velocity components are obtained using the kinetic energy conservation law in each sub-layer and the assumption of negligible value of $\omega \cdot \Delta t$, where $\omega = qB/Mc$, Δt – particle transit time in a sub-layer. Using the calculated velocities particle impact energy and angle on the surface were obtained.

The suggested model can be easily applied for different plasma and experiment conditions. The angular distributions obtained from APA-model, SPICE2 code and PIC-code [5] are in good agreement (figure 3). The angular distribution from ERO code is more narrow however it has a maximum nearly at the same position.

4. Dependence of the sputtering yield on the magnetic field inclination angle

Using obtained angular and energy distributions the dependence of the sputtering coefficient on the magnetic field angle was calculated by a numeric integration with the Eckstein formula [7] (figure 4). The results for ERO code and AP-model are similar despite the different angular distributions (deviation between them is within 30%): by increasing the angle of the magnetic field from 0° to 45°, the sputtering coefficient gradually grows, but further, from 45° to 80°, the coefficient increases almost 3 times.

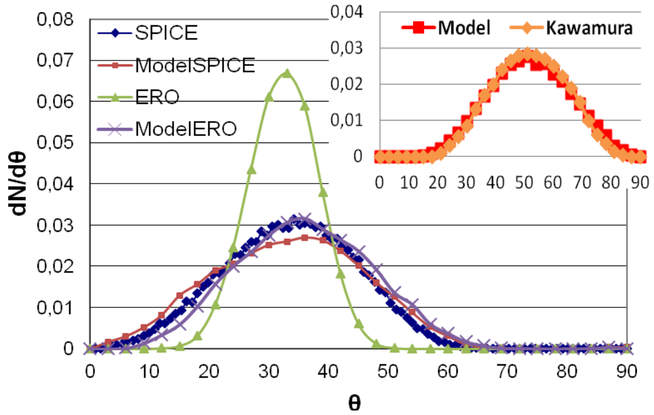

Fig.3. Angular distributions calculated from APA-model compared with SPICE2 (T_e=T_i=30eV, n=10^{14}cm^{-3}, B=3T), ERO (T_e=T_i=20eV, n=3·10^{12}cm^{-3}, B=4.1T) for α = 60° and with [5] (T_e=T_i=30eV, n=10^{12}cm^{-3}, B=5 T) for α = 70°

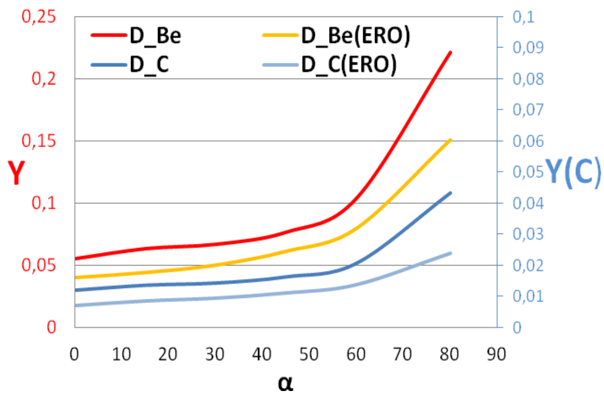

Fig.4. The magnetic field angle influence on the sputtering yield for Be and C from AP-model and from ERO (T_e=T_i=20eV, n=3·10^{12}cm^{-3}, B=4.1T)

5. Conclusion

In this work the useful analytical approximation for the electric potential profile in the presence of the oblique magnetic field (AP-model) and the analytical solution for the particle motion just before the impact with surface (APA-model) are suggested. They are in a good agreement with the Chodura and Stangeby solutions and respective PIC simulations performed with the SPICE2 code. It is found that plasma density and magnetic field strength practically do not affect the most probable incident ion angle. The effective sputtering yield considerably increases at magnetic field inclination angles more than 45˚.

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