§24. Kinetic Effects of Plasma on Physical Sputtering Yield

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Simulation codes of impurity transport are employed for various devices[1, 2, 3] to investigate the transport in the plasma and the plasma-wall interactions such as erosion and redeposition. One of the essential physics in the codes is that of impurity generation on a plasma-facing surface. In these codes, the physical sputtering yield due to the background plasma is calculated by an empirical model and a Monte Carlo code based on the binary collision model. The calculation of the yield is, however, carried out without magnetic field[4]. That can lead to an incorrect estimation if the incident velocity on the the surface is nearly parallel to it due to the gyro-motion; Therefore, the particle flux for each incident energy and angle have been calculated by PIC (particle-in-cell) simulation in this work.

We have developed a 1D electrostatic PIC simulation code with a 3D velocity space. We employed the distribution function given in our previous work in the parallel velocity space and a Maxwellian with the temperature T_i in the perpendicular velocity space. The other boundary, $x = L$, is assumed to face an electrically floating wall and thus, the charged particles crossing the boundary are removed from the simulation box. The electrostatic potential is solved by Poisson's equation at each time step with the boundary condition, $\phi(0) = 0$ and $d\phi/dx|_{x=L} = -E_\mathrm{surf}$, where the surface electric field, E_surf, is determined from the accumulated charge on the surface. The spatial coordinate, x, is normalized by the Debye length at $x = 0$. A uniform magnetic field with angle, φ, relative to the x-coordinate can be applied on the plasma. We choose a set of plasma parameters from the deuterium SOL plasma of TEXTOR[1]; plasma temperature, $T_\mathrm{i} = T_\mathrm{e} = 40\mathrm{eV}$, and density, $n = 4\times10^{18}\mathrm{m}^{-3}$, and the magnetic field, $B = 2.25\mathrm{T}$, at the last closed flux surface (LCFS). Non-dimensionsional parameter, $\rho_\mathrm{i}/\lambda_\mathrm{De} \simeq 17$ at LCFS, represents normalized mangeitc field strngth or plasma density. It stands for a ratio of the ion thermal Larmor radius, $\rho_\mathrm{i} \equiv \sqrt{mT_\mathrm{i}}/qB$, to the Debye length.

The kinetic information associated with the particle injections on the surface can be seen clearly in a contour plot of the particle flux on the surface in Fig. 1. The plot shows the deuterium ion flux as a function of the incident energy and the angle, θ, measured from the surface normal. The magnetic field is given by the non-dimensional parameter, $\rho_\mathrm{i}/\lambda_\mathrm{De} = 15$. The angle of the magnetic field line is chosen to be $\theta = 83°$ in this simulation. The acceleration makes both the parallel and perpendicular velocities larger because the polarization drift due to the parallel motion is large in the case of the shallow magnetic field. It also increases the sputtering yield from 2.3% to 4.5% when $T_\mathrm{i} = T_\mathrm{e} = 40\mathrm{eV}$.

We carried out parameter scans of the yield for the nondimensional parameters, $\rho_\mathrm{i}/\lambda_\mathrm{De}$. The angle of the magnetic field was taken from $\theta = 0°$ to $\theta = 86.4°$. Figure 2 shows the clear dependence on magnetic field angle. The enhancement of the yield for shallow impacts is observed at large magnetic field angle, $\varphi > 75°$. The plasma without magnetic field gives the same result as that of the angle, $\varphi = 0°$. Smaller $\rho_\mathrm{i}/\lambda_\mathrm{De}$, i.e. strong magentic field or small density, gives a larger yield because the gyrating motion makes more and more shallow impacts. This effect is, however, smaller than that of the magnetic field angle.

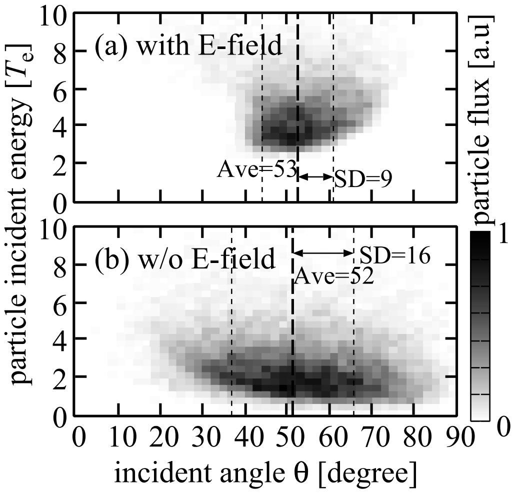

Fig. 1: Contour plot of the particle flux in the case of magnetized plasma for (a) with and (b) without electric field. The averaged angle and the standard deviation of the flux are shown as Ave and SD in the figure. The magnetic field angle is $\theta = 83°$.

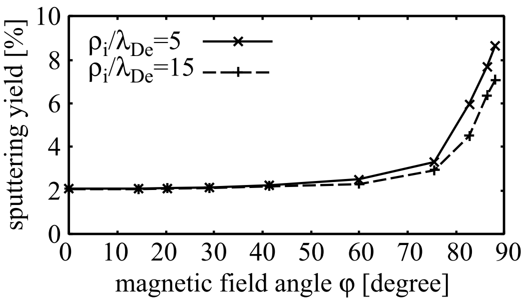

Fig. 2: Physical sputtering yield calculated by the Bohdansky-Yamamura model from the PIC simulation results; dependences on $\rho_\mathrm{i}/\lambda_\mathrm{De}$.

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