§17. Kinetic Analysis of Ion Incident Angle Distribution on a Plasma-facing Wall

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Understanding of the plasma-surface interaction (PSI) has been recognized as a crucial physical and engineering issue in fusion devices. One of the essential physical factors in PSI is impurity sputtering from the plasma-facing wall by ion impacts. In addition to the plasma flux to the surface, the incident angle is also essential to evaluate the sputtering yield. In the precedent studies$^{1,2)}$, they give the parameter dependence of the averaged incident angle only. Our work is motivated by the necessity of more detailed analyses including the distribution of the incident angle to understand PSI deeply.

We employ 1D particle-in-cell (PIC) simulation technique. The coordinate system used here is illustrated in Fig. 1. The spatial coordinate x is taken to be normal to the wall surface and the system length, or the position of the wall, is denoted by L. The plasma profiles such as density n and potential ϕ are assumed to vary only in the x direction. We have developed a PIC code to solve the equations of motion and Poisson's equation self-consistently. The magnetic field is assumed to be uniform and its direction is specified by the angle φ in the x-y plane, or $\mathbf{B} = B\cos\varphi\hat{\mathbf{x}} + B\sin\varphi\hat{\mathbf{y}}$. The coordinate y is chosen as a arbitrary direction on the surface. The incident angle of the ion is denoted by θ, i.e. $\cos\theta = \hat{\mathbf{x}}\cdot\mathbf{v}/v$. Here velocity of each particle hitting the wall surface is denoted by $\mathbf{v}$. The wall is perfectly absorbing and electrically floating. The electric field at $x = L$ is determined by the Gauss' theorem from the charge on the wall. Since the mean-free-path of the collisions between ions, electrons and neutrals are much longer than the Larmor radius, particle source is not included in the simulation. Instead, we place a source boundary at $x = 0$, where the velocity distribution is fixed to a given function which models kinetic effects of the collisional presheath$^{3,4)}$.

The energy flux distributions as a function of the incident angle θ are shown in Fig. 2. We used the thermal ion Larmor radius of $r_L/\lambda_{De} = 4$, where the Debye length is denoted by λ_{De}. The cross, plus and asterisk marks represent the simulation results for $B_x/B = 15/16$, $1/2$ and $1/16$ respectively. Smaller B_x/B corresponds to more shallow magnetic field lines on the surface. In order to describe the characteristics of the profiles, we introduce a fitting function

$$Q(\alpha,\beta,\gamma;\theta) = \alpha\sin 2\theta\exp\left[-\beta(\theta-\gamma)^2\right], \qquad (1)$$

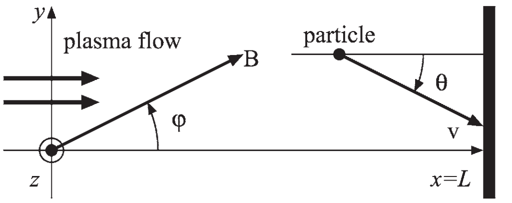

Fig. 1: Coordinate system used in the PIC simulation.

where the parameter α, β and γ are functions of the magnetic field strength and direction. The factor, $\sin 2\theta \equiv 2\sin\theta\cos\theta$, represents variations proportional to the solid angle, $\sin\theta$, and the normal component of the flux, $\cos\theta$. We obtained the best fitting parameters and plotted them as the solid, dashed and dotted curves in Fig. 2. The fitting curves agree with the simulation results quite well.

We examined the dependences of the parameters β and γ in Eq. (1) on the magnetic field. The parameter α is ignored in this work because it represents the normalization factor and can be obtained from the other parameters. We carried out the particle simulation for the following parameters; $r_L/\lambda_{De} = 1$, 2, 4, 8, 16 and 32, and $B_x/B = 1/16, 1/8, 1/4, 1/2, 3/4, 7/8$ and $15/16$. $r_L/\lambda_{De} = 1/8 - 32$ and $B_x/B = 1/32 - 31/32$.

From a parameter survey for magnetic field strength B and its direction φ, we obtained a fitting form of the normalized energy flux as Eq. (1) with the following variables:

$$\beta = 7.2\exp\frac{\beta_1\varphi^2}{\beta_2 - \varphi}, \qquad (2)$$

$$\gamma = \frac{\pi}{2}(1-\cos\varphi) - \varphi^2\sqrt{\frac{\pi}{2}-\varphi}\left[\gamma_1\varphi - \gamma_2\left(\frac{\pi}{2}-\varphi\right)\right], \qquad (3)$$

where the four coefficients in the equations are determined as follows; $\beta_1 = 0.34 + 0.30\tanh[1.2(\ln(r_L/\lambda_{De}) - 2.1)]$, $\beta_2 = 2.0 + 0.38\tanh[1.2(\ln(r_L/\lambda_{De}) - 2.1))]$, $\gamma_1 = 0.22 + 0.18\tanh[0.64(\ln(r_L/\lambda_{De}) - 1.5)]$ and $\gamma_2 = 0.41 - 0.28\tanh[1.3(\ln(r_L/\lambda_{De}) - 0.37)]$. The total energy flux, i.e. $\int_0^{\pi/2} Q\,d\theta$, is proportional to B_x/B in our simulation because we fixed the electron temperature and changed B_x/B and B only. Although these results were obtained from the PIC simulation for $1/8 < r_L/\lambda_{De} < 32$, they can be applied for the case of weaker or stronger magnetic field because saturation occurs on the parameter β and γ. The fitting form, Eqs. (1) – (3), can provide the θ distribution for asymptotic cases such as $\varphi = \pi/2$ and $r_L = 0$. This is a great advantage of this approach over the PIC simulation because vast amount of simulation time is required for such cases.

1) J. P. Gunn, Phys. Plasmas 4 (1997) 4435
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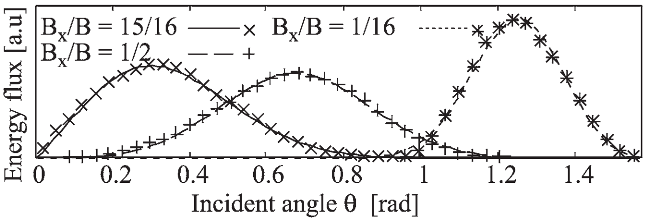

Fig. 2: Distribution of energy fluxes as functions of the ion incident angle θ. Simulation results (×, + and $*$ marks) and fitting curves (solid, dashed and dotted curves) show quite good agreements.