§13. Charging of Dust Particle in SOL/Divertor Plasma

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The dust particle in relatively low temperature plasmas at SOL/divertor region is negatively charged due to the high mobility of plasma electrons. The dust charge q_d ($=-Z_d e$, $Z_d > 0$) is mainly determined by the plasma particle fluxes to the dust particle:

$$\frac{dq_d}{dt} = I_{di} + I_{de} \quad (1)$$

where I_{di} and I_{de} are the ion and electron absorption current to the dust particle, respectively. According to the OML theory for the spherical shape dust, the ion current with the radius R_d is obtained with respect to the relative speed of the ion flow velocity $\vec{V}$ to the dust velocity $\vec{\upsilon}_d$:

$$I_{di} = \frac{\pi R_d^2 Z_i e\, n_i \upsilon_{th,i}}{2u}\{\frac{2u}{\sqrt{\pi}} e^{-u^2} + [1+2(u^2+\frac{Z_d Z_i e^2}{4\pi\varepsilon_0 R_d T_i})]\mathrm{erf}(u)\} \quad (2)$$

Here $u = \left|\vec{V}_i - \vec{\upsilon}_d\right| / \upsilon_{th,i}$ is the relative speed normalized by the ion thermal speed $\upsilon_{th,i} (= \sqrt{2T_i / m_i})$. The parameters n_i, T_i, and Z_i are the density, the temperature and charge state of plasma ions, respectively. On the other hand, since the thermal speed of electrons is much higher than its flow speed, the electron current I_{de} is expressed for the case of Maxwell velocity distribution:

$$I_{de} = -e\pi R_d^2 n_e \sqrt{\frac{8T_e}{\pi m_e}} \exp(-\frac{Z_d e^2}{4\pi\varepsilon_0 R_d T_e}) \quad (3)$$

where n_e and T_e are the electron density and temperature, respectively. The equilibrium charge $Z_{d,eq}$ of the dust particle is determined by the relation of the equal fluxes:

$$\frac{1}{2u}\{\frac{2u}{\sqrt{\pi}} e^{-u^2} + [1+2(u^2+\frac{Z_i e}{4\pi\varepsilon_0}\frac{T_e}{T_i}\xi_{d,eq})]\mathrm{erf}(u)\} = \sqrt{\frac{4}{\pi}\frac{m_i}{m_e}\frac{T_e}{T_i}} \exp(-\frac{e}{4\pi\varepsilon_0}\xi_{d,eq}) \quad (4)$$

Here the quantity $\xi_{d,eq}$ is defined as $Z_{d,eq} / R_d T_e$, which is the function of the relative speed and the temperature ratio of plasmas. For hydrogen plasmas, the dependence of the quantity $\xi_{d,eq}$ on the relative speed is shown in Fig.1 for the several temperature ratios, where the dust radius and the electron temperature are denoted with the unit in mm and eV, respectively. The equilibrium dust charge with the radius of 1mm and the small relative speed (u <1.0) in the plasma temperature of 10 eV becomes as high as 1.74×10^4 for the lower relative speed. In the case of the low relative speed, the dependence of the relative speed is weak and the maximum charge $Z_{d,eq}$ at the medium temperature ratios ($T_i/T_e \sim 3.0$). On the other hand, the higher the relative speed becomes, the lower the charge state of the dust particle becomes and the higher temperature ratio brings about the lower charge state. The higher normalized relative speed, which means the ion flux is larger than the electron flux to the dust particle, leads the positive charge state of the dust ($Z_d < 0$).

The charging time $\tau_{ch,j}$ ($j = e, i$) of the dust particle is defined as the relaxation time from the infinitesimal deviation from the equilibrium dust charge to the equilibrium state. In Fig.2 the charging rates are shown as a function of the normalized relative speed for the case of the dust particle with the radius 1 μm in the hydrogen plasma of $n_e = 10^{19}$ m^{-3}, $T_e = T_i = 10$ eV. The charging time (~ few nanoseconds) of the dust around $R_d \sim 1$ μm in the usual SOL/Divertor plasma of tokamaks is so fast compared to the dynamics of the dust particle (> few milliseconds).

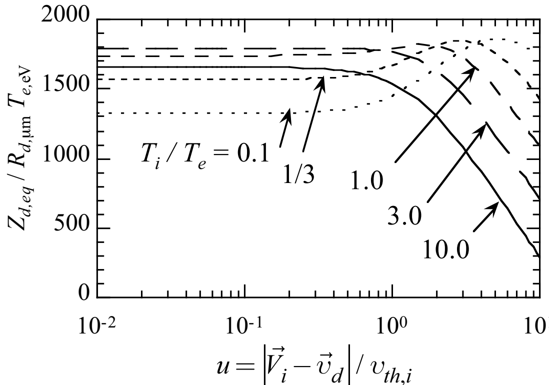

Fig.1 The equilibrium charge state of the hydrogen plasma as a function of the normalized relative speed u for the several plasma temperature ratios.

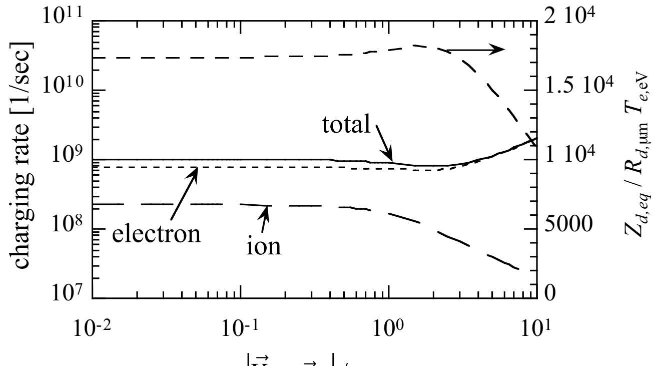

Fig.2 The charging rates of plasma ion (dashed line), plasma electrons (dotted line) and the total one (straight line) as well as the equilibrium dust charge (short dashed line) as a function of the relative speed. Here the dust particle with the radius 1 μm is immersed in the hydrogen plasma of $n_e = 10^{19}$ m^{-3}, $T_e = T_i = 10$ eV.