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Theory of a plane probe in a collisional plasma with fast electrons producing secondary electrons at the probe surface

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Introduction

Fast electrons can strongly influence the current-voltage characteristics of a Langmuir probe (see [1, 2] and references there). Thus, the development of corresponding analytical models and numerical simulations is of high interest for plasma diagnostic techniques using electrical probes. The aim of our work is to develop a model of the plasma-wall transition (PWT) region with different populations of electrons, including effects of collisions between charged and neutral particles, and secondary-electron emission (SEE) at a plane probe surface. We demonstrate that this model allows us to estimate the secondary-electron emission coefficient of the plane-probe material. For sufficiently high SEE, the probe characteristic shows an interesting feature in that it contains three floating-potential values [3]. In this work we consider a plane probe immersed in a low-temperature plasma, with three electron populations: two thermal ones (typical of the Double-Plasma (DP) machine [4]), and one high-energy electron beam [5] originating from an electron gun. The probe surface is perfectly absorbing with respect to the incoming particles and emits secondary electrons due to the impact of beam electrons.

1. THEORY

1.1 Negatively biased probe

In front of a plane probe, located at the left-hand side of our model system and biased negatively with respect to the surrounding unperturbed plasma, a positive-space-charge region ("ionic sheath") is formed, connected with the bulk plasma by a quasi-neutral "presheath" region. In our model we assume plane geometry and a vanishing (or normal to the probe surface) magnetic field, so that we have a collisional presheath (CP) determined by ion-neutral collisions and electron-impact ionization.

We derive the expression of the total current at the sheath entrance (SE), assuming that this current is mainly given by those electrons which did not suffer inelastic collisions inside the CP. This assumption looks reasonable because only the fastest electrons can reach the wall (and contribute to the current) and during the inelastic collisions with neutrals the electron loses the part of its energy. For each electron component we take into account a cut-off distribution function, which is due the absorption of superthermal electrons by the probe. Thus, the total electron current is given as

$$I_n^e = Se\left[\sum_{j=1}^{2} n_{\infty,j}^t \sqrt{\frac{kT_{\infty,j}^t}{2\pi m_e}} \frac{2}{1+erf\sqrt{eU_{tot}/kT_{\infty,j}^t}} \exp\left(-\frac{eU_{tot}}{kT_{\infty,j}^t}\right) + (1-\delta) n_\infty^b v_{ft} \right.$$
$$\left. \times\left(3+erf\frac{v_{c0}-v_{sh}}{v_{ft}}\right)^{-1} \left\{\frac{1}{\sqrt{\pi}}\exp\left[-\left(\frac{v_{c0}-v_{sh}}{v_{ft}}\right)^2\right] + \frac{v_{sh}}{v_{ft}}\left(1-erf\frac{v_{c0}-v_{sh}}{v_{ft}}\right)\right\},\right] \tag{1}$$

where the first term represents the thermal-electron current and the second one represents the beam- and secondary-electron currents; U_{tot} is the absolute value of the total potential drop between the probe and the unperturbed plasma, S is the probe area, $T_{\infty,1,2}^t$ and $n_{\infty,1,2}^t$ are the two thermal-electron temperatures and densities far from the probe; $v_{ft} = \sqrt{kT_\infty^b / m_e}$ is the thermal velocity of the beam electrons, with T_∞^b the fast-electron temperature far from the probe, and $v_{c0} = \sqrt{2eU_{tot}/m_e}$ and v_{sh} are the cut-off velocity and the drift velocity of the beam-electron distribution function, respectively. Here and below we assume $v_{ft} << v_{sh}$. δ is the secondary-emission coefficient, which depends on the energy of the incoming fast electrons, E_{sh}, as in [6]: $\delta = \delta_m (E_p / E_0) \exp\left[2\left(1-\sqrt{E_p/E_0}\right)\right]$, $E_p = E_{sh} - U_{tot}$, where the parameters δ_m and E_0 are characterised by the surface material.

To determine the ion current at the SE we use the fluid model [7]. Assuming that the ion velocity, u_i, there satisfies the Bohm condition [8] $u^i = c_s = \sqrt{k(T_e^* + \gamma T^i)/m_i}\Big|_{SE}$, we obtain the ion current at the SE $I_{sat}^i = Sen_{SE}^i c_s$. Here T_e^* is the electron screening temperature [8] and γ is the "local" polytropic coefficient [9]. For our multi-electron-component plasma T_e^* is given by

$$T_e^* \equiv \frac{e}{k} n^e \left(\frac{dn^e}{d\phi}\right)^{-1}, \qquad n^e = n_1^t(x) + n_2^t(x) + n^b(x) + n^s(x), \tag{2}$$

where $n^t_{1,2}(x)$, $n^b(x)$ and $n^s(x)$ are the thermal- beam- and secondary-electron densities, respectively. Neglecting the fast-electron temperature and the thermal spread of the secondary electrons, we obtain after some transformations

$$T_e^* = \left\{ \sum_{i=1}^{2} \frac{n^t_{\infty,i}}{T^t_{\infty,i}} \left\{ 1 + \exp\left(-\frac{e(\phi(x) - V_p)}{kT^t_{\infty,i}} \right) \left[\sqrt{\frac{e\pi(\phi(x) - V_p)}{kT^t_{\infty,i}}} \left(1 + erf \sqrt{\frac{e\phi(x) - V_p}{kT^t_{\infty,i}}} \right) \right]^{-1} \right\} \right. \tag{3}$$

$$\left. + \sqrt{\frac{m_e}{8e}} \Gamma_0^b \left(\left[E_{sh} - \phi(x) \right]^{-\frac{3}{2}} + \delta \left[V_p - \phi(x) \right]^{-\frac{3}{2}} \right) \right\}^{-1} \left\{ \sum_{i=1}^{2} \frac{n^t_{\infty,i}}{T^t_{\infty,i}} \left[1 + erf\left(\sqrt{\frac{e(\phi(x) - V_p)}{kT^t_{\infty,i}}} \right) \right] \right.$$

$$\left. \times \left[1 + erf\left(\sqrt{\frac{eU_{tot}}{kT^t_{\infty,i}}} \right) \right]^{-1} \exp\left(\frac{e\phi(x)}{kT^t_{\infty,i}} \right) + \Gamma_0^b \left[\frac{2e}{m_e} \left(E_{sh} - \phi(x) \right) \right]^{-\frac{1}{2}} + \delta \Gamma_0^b \left[\frac{2e}{m_e} \left(V_p - \phi(x) \right) \right]^{-\frac{1}{2}} \right\},$$

where Γ_0^b is the beam-electron flux at the collisional-presheath entrance (CPE). This function for the ion-saturation-current regime with $\gamma = 1$ (see [9]) is plotted in Fig. 1. The plasma parameters chosen are typical of DP-machine plasmas: $T^t_{\infty 1} = 0.5eV, T^t_{\infty 2} = 5eV$, $T^i_\infty = 0.1eV, T^{ed}_\infty = 0.3\,eV$, $n^t_{\infty 1} = 9 \times 10^{14} m^{-3}$, $n^t_{\infty 2} = n^b_\infty = 10^{14} m^{-3}$, $n^i_\infty = 1.1 \times 10^{15}\ m^{-3}$. The ion density at the SE, n^i_{SE}, can be obtained from the ion particle and momentum conservation equations [7, 9] as

$$\ln \frac{n^i_{SE}}{n^i_\infty} = -\frac{\nu_i + \nu_{mt}/2}{\nu_i + \nu_{mt}} \ln \left[\left(2\nu_i + \nu_{mt} \right) \cdot \left(\nu_i + \left(\frac{u^i_\infty}{c_s} \right)^2 \left(\nu_i + \nu_{mt} \right) \right)^{-1} \right] \tag{4}$$

where ν_i and ν_{mt} are the electron impact ionization and the ion-neutral momentum transfer collision frequency, respectively; u^i_∞ is the ion average velocity at the CPE. As a result we obtain the total current $I = I^e_n - I^i_{sat} \quad for\ \ V_p < 0$.

1.2 Positively biased probe

For the positively biased probe we assume the potential to be monotonically increasing towards the probe. Then the total electron at the CPE is given by

$$I^e_p = Se \left\{ \sum_{j=1,2} n^t_{\infty,j} \sqrt{\frac{kT^t_{\infty,j}}{2\pi m_e}} + (1 - \delta) n^b_\infty \left\{ \frac{v_{ft}}{\sqrt{\pi}} \exp\left[-\left(\frac{v_{sh}}{v_{ft}} \right)^2 \right] + v_{sh} \left(1 + erf \frac{v_{sh}}{v_{ft}} \right) \right\} \right\}, \tag{5}$$

where we have neglected the contribution of electrons suffering collisions with neutrals and propagating back towards the bulk plasma. In the electron-saturation-current regime, the ion current is negligibly small compared to the electron one. Thus, the total current at the SE (which is the same as the current to the wall) can be given as $I \approx I_p^e \quad for \;\; V_p > 0$.

The total Volt-Ampère characteristics for different values of δ and the same plasma parameters as for Fig. 1 are plotted in Fig. 2; the non-constant δ corresponds to tungsten-probe material.

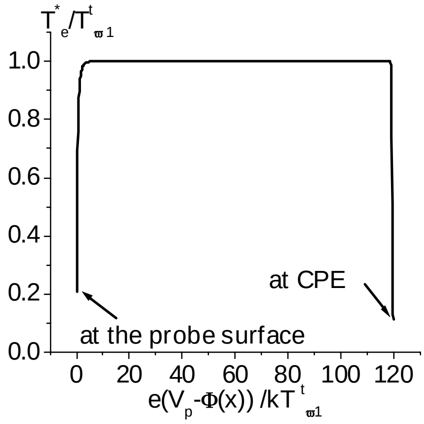

Fig. 1 Normalized screening temperature versus normalized potential drop in the ion saturation regime.

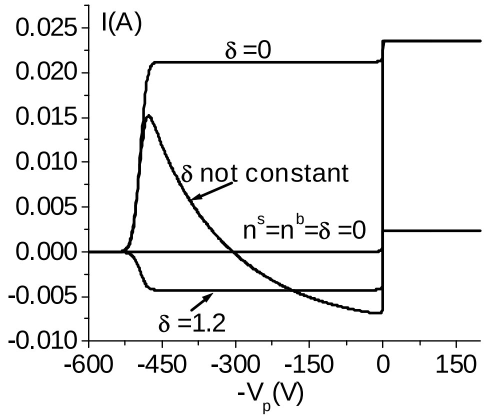

Fig. 2 Volt-Ampère Characteristic including SEE effects

2. CONCLUSIONS

We have presented a theoretical model for the plane probe in multi-electron-component plasmas, including SEE effects and introducing collisional corrections to the ionic current. To check our model, corresponding kinetic (PIC) simulations are planned for the near future.

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