SHEATH FORMATION OF A PLASMA CONTAINING MULTIPLY CHARGED IONS, COLD AND HOT ELECTRONS, AND EMITTED ELECTRONS

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Abstract

A model of sheath formation was extended to a plasma containing multiply charged ions (MCIs), cold and hot electrons, and secondary electrons emitted either by MCIs or hot electrons. In the model, modification of the "Bohm criterion" was given; thereby the sheath potential drop and the critical emission condition were also analyzed.

INTRODUCTION

It is quite well known since Geller's remarks [1] that ion confinement is an important factor in an electron cyclotron resonance ion source (ECRIS). Particularly, it has been pointed out that the ion confinement is closely related to the plasma potential, since many empirical techniques (wall coatings, secondary electron materials, electron injection and biased disks, and gas mixing) were found to lower plasma potential [2]. In this sense, the detailed sheath formation is very important in understanding how multiply charged ions (MCIs), bulk (cold and hot) electrons, and secondary electrons (either by MCIs and bulk electrons) are contributing to the plasma potential (sheath potential drop). The present study was motivated by the fact that the secondary electron yields are strongly dependent on the charge state of the ions and on the incident energy of electrons; secondary electron yield γ_j by ion bombardment is almost linearly proportional to the charge state j, so that the ratio γ_j /j reaches around unity for Ar^{8+} ion [3], and secondary electron yield γ_e by electron bombardment is typically larger than 0.5 for the incident energy larger than 100 eV [4]. Therefore, the contributions of the secondary electron emissions on the sheath formation would be severe if the charge state of ions and/or the energy of electrons are high.

MODEL

We consider an unmagnetized plasma composed of different MCIs, cold and hot electrons, and emitted electrons from the wall. The wall is located at x=0 and is contact with plasma, which is assumed to be zero. The electric field is also zero there. The wall potential V_w is negative with respect to the plasma potential V_s. We assume bi-Maxwellian electrons (cold and hot electrons), which has two different electron temperatures. The secondary electrons are assumed to be emitted from the wall with the same initial velocity v_{em}. The above all considerations are illustrated in Fig. 1.

The potential profile $V(x)$ in the sheath is obtained by solving Poisson's equation,

$$\frac{d^2V(x)}{dx^2} = -\frac{1}{\varepsilon_0}\left[\sum\nolimits_j e_j n_j(x) - e n_e(x)\right], \qquad (1)$$

where $n_e(x) = n_{ec}(x) + n_{eh}(x) + n_{em}(x)$, and n_j, n_{ec}, n_{eh}, and n_{em} are the densities of j-charged ions, cold electrons, hot electrons, and emitted electrons from the wall surface, respectively.

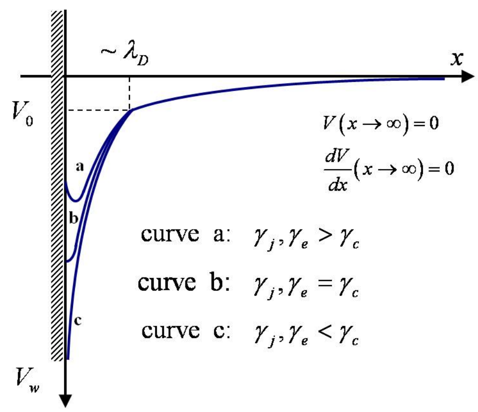

Figure 1: Sheath model & potential variations in front of the wall surface which emits electrons.

The behaviour of the j-charged ions can be described by continuity equation and momentum equation, therefore yielding following equation [5]

$$dn_j/dV = n_j e_j / m_j v_j^2, \qquad (2)$$

where m_j and v_j are the mass and velocity of j-charged ion.

The densities of cold and hot electrons are assumed to obey the Boltzmann relation,

$$n_{ec}(x) = n_{ec0}\exp(\psi), \quad n_{eh}(x) = n_{eh0}\exp(\psi). \qquad (3)$$

Here $n_{ec}(x)$ and $n_{eh}(x)$ are the cold and hot electron densities at x from the sheath edge, and n_{ec0} and n_{eh0} are the cold and hot electron densities at the sheath edge. The dimensionless potential ψ and the ratio (θ) of cold and hot electron temperatures (T_{eh}, T_{ec}) are defined in the following way:

$$\psi = -e\left(V_0 - V(x)\right)/kT_{ec}, \quad \theta = T_{eh}/T_{ec}. \qquad (4)$$

Therefore, ψ is a negative dimensionless potential measured with respect to the potential at the sheath edge.

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The density of the secondary electrons is given by continuity equation and energy conservation,

$$n_{em}(x) = n_{ems} \Big/ \sqrt{1-\psi/\psi_w - N^2\mu/2}\,, \tag{5}$$

with the introduction of the dimensionless potential drop and mass ratio of electron and ion:

$$\psi_w = -e\left(V_0 - V_p\right)\big/ kT_{ec}\,, \quad \mu = m_e/m_j\,, \tag{6}$$

where the initial velocity v_{em} is assumed to the ion sound speed multiplied by a dimensionless factor N:

$$v_{em} = N\sqrt{kT_{ec}/m_j}\,. \tag{7}$$

Using Eqs. (1)-(7) and dimensionless variable $\xi=x/\lambda_D$, multiplying Eq. (1) with the field strength $dV/d\xi$, and then integrating yields

$$\varepsilon_0 E^2 + \left(\sum_j e_j \frac{dn_j}{dV} - e\frac{dn_e}{dV}\right)\Bigg|_{V=0} V = \text{const.} \tag{8}$$

Then Applying sheath edge condition ($V\to 0$ for $\xi\to 0$) gives const.=0 and yields general sheath condition

$$\left(\sum_j e_j \frac{dn_j}{dV} - e\frac{dn_e}{dV}\right)\Bigg|_{V=0} \le 0. \tag{9}$$

Engaging Eq. (2), the differentiations of Eqs. (3) and (5), and applying the general sheath condition (9) we have

$$\frac{kT_{ec}}{e^2}\sum_j \frac{e_j^2 n_{js}}{m_j v_j^2} \le n_{es}, \text{ where}$$
$$n_{es} = n_{ecs} + \frac{n_{ehs}}{\theta} + \frac{n_{ems}}{2\left(\psi_w - N^2\mu/2\right)}. \tag{10}$$

In spite of the discussions on the ion velocities at the sheath edge in multicomponent plasma, if we assume that all ions have the same velocity at the sheath edge [6], Eq. (10) can be written as

$$v_s^2 \ge \frac{kT_{ec}}{m_j}\sum_j \frac{e_j^2 n_{js}}{e^2 n_{es}}. \tag{11}$$

The ion velocity v_s at the sheath edge can be normalized by the ion sound speed $(kT_{ec}/m_j)^2$ and then be rewritten as

$$M^2 \ge \sum_j \frac{e_j^2 n_{js}}{e^2 n_{es}}. \tag{12}$$

According to the formalism in Ref. [7], we can use the relation between the flux of secondary electrons j_{em} from the wall and the fluxes of cold and the hot electrons j_{ec} and j_{eh}, and ions j_i to the wall. Here j_{em} is assumed to be proportional to j_{ec}, j_{eh}, and j_i in the form:

$$j_{em} = \gamma_e(j_{ec} + j_{eh}) + \gamma_j j_i. \tag{13}$$

The proportionality constant γ_e (γ_i) is defined as the number of emitted secondary electrons per incident electron (ion). j_{ec}, j_{eh}, j_{em}, and j_i can be given by

$$j_{ec} = en_{ecs}\exp(\psi_w)\sqrt{kT_{ec}/2\pi\mu m_j}\,, \tag{14}$$

$$j_{eh} = en_{ehs}\exp(\psi_w/\theta)\sqrt{kT_{ec}\theta/2\pi\mu m_j}\,, \tag{15}$$

$$j_{em} = j_{ems}N\sqrt{kT_{ec}/m_j}\sqrt{1-2\psi_w/N^2\mu}\,, \tag{16}$$

$$j_i = en_{es}M\sqrt{kT_{ec}/m_j}\,. \tag{17}$$

From Eqs. (13)- (17) we obtain

$$n_{ecs} = \frac{n_{es}\left(1-G_j\right)}{1+\beta+G_e},\quad n_{ehs} = \frac{\beta n_{es}\left(1-G_j\right)}{1+\beta+G_e}, \tag{18}$$

$$\text{and}\quad n_{ems} = \frac{n_{es}\left(G_e + G_j(1+\beta)\right)}{1+\beta+G_e}, \tag{19}$$

where following variables have been employed:

$$\beta = \frac{n_{ehs}}{n_{ecs}},\quad G_j = \frac{\gamma_j M}{\sqrt{N^2 - 2\psi_w/\mu}}, \tag{20}$$

$$\text{and}\quad G_e = \frac{\gamma_e\left(\exp(\psi_w) + \beta\sqrt{\theta}\exp(\psi_w/\theta)\right)}{\sqrt{2\pi\mu\left(N^2 - 2\psi_w/\mu\right)}}. \tag{21}$$

Combining Eqs. (18) and (19), and inserting into Eq. (12) gives a newly modified form of Bohm criterion:

$$M = \sqrt{\sum_j \frac{j^2 n_{js}}{n_{es}} \frac{1+\beta+G_e}{\left(1-G_j\right)\left(1+\beta/\theta\right)\left(\frac{G_e+G_j(1+\beta)}{2\left(\psi_w - N^2\mu/2\right)}\right)}}. \tag{22}$$

Now the floating potential of the wall surface can be found by using the above Eq. (22), Eqs. (14)- (17), and following floating condition:

$$j_{tot} = j_i + j_{em} - j_{ec} - j_{eh} = 0. \tag{23}$$

Also, we can find the wall potential the critical condition occurs. As illustrated Fig. 1, if the emission of secondary electrons from the wall surface increases, the density of secondary electrons and consequently the negative charge in front of the probe eventually becomes so high that electric field at the wall surface becomes zero. This is called the critical emission where the emitted current starts to be space-charge limited. By applying the boundary condition

$$\left.\frac{d\psi}{d\xi}\right|_{\psi=\psi_w} = 0 \tag{24}$$

we find the condition of the critical secondary emission,

$$0 = \frac{1}{1+\beta+G_e}\begin{bmatrix} \left(1-G_j\right)\left(\exp(\psi)-1\right)+ \\ \beta\theta\left(1-G_j\right)\left(\exp(\psi/\theta)-1\right)+ \\ +2\left(G_e+G_j(1+\beta)\right)\times \\ \times\left(\psi_p-\frac{N^2\mu}{2}\right)\left(1-\sqrt{1-\frac{\psi}{\psi-N^2\mu/2}}\right) \end{bmatrix}. \tag{25}$$

The formalism is described in more detail in a thesis [8].

RESULTS

The dependence of floating potential (ψ_f) of the wall is calculated by Eq. (23) and plotted as a function of the emission current ($J_{em}=j_{em}/j_0$, where $j_0=en_{es}(kT_{ec}/m_j)$) in Fig. 2(a). Here following sets of parameters are assumed: $\bar{j}=\sum_j I_j \big/ \sum_j \left(I_j/j\right)=1$, μ=4/1840, N=0, J_{em}=40, $G_e=2G_j$, and 7 combinations of (β, θ), where I_j is j-charged ion current obtained from the beam spectra. It is shown that the floating potential and its saturated potential (under high values of emission current) are strongly affected by the presence of hot electrons and the emission current (J_{em}). It is noted that sheath potential drop (floating potential) is significantly reduced by the emission current (J_{em}).

The critical emission potential (ψ_{w0}) implicated in Eq. (25) also can be calculated. Fig. 2(b) shows the dependence of ψ_{w0} and ψ_f on J_{em} for the following set of parameters: $\bar{j}$ =1, μ=4/1840, β=0.5, θ=6, J_{em}=40, $G_e=2G_j$, and three values of N=0, 50, 100. When J_{em} is increased, ψ_{w0} decreases and ψ_f increases, and then finally both values (ψ_{w0}, ψ_f) are merged to one value. Also, when the initial velocity (N) of the secondary electrons becomes higher, the critical emission potential (ψ_{w0}) is more slowly decreased with the emission current (J_{em}) and reaches a higher saturated value. It is also important to realize that that ψ_f and ψ_{w0} become independent of J_{em} when J_{em} is higher than critical emission current (J_{emc}) where critical emission occurs, and that even higher J_{em} is needed for the cases of higher initial velocities (N's) in order for ψ_f and ψ_{w0} to be independent of J_{em}.

Therefore, we conclude that the presence of hot electrons and emitted electrons strongly affects the sheath formation so that smaller hot electrons and larger emission current result in reduced sheath potential (or floating potential). However the sheath potential was found to become independent of the emission current J_{em} when $J_{em} > J_{emc}$ (or γ_e and $\gamma_i > \gamma_c$).

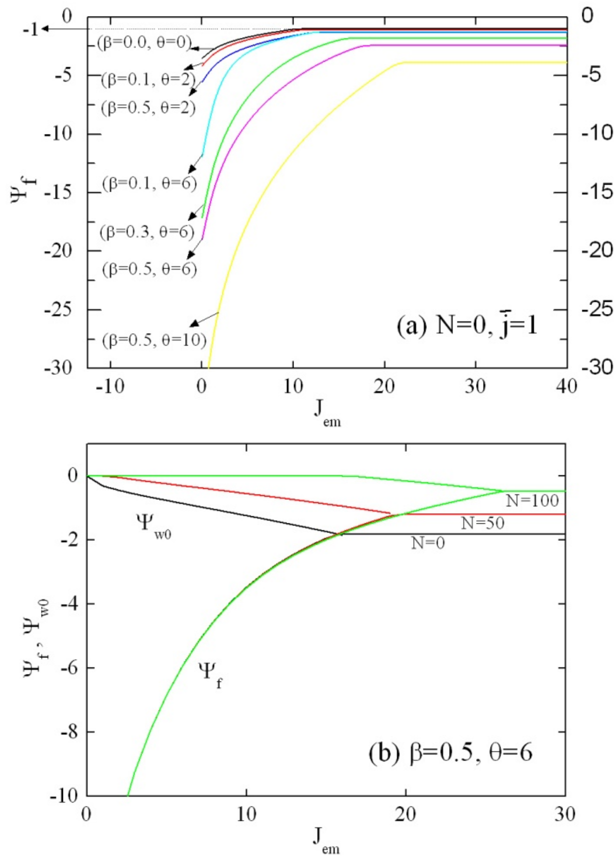

Figure 2: Floating potentials (ψ_f) and critical emission potentials (ψ_{w0}) dependent on the emission current (j_{em}) and the hot electron density and the temperature.

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