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Plasma potential formation in front of a floating electron emitting electrode in a two-electron temperature plasma

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1 Introduction

In many plasma devices for material processing plasmas with additional energetic electrons or with two-temperature electron population are readily produced. Also in fusion machines such electron populations appear due to strong rf fields during ion cyclotron and lower hybrid wave heating and rf current drive. The presence of the energetic electrons has a remarkable effect on potential formation in the plasma and consequently on particle losses to the wall, because it is closely associated with the electron energy distribution.

In this work we investigate theoretically the formation of a plasma potential in front of an electron emitting electrode immersed in a plasma with two electron populations that have different temperatures.

2 Model and assumptions

The bounded plasma system is modelled after Schwager and Birdsall [1,2]. The plasma source is located at $x = 0$. The system is bounded at $x = L$ by a floating collector. The plasma, that is injected from the source, consists of 4 species of charged particles: singly charged positive ions (index i), cool electrons (index $e1$), hot electrons (index $e2$) and secondary electrons emitted from the collector (index $e3$). It is assumed that all the ions are absorbed by the collector and that a large part of electrons is repelled by the collector and refluxed at the source. We set the potential at the plasma source to zero $\Psi(x = 0) = 0$. The plasma potential $\Psi_P(x)$ is therefore negative for any x. The floating potential of the collector is $\Psi(x = L) = \Psi_C$. All the potentials are dimensionless and normalized to the cool electron temperature at the source T_{Se1}. We assume that the plasma is collisionless and that the energy of particles is a constant of motion. The velocity distribution functions of all 4 species are Maxwellian with different temperatures and cutoff velocities. The ions that are born at the source with zero velocity, have at the distance x from the source velocity $u_{m_i} = \sqrt{-\mu\Psi}$. The velocity u_{m_i} is normalized to the electron thermal velocity of the cool electron population $v_0 = \sqrt{2kT_{Se1}/m_e}$. An electron that has almost reached the collector, but has then been repelled, or a secondary electron that has been emitted from the collector with zero velocity, will have at the distance x from the source the velocity $u_{m_e} = -\sqrt{\Psi - \Psi_C}$. This velocity is also normalized to v_0. The complete set of the normalized variables is the following:

$$\mu = \frac{m_e}{m_i},\ \ \tau = \frac{T_{Si}}{T_{Se1}},\ \ \Theta = \frac{T_{Se2}}{T_{Se1}},\ \ \sigma = \frac{T_{Ce3}}{T_{Se1}},\ \ \Psi = \frac{e_0\Phi(x)}{kT_{se1}},$$

$$\alpha = \frac{n_{Si}}{n_{Se1}},\ \ \beta = \frac{n_{Se2}}{n_{Se1}},\ \ \varepsilon = \frac{n_{Ce3}}{n_{Se1}},\ \ v_0 = \sqrt{\frac{2kT_{Se1}}{m_e}},\ \ u = \frac{v}{v_0}. \tag{1}$$

Here n_{Si}, n_{Se1}, n_{Se2} and n_{Ce3} are the ion and electron densities at the source or at the collector, T_{Si}, T_{Se1}, T_{Se2} and T_{Ce3} are the temperatures of the respective particles at the source or at the collector, k is the Boltzmann constant and $\Phi(x)$ is the potential at the position x measured in volts. With these variables the distribution functions are written in the normalized form:

$$\mathcal{F}_i = \alpha\frac{1}{\sqrt{\pi\tau\mu}}\exp\left(-\frac{\Psi}{\tau}\right)\exp\left(-\frac{u^2}{\mu\tau}\right)\cdot H(u - u_{m_i}), \tag{2}$$

$$\mathcal{F}_{e1} = \frac{1}{\sqrt{\pi}} \exp(\Psi) \exp\left(-u^2\right) \cdot H(u - u_{m_e}), \tag{3}$$

$$\mathcal{F}_{e2} = \beta \frac{1}{\sqrt{\pi \Theta}} \exp\left(\frac{\Psi}{\Theta}\right) \exp\left(-\frac{u^2}{\Theta}\right) \cdot H(u - u_{m_e}), \tag{4}$$

$$\mathcal{F}_{e3} = \varepsilon \frac{1}{\sqrt{\pi \sigma}} \exp\left(\frac{\Psi - \Psi_C}{\sigma}\right) \exp\left(-\frac{u^2}{\sigma}\right) \cdot H(u_{m_e} - u), \tag{5}$$

here H is the Heaviside function. Zero (densities) and first moments (fluxes) of the distribution functions are then calculated

$$\mathcal{N}_k = \int_0^\infty \mathcal{F}_k \mathrm{d}u, \quad \mathcal{J}_k = \int_0^\infty u \mathcal{F}_k \mathrm{d}u. \tag{6}$$

Here k stands for i, $e1$, $e2$ and $e3$. We assume that the collector is floating, so the total flux of the charged particles must be zero and that the flux of secondary electrons emitted from the collector is proportional to the incoming flux of cool and hot electrons to the collector. The proportionality constant is γ. Sometimes it is also called the emission coefficient.

$$\mathcal{J}_i + \mathcal{J}_{e3} = \mathcal{J}_{e1} + \mathcal{J}_{e2}, \quad \mathcal{J}_{e3} = \gamma(\mathcal{J}_{e1} + \mathcal{J}_{e2}). \tag{7}$$

From equations (7) α and ε are eliminated. Somewhere between the source and the collector sheaths the plasma potential Ψ_P is characterised by the condition $\nabla^2 \Psi_P = \mathcal{N}_i - \mathcal{N}_{e1} - \mathcal{N}_{e2} - \mathcal{N}_{e3} = 0$. Hence setting the net charge density to zero finds this inflection point of the plasma potential. We put $\Psi = \Psi_P$ into integrals for $\mathcal{N}_k$, eq. (6) and obtain a quasineutrality condition of the form:

$$\mathcal{N}_i - \mathcal{N}_{e1} - \mathcal{N}_{e2} - \mathcal{N}_{e3} = 0. \tag{8}$$

At the inflection point of the potential also the electric field must be zero. The electric field is proportional to $\nabla \Psi_P$. But this is equivalent to integrating the charge density once in the form:

$$\mathcal{E}_k = \int_0^{\Psi_P} \mathcal{N}_k(\Psi) \mathrm{d}\Psi.$$

Index k stands for i, $e1$, $e2$ and $e3$. In this way the zero field condition at the inflection point is obtained in the following form:

$$\mathcal{E}_i - \mathcal{E}_{e1} - \mathcal{E}_{e2} - \mathcal{E}_{e3} = 0. \tag{9}$$

If the emission coefficient γ increases, eventually the density of the secondary electrons in front of the collector becomes so high, that the electric field at the collector becomes zero. The value of γ, at which the electric field at the collector becomes zero, is called the critical emission coefficient γ_c. This fact can be used to derive another expression relating Ψ_P and Ψ_C. Zero field condition at the collector is written in the following form:

$$\mathcal{P}_i - \mathcal{P}_{e1} - \mathcal{P}_{e2} - \mathcal{P}_{e3} = 0, \tag{10}$$

where

$$\mathcal{P}_k = \int_{\Psi_P}^{\Psi_C} \mathcal{N}_k(\Psi) \mathrm{d}\Psi.$$

Equations (8), (9) and (10) form a set of 3 equations, from which 3 unknown parameters Ψ_P, Ψ_C and γ_c can be calculated if the other parameters $(\mu, \tau, \Theta, \beta, \sigma)$ are selected. Equations (8) - (10) are in fact long and complicated sums of exponentials and error functions containing potentials Ψ_P and Ψ_C, temperature ratios τ, Θ and σ, electron to ion mass ratio μ and of course β and γ. For a detailed derivation of the system (8) - (10) see [3].

3 Results

In this section we present some preliminary results of our calculations. In fig. 1 we show the dependence of Ψ_P, Ψ_C and γ_c on β. The other parameters are: $\Theta = 20$, $\sigma = 0.01$, $\tau = 0.1$ and $\mu = 1/1836$. Note that in a certain region of β a triple solution exists for Ψ_P, Ψ_C and γ_c. So we study this region in more detail. In fig. 2 we show the dependence of the potentials Ψ_P and Ψ_C on the emission coefficient γ. To find this dependence we simultaneously solve equations (8) and (9), while we gradually increase γ. The parameters are chosen such that a triple solution exists. We put $\mu = 1/1836$, $\sigma = 0.01$, $\tau = 0.1$, $\Theta = 20$ and $\beta = 0.32$. In this case the three solutions of the system (8) - (10) are: Ψ_P = -13.97, Ψ_C = -27.986, $\gamma_c = 0.857$; Ψ_P = -6.99, Ψ_C = -28.72, $\gamma_c = 0.852$ and Ψ_P = -1.81, Ψ_C = -24.41, $\gamma_c = 0.876$. Each solution shown in fig. 2 is labeled by the corresponding γ_c. Note the difference in the dependence of Ψ_P on γ between the middle solution on one hand and the other two solutions on the other hand.

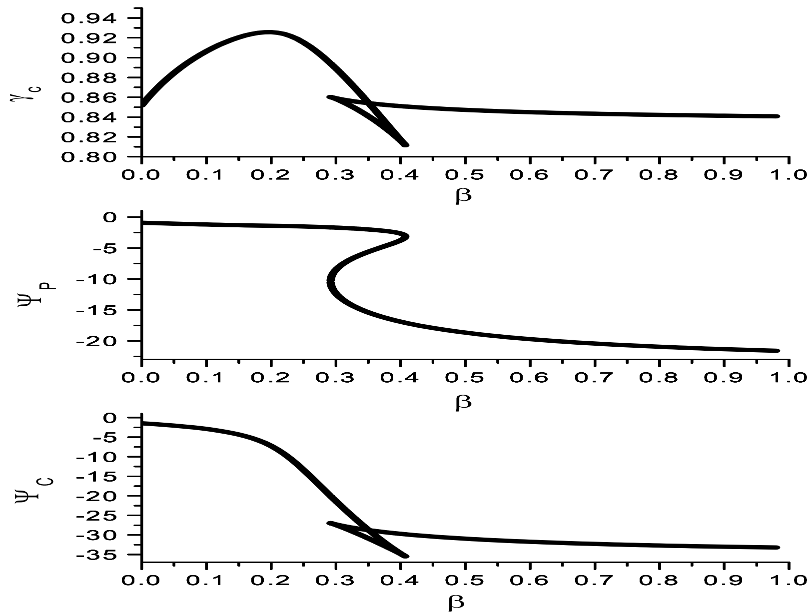

Figure 1: Dependence of Ψ_P, Ψ_C and γ_c on β for $\Theta = 20$. The other parameters are: $\mu = \frac{1}{1836}$, $\sigma = 0.01$, $\tau = 0.1$.

4 Conclusions

In this paper we report on the first preliminary results of a theoretical study of the plasma potential formation in the sheath and presheath region of a floating collector that emits secondary electrons. The source sheath potential drop (or plasma potential in the presheath region) Ψ_P, the collector potential Ψ_C and the critical emission coefficient γ_c were calculated as the functions of the density β of the hot electrons. If the temperature Θ of the hot electron population is high enough, there exists a certain region of β where triple solutions of the system of equations (8) - (10) for Ψ_C, Ψ_P and γ_c are obtained. The solutions with the high and low values of Ψ_P can be ascribed to a high and low potential plasma, that exist simultaneously in the region between the source and the collector. If this is the case, then both plasmas must be separated spatially by a double layer. The high potential plasma must be located closer to the source and the low potential plasma closer to the collector and the potential profile has a step. The middle

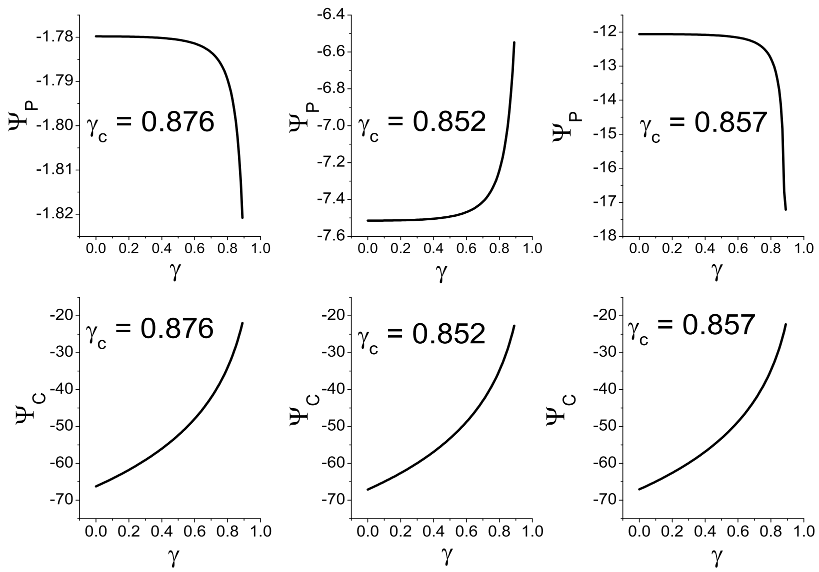

Figure 2: Dependence of Ψ_P, Ψ_C on γ. The parameters are $\mu = 1/1836$, $\sigma = 0.01$, $\tau = 0.1$, $\Theta = 20$ and $\beta = 0.32$. This is in the region where a triple solution exists. Each of the solutions is labeled by the corresponding γ_c

solution is believed to be non-physical [1]. That such double layers can indeed be formed has already been shown in computer simulations for very similar model, only without secondary electron emission from the collector [4] and experiments [5,6].

We have also examined the dependence of potentials Ψ_P and Ψ_C on γ. When γ increases, Ψ_C also increases monotonically. That a floating potential of an electrode that emits electrons increases (becomes less negative) because of the electron emission, is predicted also by fluid models [7]. More interesting is the dependence of Ψ_P on γ. When γ is increased, Ψ_P remains almost constant until γ comes close to γ_c. When this happens, Ψ_P decreases rapidly. When the parameters are such that a double layer can be created and triple solution of the system of equations (8) - (10) is obtained, the high and the low solution behave in the same way. The middle solution behaves differently. Here Ψ_P increases, when γ approaches γ_c. This is another indication that the middle solution is very probably non-physical.

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