STRUCTURE OF A DISCHARGE PLASMA WITH NEGATIVE IONS: MODEL AND SIMULATION

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1. Introduction.

Hot cathode discharge plasmas with negative ions are widely used in fusion research and development and in modern plasma processing technologies. In the former case they have found their place in negative ion sources needed for the production of neutral beams for auxiliary heating of fusion plasmas. In technological applications such plasmas often contain electronegative gases or, on the other hand, dust particles are produced during the processes and which are charged negatively. It has been experimentally confirmed that in hot cathode discharges the electron energy distribution consists of two populations and that it can be conveniently represented by a bi-Maxwellian [1,2]. The bulk of the electrons have low temperature and the second group has a considerably higher temperature and contains the primary electrons emitted from the hot cathode. The presence of the energetic electrons has a remarkable effect on potential formation in the plasma and consequently on particle losses to the wall. Several authors have studied the effects of an additional hot Maxwellian population [3-7] on the sheath and presheath potential in collisional and collisionless plasma systems. In particular, we have also thoroughly investigated theoretically, with computer simulations and experimentally the influence of hot truncated bi-Maxwellian electron distribution on floating potential of a collector immersed in a collisionless plasma [8]. On the other hand, the presence of negative ions in the plasma has also significant impact on the potential structure and consequently on the ion flux from electronegative plasmas [9-11]. It is therefore from fundamental and from practical point of view of interest to investigate and to understand the structure of electronegative plasmas with two electron populations. The investigation presented in this contribution is based on fully kinetic self-consistent theoretical description of the plasma sheath and presheath, first developed to investigate the potential formation in finite ion temperature plasma with Maxwellian electrons [12]. It was later extended to include a second hot electron population or a negative ion population [8, 13].

2. Analytical treatment

The distributed plasma source in the model is represented by a planar source at one side of the system. The potential is defined to be zero there. At the opposite side, a floating collector bounds the system. The plasma, which is injected from the source, consists of positive ions, negative ions and cool and hot electrons. At the floating collector all positive ions are absorbed and negative particle species are assumed to be reflected. A small amount of fast electrons are lost at the collector to neutralize the ion current. Particles which return to the source are refluxed in the system with temperature characteristics of the corresponding source species. By this process no charge accumulates at the source plane and zero electric field results at the plasma boundary. Because equal fluxes of positive and negative particles are injected from the source, the net injected charge density is not zero and a source sheath forms in order to neutralize the injected plasma. The electric field is therefore constant at the collector sheath boundary and is chosen to be zero when the source and collector sheaths are many Debye lengths appart.

In general, the electrostatic potential is assumed to be decreasing with distance from the source. The positive ions are therefore described by an accelerated half-Maxwellian velocity distribution and negative ion and electron populations by truncated full Maxwellian distributions. The particle densities $n_{+,-,e}(\psi)$ in the system are obtained by calculating the first moments of the corresponding distribution fuctions and particle fluxes $j_{+,-,e}$ (ψ) by calculating the second moments of the same distribution fuctions. In order to calculate the collector floating potential ψ_C and source sheath potential drop ψ_P as functions of negative ion fraction in the source $\alpha_0 = n_{-0}/(n_{ec0}+n_{eh0}+n_{-0})$, we make use of three boundary conditions. Setting the net charge at ψ_P to zero, we obtain the first equation which relates ψ_C and ψ_P. A second equation relating ψ_C and ψ_P is obtained from the assumption of zero electric field at the source boundary ($\psi = 0$) and at the collector sheath boundary ($\psi = \psi_P$). The third equation, which enabled us to express the particle density ratios as a function of the potential ψ_C, was obtained from the zero net collector current condition.

In Fig.1 and in Fig.2 three sets of plots are shown in which potentials ψ_P and ψ_C as functions of negative ion density fraction α_0 are plotted. In Fig.1 the positive and negative ion temperature is set to $\tau_{+,-} = 0.1$ in which case no special potential structure is expected to form in the plasma [13]. In the first set, where there are no hot electrons present in the source plasma ($\beta_0 = n_{eh0}/(n_{ec0}+n_{eh0}+n_{-0}) = 0$), the presheath potential drop ψ_P decreases with increasing negative ion fraction from -0.85 towards 0. The same behaviour can be observed for collector floating potential ψ_C, it decreases from –3.4 in pure positive ion hydrogen plasma towards 0 in plasma with very high fraction of negative hydrogen ions.

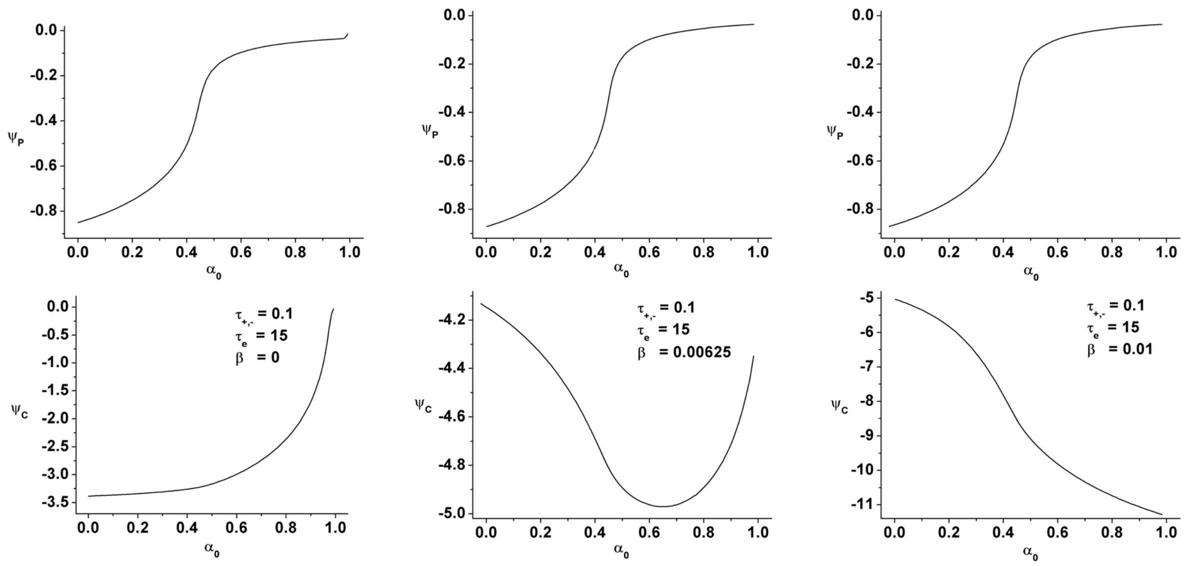

Fig.1. The normalized presheath potential $\psi_P = \phi_P/T_{ec}$ and collector floating potential ψ_C as a function of the negative ion density fraction α_0 in a hydrogen plasma ($M_{+,-}/m_e$ = 1836) with high ion to electron temperature ratios $\tau_{+,-}$

When only a very small amout of hot electrons (β_0 = 0.00625, τ_e = 15) is present in the plasma, a very drastic change in collector potential dependence is observed. First it slightly increases from –4.13 at α_0 = 0 to –4.97 at α_0 = 0.65 and afterwards decreases back to a value –4.35 at very high value of α_0. In a crude comparison to former behaviour with β_0 = 0 it remains almost constant. With higher, but still very small, amount of hot electrons (β_0 = 0.01) the α_0-dependence of the collector floating potential is completely turned around. In this case it gradually increases from –5 at α_0 = 0 to –11.25 at very high values of α_0 when only negative ions and hot electrons beside positive ions are present in the plasma. In all three cases the presheath potential drop ψ_P behaviour does not change significantly as can be observed in the plots. In Fig.2 the ψ_P and ψ_C dependence on negative ion fraction α_0 is shown for the case when the ion to electron temperature ratio is lower ($\tau_+ = \tau_-$ = 0.05). In such a case in a plasma with a single cool electron population a double layer structure is formed which confines negative ions in the bulk of plasma. As already shown [9, 13] the double layer can be observed in plasmas with α_0 lying in the region where multiple solutions of ψ_P are found. Again the overall behaviour of the potentials ψ_P and ψ_C is similar to the former case with higher ion to electron temperature ratio. Already a very small amount of hotter electrons changes the decreasing dependence of the floating potential ψ_C on α_0 to an increasing one.

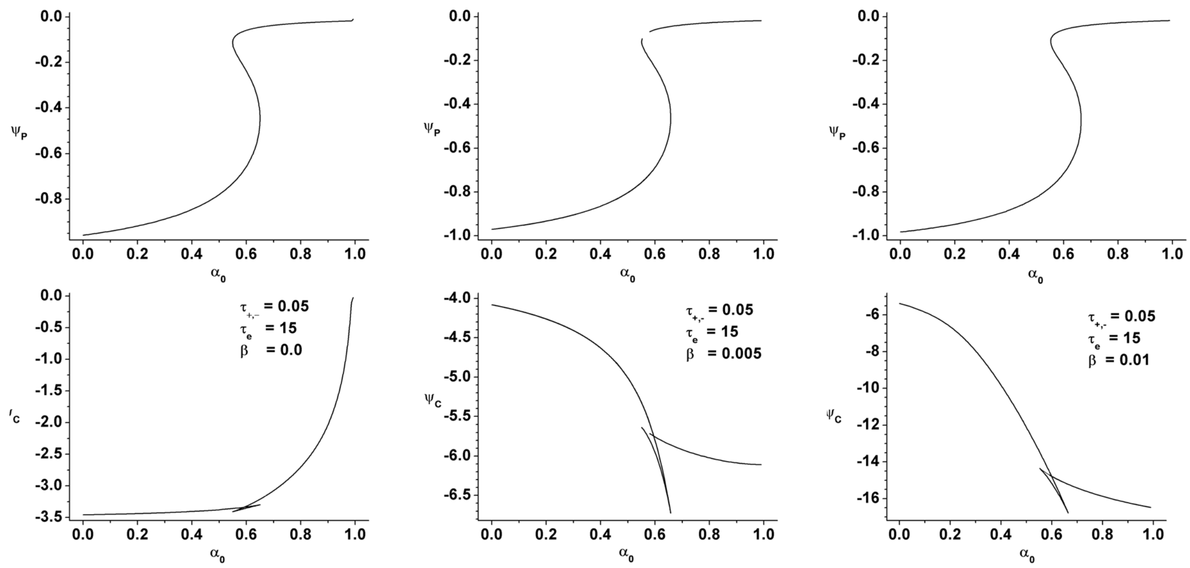

Fig.2. The normalized presheath potential $\psi_P = \phi_P/T_{ec}$ and collector floating potential ψ_C as a function of the negative ion density fraction α_0 in a hydrogen plasma ($M_{+,-}/m_e$ = 1836) with low ion to electron temperature ratios $\tau_{+,-}$

3. Simulations

We complemented the results of the analytical calculations with a simulation experiment using the XPDP1 particle-in-cell computer code [12] in an extended configuration in which we included also additional negative particle species [7,13]. The results are in complete accordance with the calculations, showing the extreme sensitivity of the collector floating potential on energetic electrons in electronegative plasmas.

4. References

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