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Double layer formation in a negative ion plasma with a bi-Maxwellian electron distribution

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1. Introduction

It is well known that in plasmas with multiple negative particle species potential double layers are formed under special conditions. Recently, we have studied the formation of such nonlinear potential structure in warm positive ion plasma with a bi-Maxwellian electron velocity distribution [1]. In a very narrow interval of electron density ratio and at electron temperature ratios > 10 a double layer was formed, which separated the bounded plasma into two different regions – in one closer to the plasma source where both electron species were present and in a second one in front of the floating collector where only the hotter electron population was found. On the other hand, the positive ions were accelerated through the potential structure to very high energies.

Similarly, we found double layers in Maxwellian plasma with negative ions [2]. They were investigated by many authors [3], but we have extended the investigation to the plasma with warm positive ions. Again, it was confirmed that the plasma could be under certain parameter conditions stratified in two regions, with the absence of negative ions close to the collector. We were not able to find the oscillations of the potential and plasma density on the downstream side of the double layer. Other investigators on the other hand found such oscillations, but they still need to be found also experimentally.

In a very recent investigation we started to study the potential formation in plasma with negative ions and bi-Maxwellian electron velocity distribution. Such plasma can be readily found in hot cathode discharges used as negative ion beam sources in neutral beam heating installations on fusion machines. On the other hand, dust particles charged negatively are found in many technological types of plasma. In the case of higher density ratios of energetic electrons investigations show that a stratification of plasma is possible by two kinds of double layers, one formed by cool and hot electrons and the second by negative ions and hot electrons. In this contribution we first present results of the analytical treatment, which are than compared with results from PIC simulations [4].

2. Analytical treatment and PIC simulations

As in our previous studies we model the plasma system with one dimensional planar plasma device. The distributed plasma source is represented by a planar source at one side of the device and on the other side a floating electrode or collector bounds the device. The plasma, which is injected from the Maxwellian source, consists of positive ions, negative ions and cool and hot electrons. The collector floating potential $\psi_C = \varphi_c/kT_{ec0}$ and the source sheath potential drop $\psi_P = \varphi_P/kT_{ec0}$ are calculated as functions of negative ion fraction in the source $\alpha_0 = n_{-0}/(n_{ec0}+n_{eh0}+n_{-0})$ using 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 order to study the stratification in such plasma we gave the plasma parameters the following values: $M = m_i/m_e = 40$, $\tau_{+-} = T_{+-0}/T_{ec0} = 0.16$, $\tau_e = T_{eh0}/T_{ec0}, = 20$, $\beta = n_{eh0}/(n_{ec0}+n_{eh0}+n_{-0}) = 0.125 – 0.250$. We have chosen a reduced value of the normalized ion mass (positive and negative ions of equal mass) in order to save the computer time in simulations. It has been proven that such small value of M has negligible effect on the obtained results. The negative ion temperature ratio τ_- was higher than $\tau_- > 0.1$. In such cases no DL is formed in negative ion plasma with single Maxwellian cool electron distribution. On the other hand, the electron temperature ratio was set to $\tau_e > 10$ in which case (with α_0=0) a DL is readily formed in certain electron density ratio interval in positive ion plasma. In Fig 1. three sets of plots are shown in which potentials ψ_P and ψ_C as functions of α_0 are plotted. In the left set we can divide the α_0 interval into two parts. In the first, where $0 < \alpha_0 < 0.44$, the presheath potential ψ_P is single valued and almost constant, $\psi_P = 1$. It is determined mainly by cool electrons, negative ions are reflected to the source region already at the source potential drop. The collector floating potential slowly increases from ψ_C = 20 V to 28V, these values being determined by hot electrons. In the second half of the interval the presheath potential is double valued, a DL is formed in the preasheath region. The upstream value is determined by negative ions (cool electrons being now the minority species) and the downstream is dominated by hot electrons. The negative ions are reflected back to the source at the DL potential step ($\Delta\psi_P$ = -17). The second set of plots (β = 0. 20) is far more interesting. The whole interval of α_0 can now be divided into four intervals. In the left interval, the presheath potential is still single valued and the behaviour of both potentials is similar as in the first set of plots. The very right interval is also very similar to the right interval in the first set. The collector potential increases continuously along the solution corresponding to the lower solution for the presheath potential. The upstream side of the DL region in the second interval is determined by cool electrons, a situation missed in the first case. A very interesting new situation appears in the narrow third interval. The upper solution is double-valued (the third solution being physically unreal), which means that a new DL is formed. The potential step measures less then -1. It separates negative ions from the downstream region where both species of electrons are present. Mainly cool electrons determine the value of the potential here. A second DL is formed further downstream, where the cool electrons are separated from hot electrons. The potential step here measures –11.5. The plasma system is in this interval well stratified: it has three regions with different plasma! In the third set of plots the solutions for ψ_P and ψ_C are shown for β = 0.22. As α_0 increases from 0 towards 0.78 the plasma system first consists of a simple presheath with cool and hot electrons and ions being reflected back to the source region already at the source potential drop. It is more than ψ_P = -1 deep. The collector potential is slowly decreasing as in previous cases. In the second region a DL is formed, at the potential step the cool electrons are separated from hot electrons and reflected back to the source. In the very narrow interval of α_0, which follows next, the cool electrons are already reflected back to the source at the source potential step and in the plasma system we can find only hot electrons. Finally, the density of negative ions in the plasma source is high enough, so that we find them also in the preheat region. A DL is formed there and at the potential step they are then reflected back to the source region. It is interesting to mention that also cool electrons are again present in the upstream region and are reflected back to the source at the same DL step as the negative ions. The downstream potential ψ_P = 13 and gradually decreases with increasing α_0. The collector floating potential is still decreasing, but along the second branch of solutions. It is worth mentioning that the gap in which no low energy negative particles are present in the system increases with increasing hot electron density ratio β.

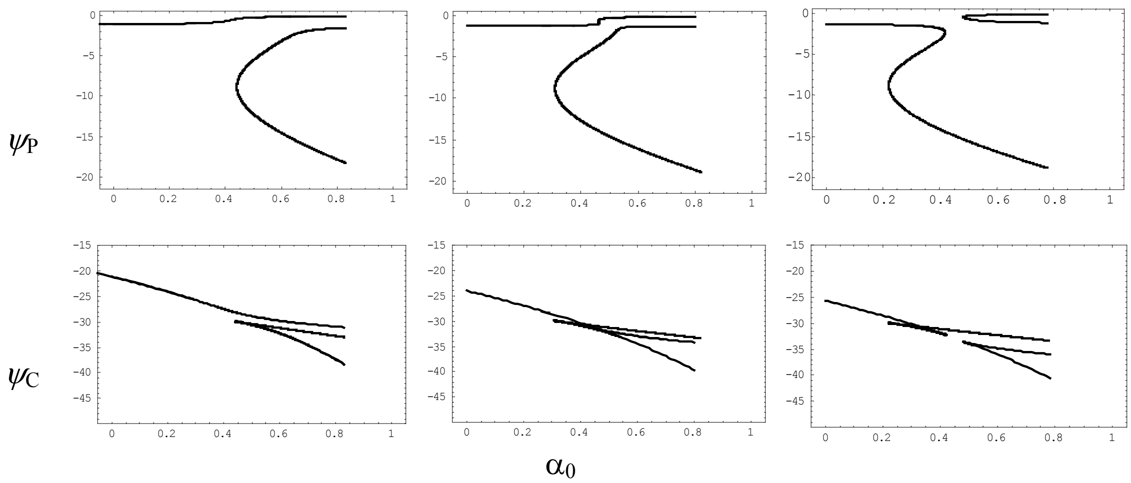

Fig.1. The normalized preheat potential ψ_P (upper row) and collector floating potential ψ_C (lower row) as a function of the negative ion density fraction α_0 in plasma with different hot electron densities, β_0 = 0.17, 0.20 and 0.22, respectively.

In Fig.2. two plots of potential profiles are shown, which were obtained by PIC simulations. On the left plot the potential profile corresponds to the the very narrow interval (Fig.2., right plot) of α_0 in which the cool electrons are already reflected back to the source at the source potential step and in the plasma system we can find only hot electrons. On the second plot the profile is shown, which correspond to the case with high enough density of negative ions in the plasma source, so that we find them also in the presheath region. On the third expanded plot the potential profile near the source is shown. The value of the presheath potential is determined by negative ions. A DL is formed and there the negative ions are reflected back to the source region. The accordance with the analytical findings is very good.

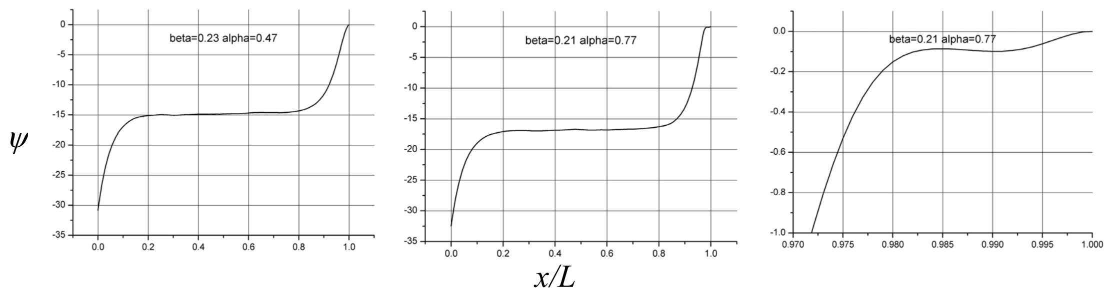

Fig.2. Potential profiles for different density ratio α_0 of negative ions, obtained from PIC simulations. The plasma parameters are the same as in analytical calculations

3. References

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