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Electron dynamics at the initial stage of floating-sheath formation

C. Lupu^a, D. D. Tskhakaya sr.^{c,d}, S. Kuhn^c, M. Cercek^b,
R. Schrittwieser^e, G. Popa^a

^a *Plasma Physics Department, Faculty of Physics, Al. I. Cuza University,
RO-700506 Iasi, Romania,*

^b *J. Stefan Institute, University of Ljubljana, Jamova 39, SLO-1000 Ljubljana,
Slovenia,*

^c *Association Euratom-OAW, Department of Theoretical Physics, University of
Innsbruck, A-6020 Innsbruck, Austria,*

^d *Permanent address: Institute of Physics, Georgian Academy of Sciences, 380077
Tbilisi, Georgia,*

^e *Association Euratom-OAW, Department of Ion Physics, University of Innsbruck,
A-6020 Innsbruck, Austria*

Abstract

The problem of sheath formation in front of a conductive planar plate inserted into the plasma is formulated. Initially, the plate is assumed to be neutral. It is shown that the charging-up process of the plate is accompanied by the excitation of electron plasma waves.

1 Introduction

Investigations of sheath formation in front of a floating plate have hitherto been restricted to fluid studies on the ion time scale [1]. By contrast, the response of the plasma in the very early stages of sheath formation is not well known. In this paper, we present PIC simulations of the plasma dynamics over just a few electron plasma periods after the beginning of the process. These simulations have been performed by means of the BIT1 code [2], developed on the basis of the XPDP1 code from U. C. Berkeley [3].

A floating plate is placed in contact with a uniform, quasi-neutral plasma, which is assumed to be infinitely extended on one side. Due to the higher thermal velocity of the electrons, the plate starts charging up negatively, so that electrons are gradually repelled, ions are attracted, and a positive-space-charge sheath begins to form. An electron plasma wave is observed the properties of which strongly depend on the plasma characteristics (electron and ion temperatures, plasma density, etc.).

Our PIC simulations are performed with different numerical set-ups and plasma characteristics. A full set of simulation diagnostics is used to measure the properties of the electron waves.

2 Simulation set-up

We consider a one-dimensional system. The planar conducting plate and the (artificial) right-hand boundary of the systems are placed at positions $x = 0$ and $x = L > 0$, respectively. The length L is to be chosen large enough for this system to reasonably approximate a semi-infinite plasma ($L \gg \lambda_D$, with λ_D the electron Debye length). In order to have adequate resolution in space, the length of the grid cells has been selected as $\Delta x \approx \lambda_D/2$.

2.1 Initial and boundary conditions

At the initial time ($t = 0$) the electron and ion densities are equal ($n_{e0} = n_{i0} = n_0$), the distribution functions of both particle species are fully Maxwellian, and the electric potential is zero ($V = 0$) everywhere in the system, including the plate surface.

Throughout the entire simulation, the following boundary conditions are applied to the particles: At the plate, all particles impinging are absorbed and no particles are injected into the plasma. At the right-hand boundary, on the other hand, all particles impinging are absorbed but new particles with half Maxwellian distribution functions are injected at a constant rate. The system is floating, i.e., the sum of particle plus displacement currents equals zero. According to these conditions we observe the following behavior.

In the unperturbed plasma region (i.e., for $x \rightarrow L$) the electron velocity distribution function will not change appreciably (so that $E(L, t) = 0$), whereas at the plate it will acquire a cut-off form. This is because the negative-velocity electrons are absorbed by the plate and charge it negatively; during this process, the ions can be considered to be at rest. With increasing negative surface charge, the negative potential drop in the region close to the plate becomes higher and more and more electrons are reflected towards the plasma. After some time this perturbation propagates into the system. The shape of the distribution function essentially depends on the potential drop at the plate.

Due to the loss of particles by absorption at the plate, the total number of particles in the system is dropping all the time. However, this aspect is not of great concern here because the total loss of particles during the entire simulation presented is negligible.

2.2 Simulation parameters

In the following tables we present the parameters used for our simulation. The (electron and ion) particle fluxes corresponding to the unperturbed plasma region are:

$$\Gamma_s = \frac{v_{th_s}}{\sqrt{2\pi}} \cdot n_{0s} \quad s = e, i \quad (1)$$

These expressions are used to calculate the particle injection fluxes from the right-hand boundary.

<i>Plasma parameters</i>		
Parameter	Value	Remarks
T_e	0.5 eV	
T_i	0.1 eV	
$n_{0i} = n_{0e} = n_0$	$8.5 \times 10^{14} \text{ m}^{-3}$	at $t = 0$
v_{the}	$2.9649 \times 10^5 \text{ m/s}$	
v_{thi}	$3.095 \times 10^3 \text{ m/s}$	
Γ_e	$1.006 \times 10^{20} \text{ m}^{-2} \text{ s}^{-1}$	
Γ_i	$1.05 \times 10^{18} \text{ m}^{-2} \text{ s}^{-1}$	
ω_{pe}	$1.64 \times 10^9 \text{ s}^{-1}$	electron plasma frequency
ω_{pi}	$3.83 \times 10^7 \text{ s}^{-1}$	ion plasma frequency
m_i	$1.67 \times 10^{-27} \text{ Kg}$	proton mass
λ_D	$1.8 \times 10^{-4} \text{ m}$	

<i>Simulations parameters</i>		
Parameter	Value	Remarks
Δx	$8 \times 10^{-5} \text{ m}$	grid-cell length $\approx \lambda_D/2$
L	0.16 m	system length
S	10^{-4} m^2	plate area
Δt	$5.398 \times 10^{-11} \text{ s}$	time step
t_{tot}	$1.079 \times 10^{-7} \text{ s}$	total simulation time

3 Simulation results

Figure 1 shows the potential profile close to the plate at $t = 6.477 \times 10^{-8} \text{ s}$. The potential drop at the beginning of the sheath evolution is monotonic in space. After quick acquisition of negative charge, the plate repels the electrons in the form of a pulse leaving behind a positive-space charge region. As a result, the potential close to the plate becomes slightly positive. In front of this region, the negative space charge produced by the primary-pulse electrons leads to a potential minimum ("virtual cathode"), which gradually reflects more and more slower electrons back into the plasma. These latter electrons spend a long time in the region of the virtual cathode and

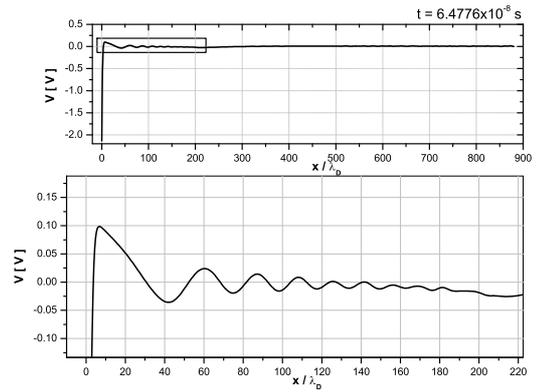


Figure 1: *Potential profile in the perturbation region at $t = 6.4776 \times 10^{-8} \text{ s}$*

hence deepen its potential further. According to Figures. 2 and 3, this first potential perturbation (consisting of a potential hill and a potential well) propagates into the unperturbed plasma, with additional similar wave structures forming behind it.

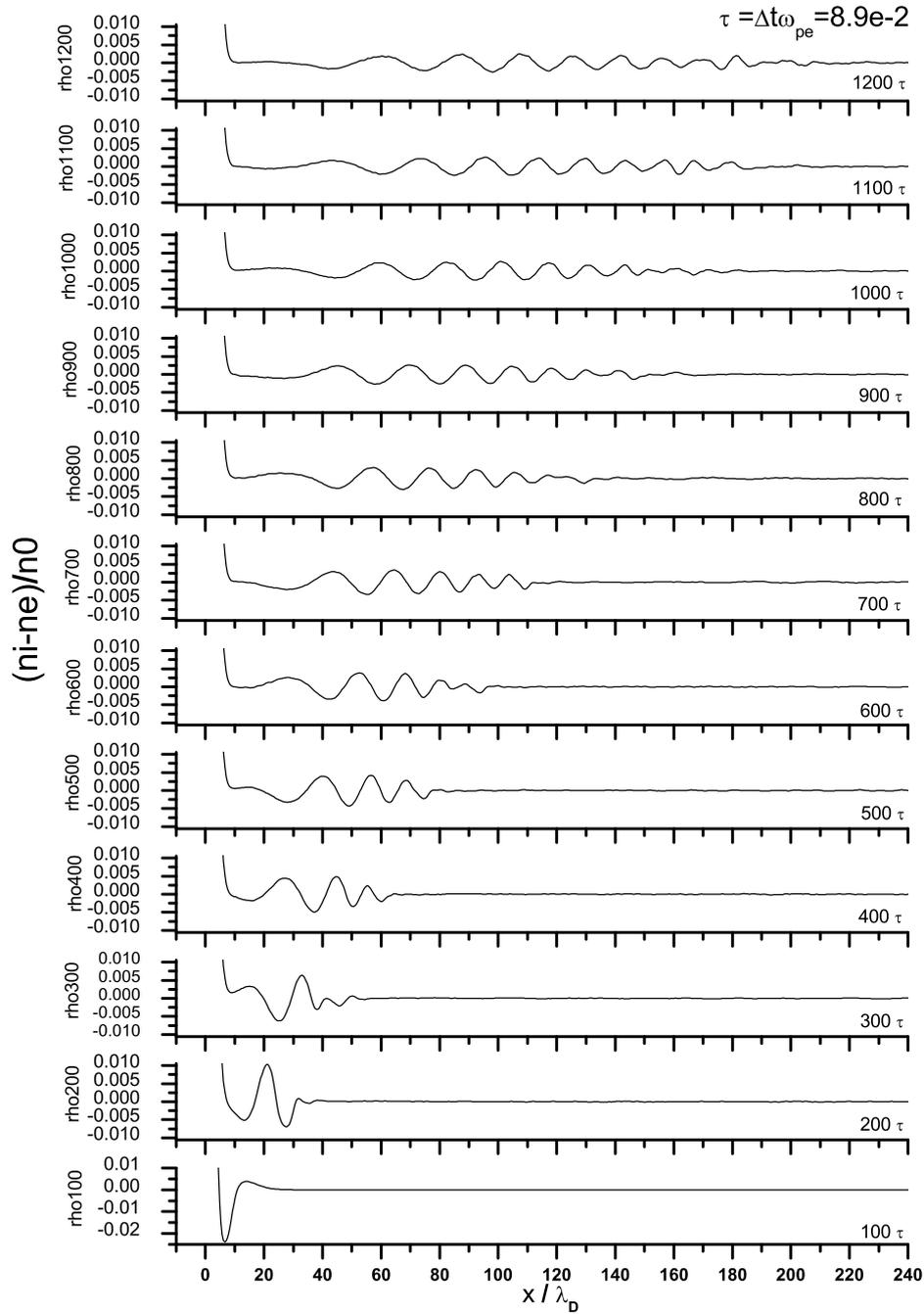


Figure 2: *Electron waves evolution*

To verify that these waves are physical and not just due to numerical effects, we have performed other simulations with different parameters. In particular, we concentrated on the electron temperature. We know that the Debye length is proportional to the square root of the electron temperature. Hence, if we increase the temperature by a factor of four, the Debye length must increase by a factor of two. Since, in addition, there is a relation between the wavelength of the electron waves and the Debye length, the variation of the electron temperature should also have an effect on the wavelength. This is clearly illustrated in Figure 4, where the wavelength is seen to increase with the square root of the electron temperature.

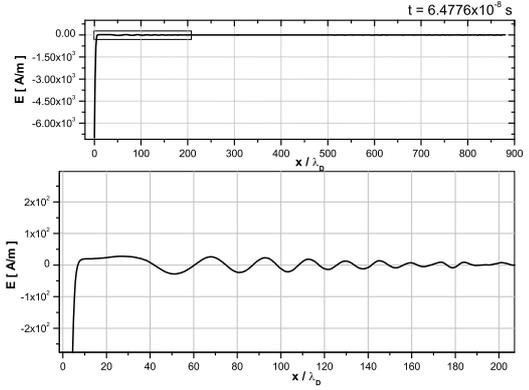


Figure 3: *Electric field profile (perturbation region); $T_e = 0.5eV$*

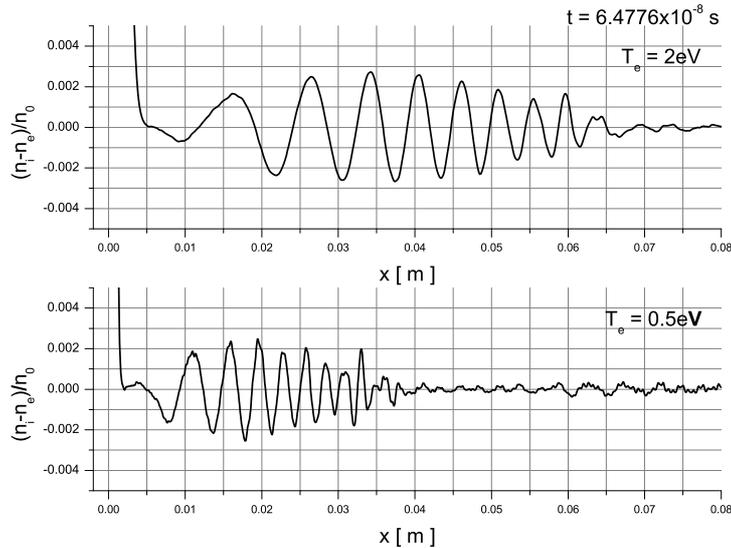


Figure 4: *Electron waves in plasma with different temperatures for electrons $T_e = 2eV$ and $T_e = 0.5eV$*

4 Summary and conclusions

This work represents the beginning of a self-consistent kinetic study of sheath formation, taking into account both electron and ion dynamics. Here, during the

short simulation time considered, the ions are practically immobile, and only the electrons take part in the process. In the next step, the effect of ion dynamics on sheath formation will be considered as well.

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