27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** (2000) 356 -359

# Study of the problem of the formation of a steep plasma gradient in front of a plate at a plasma-wall transition

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A kinetic Vlasov code is used to study the problem of the formation and existence of a steep density gradient in front of a grounded plate, and the associated charge separation and electric field. We consider the case of a one space dimension, where the ions are treated with a full kinetic code with three velocity dimensions, and the magnetized electrons are treated with a kinetic equation restricting their motion to the direction along the magnetic field. Electron kinetics determine the rates at which a multitude of electron-driven processes will proceed in low-temperature plasmas. Consequently reliable simulations of such discharges often require kinetic simulations which can self-consistently describe the electron kinetics. We consider the case where the ratio of the ions gyro-radius to the Debye length is 10. Time is normalized to $\omega_{pi}^{-1}$. Velocity is normalized to the acoustic speed $c_s$, and the length to $c_s\omega_{pi}^{-1}$. We consider a slab in which the direction *y* is the direction perpendicular to the plate. The toroidal *z* direction and the *x* direction are assumed homogenous. The constant magnetic field *B* is located in the (*y*, *z*) plane and makes an angle $\Theta$ with the *y* axis ($\Theta$ is close to $\pi/2$ since the magnetic field is almost tangential to the (*x*, *z*) plane). The magnetized electrons are treated using a kinetic equation in the direction along the magnetic field, with a distribution function $f_e(y, v_{\|})$ (where $v_{\|}$ is the velocity of the electrons parallel to the magnetic field):

$$\frac{\partial f_e}{\partial t} + v_{\|} \cos\Theta \frac{\partial f_e}{\partial y} - \frac{m_i}{m_e} E_y \cos\Theta \frac{\partial f_e}{\partial v_{\|}} = 0 \qquad (1)$$

The ions are treated using a fully kinetic equation in 1D:

$$\frac{\partial f_i}{\partial t} + v_y \frac{\partial f_i}{\partial y} + \left(v_y\omega_{ci} \sin\Theta - v_z\omega_{ci} \cos\Theta\right)\frac{\partial f_i}{\partial v_x} + \left(E_y - v_x\omega_{ci} \sin\Theta\right)\frac{\partial f_i}{\partial v_y} + v_x\omega_{ci} \cos\Theta \frac{\partial f_i}{\partial v_z} = 0 \qquad (2)$$

where $\omega_{ci}$ is normalized to $\omega_{pi}$. Equations (1-2) are calculated using a method of fractional steps[1]. The electric field is calculated from the equations:

$$\frac{\partial^2 \phi}{\partial y^2} = -(n_i - n_e); \qquad E_y = -\frac{\partial \phi}{\partial y} \tag{3}$$

We assume an initial temperature and density profiles for both electrons and ions:

$$T(y) = 0.1 + 0.9 \tanh\left((x-30)/10\right); \quad n(y) = \tanh\left((y-30)/40\right) \qquad x > 40 \tag{4}$$

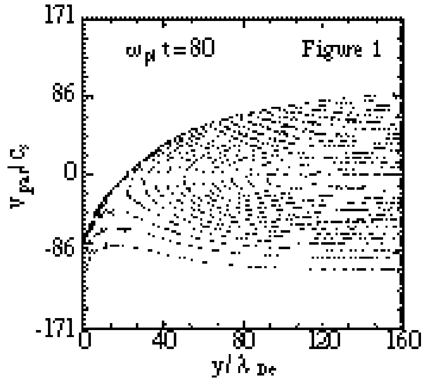
and $$T(y) = 0.1 + 0.9 \tanh\left((40-30)/10\right) \times \left(1 + \tanh\left((y-40)\ 0.1\right)\right) \qquad y < 40 \tag{5}$$

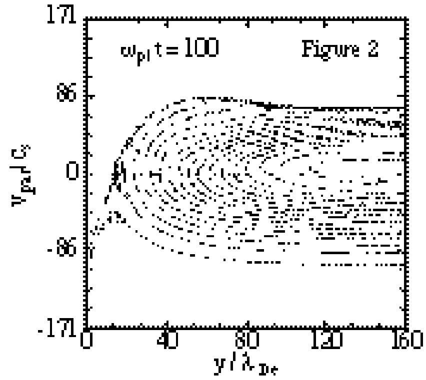
$$n(y) = \tanh\left((40-30)/40\right) \times \left(1 + \tanh\left((y-40)0.15\right)\right) \qquad y < 40$$

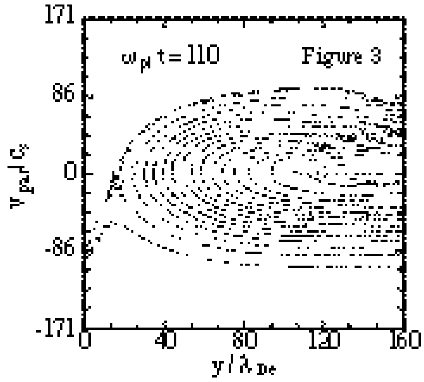
We assume an initial Maxwellian distribution:

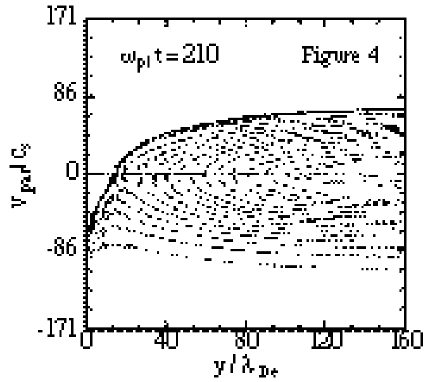
$$f_e\,(y,v_\parallel) = n(y)\ \frac{(m_e/m_i)^{1/2}}{\sqrt{2\pi T(y)}} \exp^{-(m_e/m_i)v_\parallel^2/2T(y)}\ ; f_i(y,\vec{v}) = n(y)\ \frac{e^{-(v_x^2+v_y^2)/2\,T_{io}}}{2\pi\,T_{io}}\ \frac{e^{-v_z^2/2T(y)}}{(2\pi T(y))^{1/2}}$$

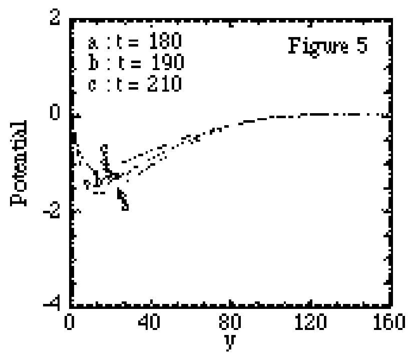
We take $\theta = 85°$ and $T_{io} = 1$. We run the code and let the initial parameters relax to an equilibrium. The electrons are first rushing towards the plate (Fig. 1), while the positive ions gyrate around the magnetic field. The electrons are then being pushed back, then return again to the plate. A sequence is shown in the $f_e(y, v_\parallel)$ contour plots (Figs. 1-4). Finally, the system seems to reach an equilibrium showing a small amplitude decreasing oscillation. We show the potential during a half-period of this oscillation between $t = 180$, $t = 210$ (Fig. 5), together with the charge, electric field, and density profile (the dotted curve in Fig. 8 is for the electrons). The ions contour plot of the phase-space $(v_z, y)$ and $(v_x, y)$ are shown at $t = 210$. In the velocity direction almost parallel to the magnetic field $v_z$, the $(v_z, y)$ contour plot shows the ions accelerating in the negative direction, reaching a value around –1.5 (i.e., $c_s$, the acoustic speed, in our normalization), in the region where the potential is minimum, and then reaching –2 close to the plate. At the same time, we see in the $(v_x, y)$ plot a current developing parallel to the plate. This picture is strongly modified at for $\theta$ going close to 90°. At $\theta = 89.25°$ for instance, the potential oscillation (Fig. 12) is stronger with a longer period, due to the cross-effect of the electron motion along the magnetic field, with the ions gyration across the magnetic field. The density profile (Fig. 13) is steeper than in Fig. 8, reducing the ion flux at the plate which is reduced to almost zero (see Fig. 14).

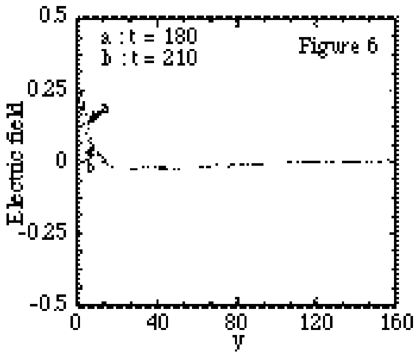


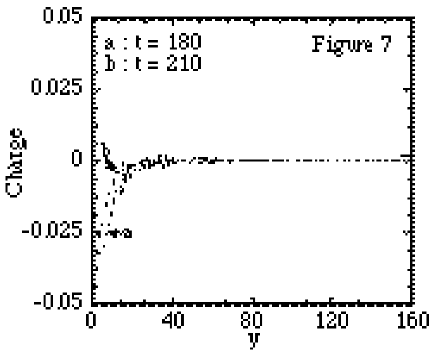



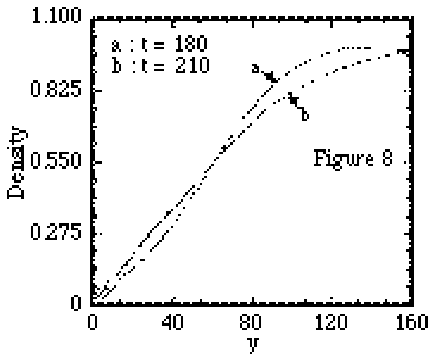



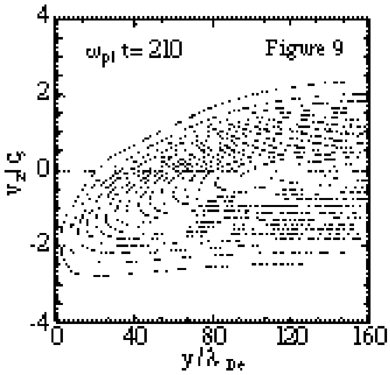



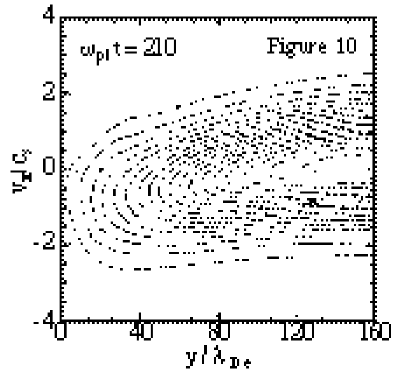



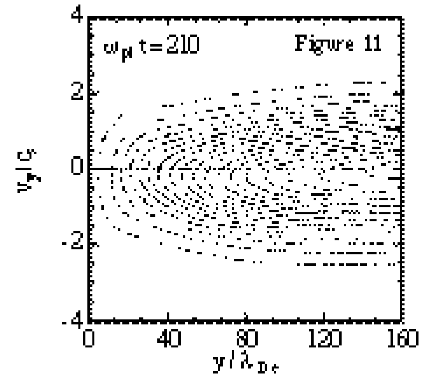



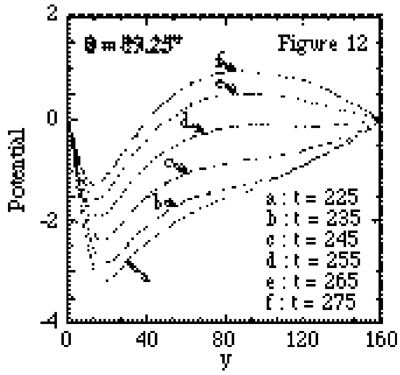



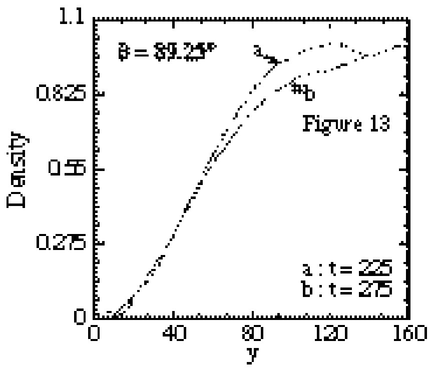

These calculations have partially been performed to obtain the heat flux transmission factor at the plate at small angles of incidence of the magnetic field. We calculate:

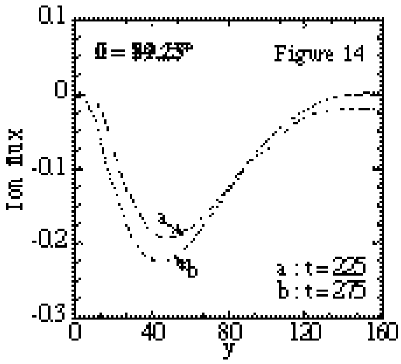



$$Q_e = \frac{1}{2}\frac{m_e}{m_i}\int v_{\parallel}\ v_{\parallel}^2\ f_e(y, v_{\parallel})\ dv_{\parallel}\ ; \quad Q_i = \frac{1}{2}\int v_{\parallel}\ v^2\ f_i(y, \vec{v})\ d\vec{v}$$

$Q_i$ is in Fig. 14 for $\theta = 89.25°$. Its value is almost zero at the plate, while at $\theta = 85°$, the value of $Q_i$ at the plate is –0.12. The corresponding values of $Q_e$ at the plate is averaged to –7 at $\theta = 89.25°$ and –10 at $\theta = 85°$. There is an obvious decrease in the $Q_e$ and $Q_i$.


[1] M. Shoucri and R. Gagné, J. Comp. Phys. 27,315 (1978); M. Shoucri, "Vlasov equation: a new efficient and structured approach", Proc. of the 10th annual Pittsburgh Conf. (April 1979, School of Engineering, Univ. of Pittsburgh), in Modeling and Simulation, Vol. 10, Part 3, p. 1187 (published and distributed by Instrument Society of America).