Numerical simulation for the formation of a steep gradient at a plasma-wall transition

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An understanding of the interface of a magnetized plasma in contact with a wall is of importance in many physical and industrial problems involving plasma-wall interaction. In tokamak physics, understanding of configurations with shallow angles of incidence of the magnetic field intersecting the wall is necessary to decrease the heat load for limiter and divertor design. These configurations are also relevant for the interpretation of probes measurement in magnetized plasma. In industrial applications, plasma etching and ion sputtering are at the core of a revolutionary electronics technology in microprocessor fabrication and in other material processing applications, whose theme is the design of matter on the molecular scale. In the present work, we study the problem of the formation of a steep gradient or plasma detachment at a plasma wall transition using a code in which the electrons, assumed to move along the magnetic field lines only, are described by a kinetic equation, and the ions are described by a fully kinetic equation in velocity space which integrates exactly the ions orbit. We consider a slab geometry in which the inhomogeneous direction *y* is the direction perpendicular to the plate. The *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 θ with the *y* axis (or $\alpha = \pi/2 - \theta$ with the *z* axis). The magnetized electrons are restricted to move along the magnetic field and are described using a kinetic equation in the direction along the magnetic field, with a distribution function $f_e(y, v_{//})$ ($v_{//}$ is the velocity of the electrons parallel to the magnetic field):

$$\frac{\partial f_e}{\partial t} + v_{\|} \cos\theta \frac{\partial f_e}{\partial y} - \frac{m_i}{m_e} E_y \cos\theta \frac{\partial f_e}{\partial v_{\|}} = 0 \tag{1}$$

The ions are treated using a fully kinetic equation in 1D which, in the present geometry, is written:

$$\frac{\partial f_i}{\partial f} + v_y \frac{\partial f_i}{\partial y} + \left(v_y\, \omega_{ci} \sin\theta - v_z\, \omega_{ci} \cos\theta\right) \frac{\partial f_i}{\partial v_x} + \left(E_y - v_x \omega_{ci} \sin\theta\right) \frac{\partial f_i}{\partial v_y} + v_x \omega_{ci} \cos\theta \frac{\partial f_i}{\partial v_z} = 0 \tag{2}$$

The electric field is calculated from Poisson equation, where $n_{i,e} = \int f_{i,e}\, d\vec{v}$:

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

In Eqs. (1-3), time is normalized to $\omega_{p_i}^{-1}$, (so the cyclotron frequency ω_{ci} in Eq. (2) is in fact $\omega_{ci} / \omega_{p_i}$). Velocity is normalized to the acoustic speed C_s, and the length to $C_s\, \omega_{p_i}^{-1} = \lambda_{De}$. We assume the initial distribution to be Maxwellian:

$$f_e(y,v_{\|}) = n(y)\,\frac{(m_e/m_i)^{1/2}}{\sqrt{2\pi(T_e/T_i)}}\,e^{-(m_e/m_i)v_{\|}^2/2(T_e/T_i)} \tag{4}$$

$$f_i(y,\vec{v}) = n(y)\,\frac{e^{-v^2/2}}{(2\pi)^{3/2}} \tag{5}$$

with T_e / T_i equal to 2 in the present calculations. We take as initial profile:

$$n_i = n_e = n(y) = 0.5\ (1 + \tanh\ ((n - L/4) / 7)) \tag{6}$$

The boundary conditions on the distribution functions is to assume that for particles leaving through the right boundary at y = L, the plasma extend to an identical plasma so that for the plasma leaving with positive velocity the point next to the boundary point is identical to the boundary point, and similarly for the entering plasma with negative velocities. At the left boundary, particles hitting the plate are lost from the system and collected through the current delivered at the plate:

$$\left.\frac{\partial E_y}{\partial t}\right|_{y=0} = -J_y\Big|_{y=0} = -\left(J_{yi} - J_{ye}\right)\Big|_{y=0} \tag{7}$$

from which
$$E_y\Big|_{y=0} = -\int_o^t J_y\Big|_{y=0}\,dt \equiv -\left.\frac{\partial\varphi}{\partial y}\right|_{y=0} \tag{8}$$

For the right boundary condition, we integrate the equation:
$$\frac{\partial E_y}{\partial y} = \left(n_i - n_e\right) \tag{9}$$

over the domain; we get :
$$E_y\Big|_{y=L} - E_y\Big|_{y=0} = \int_0^L (n_i - n_e)\,dy = \sigma \tag{10}$$

The system is initially neutral n_i=n_e. The total charge which appears in the system σ, must be equal to the difference in the electric fields at the boundaries. If $E_y\Big|_{y=L} = 0$, then $E_y\Big|_{y=0} = -\sigma$, and the charge which accumulates at the left boundary at any time calculated from Eq. (8) must be equal to the charge σ created in the system which was initially neutral. Equations (1-3) are solved with a method of fractional steps. The plasma is initially neutral. We run the code and let the initial parameters relax to an equilibrium. The time step used was Δt = 0.025. The total length of the system was 150 Debye length. We use 220 points in space and 50 points in each velocity space direction, with velocities maxima equal ±5 C_s. Figure (1) shows the phase-space $v_y - y$ calculated for the case α= 5°, $\rho_i / \lambda_{De} = 10/\sqrt{2}$. It is clear the velocity is reaching a value close to the acoustic velocity at the left plate. In the bottom of Fig. (1) the cuts in the distribution function at a) y = 2.5 λ_{De} and b) y = 5 λ_{De} shows clearly the drift of the distribution and at c) y = 15 λ_{De}; d) y = 30 λ_{De}; e) y = 75 λ_{De}. Figure (2) shows the phase-space $v_y - y$ calculated for the case α= 0.75°, and $\rho_i / \lambda_{De} = 10/\sqrt{2}$. It is clear that at the left plate there is no more acceleration as in Fig. (2). Figures (3) and (4), show the density plot (solid curve ions, broken curve electrons), for the two cases respectively. The case

$\alpha = 0.75°$ in Fig. (4) shows clearly a steeper profile and the density reaching a very low value at the plate, the plasma effectively detaching from the plate (similar results have been reported for the case when the plate was kept at zero potential [1]). The charge $n_i - n_e$ is shown in Fig. (5) for $\alpha = 5°$and in Fig. (6) for $\alpha = 0.75°$ (note the small values, especially in Fig. (6)). This charge is creating a potential. The small oscillation in Fig. (7) for $\alpha = 5°$ is small, and the oscillation in Fig. (8) for the case $\alpha = 0.75°$ is much more important. The corresponding electric fields are given in Figs (9) and (10) respectively. We present in Figs (11) and (12) the currents in the direction normal to the plate, respectively for $\alpha = 5°$, and $\alpha = 0.75°$ (solid curve for the electrons and broken curve for the ions). The values of the current are very close for the two species, the currents for $\alpha = 0.75°$ is very much reduced, reaching the plate at the left at zero values. Work is in progress to study and analyze these oscillations.

[1] M. Shoucri and K.H. Finken, Proc. EPS Conference (Budapest, June 2000).

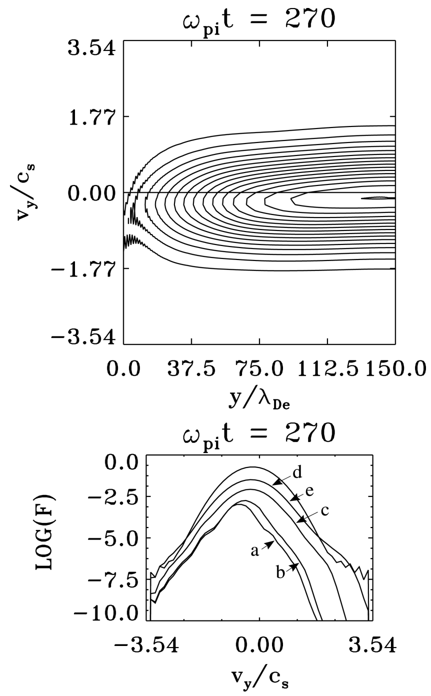

Fig. 1

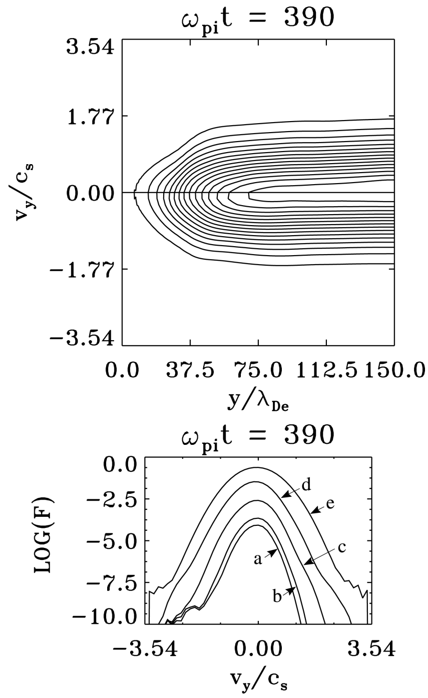

Fig. 2

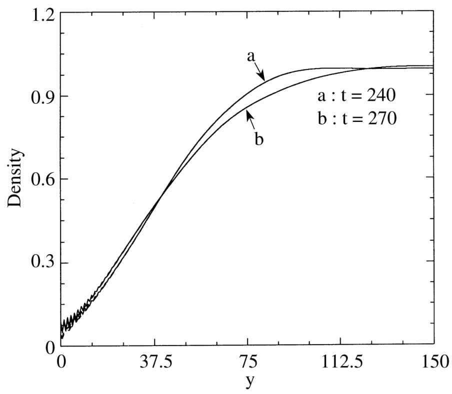

Fig. 3 - $\alpha = 5°$

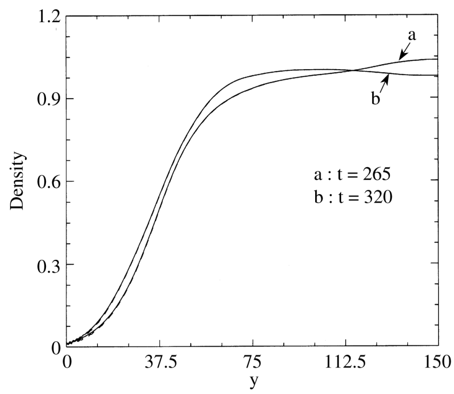

Fig. 4 - (steeper profile) $\alpha = 0.75°$

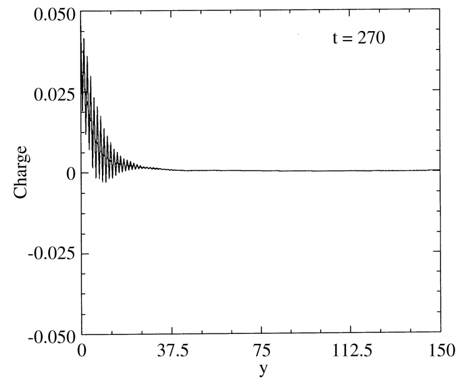

Fig. 5 - $\alpha = 5°$

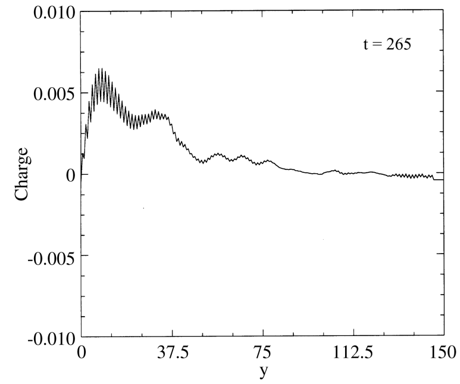

Fig. 6 - $\alpha = 0.75°$

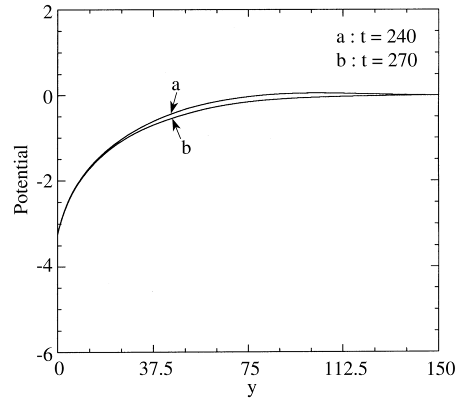

Fig. 7

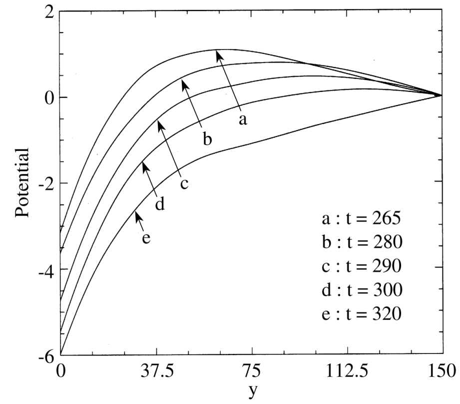

Fig. 8

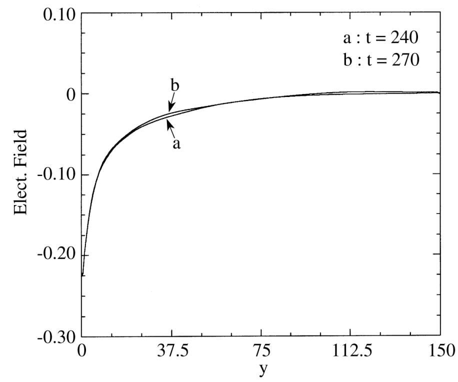

Fig. 9 - (smaller electric field) $\alpha = 5°$

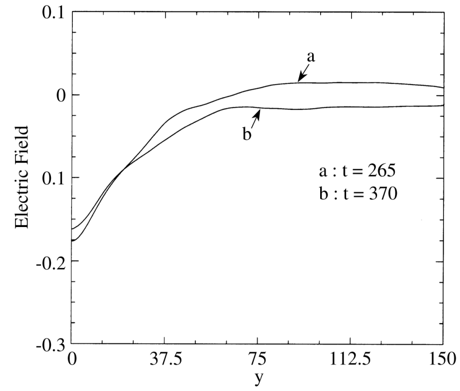

Fig. 10 - (smaller electric field) $\alpha = 0.75$

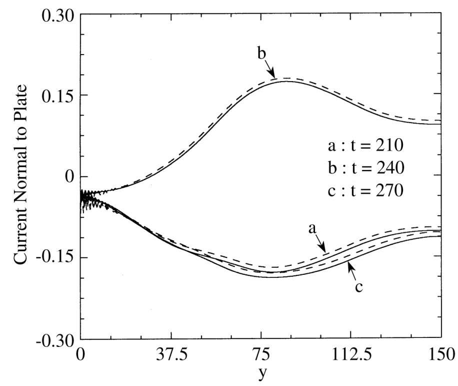

Fig. 11 - $\alpha = 5°$

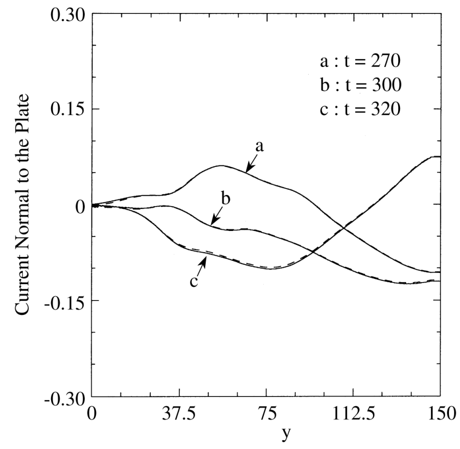

Fig. 12 - $\alpha = 0.75°$