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The Formation of a Charge Separation and an Electric Field at a Steep Plasma Edge

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The problem of the formation of a charge separation and an electric field along a steep density gradient of a plasma largely affects the edge physics associated with the high confinement mode (H mode) and the reversed shear equilibria in tokamak physics. We study this problem in one spatial dimension (1D) Cartesian geometry using a kinetic Vlasov equation for the ions, for the case where the ions gyro-radius ρ_i is much larger than the Debye length λ_{De} ($\rho_i / \lambda_{De} = 14$ in our calculation). The Vlasov equation is solved using a method of fractional steps. The plasma is assumed to be in front of a limiter with the magnetic field being aligned parallel to the limiter surface. Electrons are assumed to be frozen along the magnetic field lines. We compare the electric field at the edge with the macroscopic values for the gradient of the ion pressure and the Lorentz force term calculated from the same kinetic code. We find that these quantities balance the electric field for the case of a floating limiter [1] as well as for the case, of experimental interest [2], where the limiter is biased (positive or negative).

The Relevant Equations

The notation is the same as in Ref. [1]. The inhomogeneous direction in the 1D slab geometry considered is the *x* direction, normal to the limiter plane (*y*, *z*). The constant magnetic field is in the *y* direction (assumed to represent the toroidal direction), and *z* represents the poloidal direction. The ions are described by the 1D Vlasov equation for the distribution $f_i(x, v_x, v_z)$:

$$\frac{\partial f_i}{\partial t} + v_x \frac{\partial f_i}{\partial x} + (E_x - v_z\ \omega_{ci}) \frac{\partial f_i}{\partial v_x} + v_x \omega_{ci} \frac{\partial f_i}{\partial v_z} = 0 \qquad (1)$$

Time is normalized to the inverse ion plasma frequency ω_{pi}^{-1}, velocity is normalized to the acoustic velocity $c_s = \sqrt{T_e / m_i}$, and length to the Debye length $\lambda_{De} = c_s / \omega_{pi}$. The potential is normalized to T_e / e, and the density to the peak initial central density. The system is solved over a length $L = 150$ Debye lengths in front of the limiter plate, with an initial density profile: $n_e = n_i = 0.5(1 + \tanh((x - L/2)/4))$. It was pointed out in the analysis of H-mode power threshold in Ref. [3] that the changes in n_e and ∇n_e in the transition to H-mode are small, and changes in T_e are barely perceptible in the data. We therefore assume that the magnetized electrons are frozen along the magnetic field lines, with the constant profile previously given. In this case the electrons cannot move across the magnetic field in the gradient region to compensate the charge separation which is built up due to the finite ion orbits. To determine this charge separation along the gradient it is important to calculate the ion orbits accurately by using an Eulerian Vlasov code. The larger the ions gyroradius, the bigger the charge separation and the self-consistent electric field at the edge. (Hence the important role played by even a small fraction of impurity ions). The electric field is calculated from the Poisson equation:

$$\frac{\partial^2 \phi}{\partial x^2} = -(n_i - n_e) \quad ; \qquad E_x = -\frac{\partial \phi}{\partial x} \tag{2}$$

The following parameters are used for deuterium ions

$$\frac{\omega_{ci}}{\omega_{pi}} = 0.1; \qquad \frac{T_i}{T_e} = 1; \qquad \frac{\rho_i}{\lambda_{De}} = \sqrt{\frac{2T_i}{T_e}} \frac{1}{\omega_{ci} / \omega_{pi}} = 10\sqrt{2} \tag{3}$$

The deuterons hitting a wall at $x = 0$ are collected by a limiter. Since the magnetized electrons do not move in the x direction, there is no electron current collected at the limiter. We have at $x = 0$ the relation :

$$\left.\frac{\partial E_x}{\partial t}\right|_{x=0} = -J_{xi}\big|_{x=0} \quad \text{or} \quad E_x\big|_{x=0} = -\int_0^t J_{xi}\big|_{x=0} dt \tag{4}$$

which determines the electric field at x=0 for a floating limiter. Integrating Eq. (2) over the domain (0, *L)*, we get the total charge σ appearing in the system:

$$E_x\big|_{x=L} - E_x\big|_{x=0} = \int_0^x (n_i - n_e)\, dx = \sigma \tag{5}$$

In the case of a biased limiter, Eq.(2) is solved with the potential at $x = 0$ equal to the biasing voltage, the slope of the potential curve at x=0 determines $E_x\big|_{x=0}$.

Results

We assume that the plasma ions are allowed to enter or exit at the right boundary. The electric field at the right boundary $x = L$ must be such that the difference between the electric fields at both boundaries in Eq. (5) is equal to the charge σ appearing in the system. Figs.(1) shows the plots of the electric field E_x (solid curves). We also plot $n_i / 2$ for reference (dash-3dots curves). The electric field, when positive, is pushing the ions to the interior of the plasma. The broken curves give the Lorentz force, which is given by $< v_z > \omega_{ci} / \omega_{pi}$ in our normalized units, and the dotted curves give the pressure force $\nabla p_i / n_i$, $p_i = 0.5\, n_i (T_{ix} + T_{iz})$, with

$$T_{ix,z}(x) = \frac{1}{n_i}\int dv_x dv_z \left(v_{x,z} - < v_{x,z} >\right)^2 \; f_i\left(x, v_x, v_z\right) \tag{6}$$

$$< v_{x,z} > = \frac{1}{n_i}\int dv_x dv_z v_{x,z}\, f_i\left(x, v_x, v_z\right); \qquad n_i(x) = \int dv_x dv_z\, f_i\left(x, v_x, v_z\right) \tag{7}$$

In steady state the transport $< v_x >$ vanishes. The dash-dot curves in Fig. (1) give the sum $\nabla p_i / n_i + 0.1 < v_z >$, which show good agreement along the gradient with the solid curves E_x. In the region $x < L/2$ we have irregular oscillations in space (and time), the accuracy in this region being degraded by the division by the low density n_i. To avoid the division by n_i, we plot in Fig. (2) the quantities $n_i E_x$, ∇p_i, $0.1\, n_i < v_z >$ and the sum $\nabla p_i + 0.1\, n_i < v_z >$. We see that there is a very nice agreement for the relation $n_i E_x = \nabla p_i + 0.1\, n_i < v_z >$ (the density $n_i / 10$ is plotted with the dash-3dots curves for reference). For the case of a negative bias of -50 at the limiter shown in Figs.(1c,2c), there is a small oscillation around the equilibrium shown with a frequency $\omega_{ci} / \omega_{pi}$ =0.1. For the case of a floating potential in Fig.(2a), the electric field is essentially compensating the gradient of the pressure at the edge, the Lorentz force term is negligible. However for the case of a positive or negative bias, the Lorentz force term is more important, and inside the plasma where $\nabla p_i = 0$, the electric field is balanced by the Lorentz force due to the poloidal drift $0.1 < v_z >$. The charge σ appearing in the plasma is calculated by the code from Eq. (5), and amounts to –0.19227 for the case of a floating potential, where the charge collected at $x = 0$, which defines $E_x|_{x=0}$ from Eq. (5), is 0.19637. The difference between these two numbers is ≈ 0.0041, which is $E_x|_{x=L}$ from Eq. (5). For the case of a positive bias +50 at the limiter, the charge in the plasma from Eq.(5) is σ=-0.61476, $E_x|_{x=0}$ =0.63813 and $E_x|_{x=L}$ =0.02341, and the corresponding numbers for the case of a negative bias -50 are 0.5625, -0.67646 and -0.11397, verifying Eq.(5) in all cases (the charge collected at the limiter is negligible in the biased cases). Fig.(3) shows the potential and Fig.(4) the charge profiles for the case of a floating limiter (full curves), positive bias (dotted curves) and negative bias (broken curves). Thus between the plasma and the limiter a complex sheath structure is formed which governs the plasma-wall transition. Figs.(5,6) show the distribution function $F_i(x, v_x)$ for the cases of a negative and a positive bias respectively.

References

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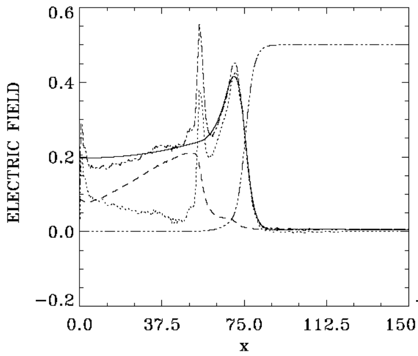

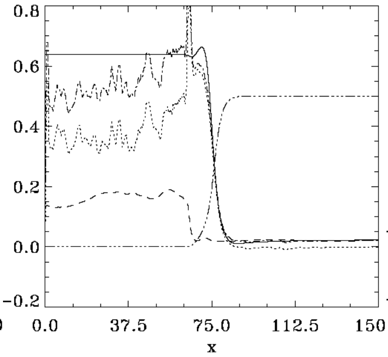

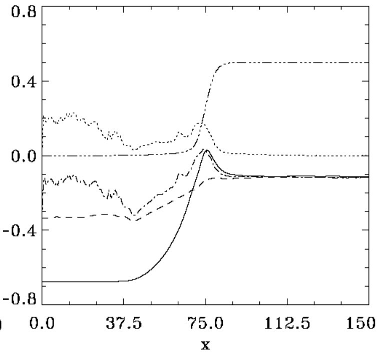

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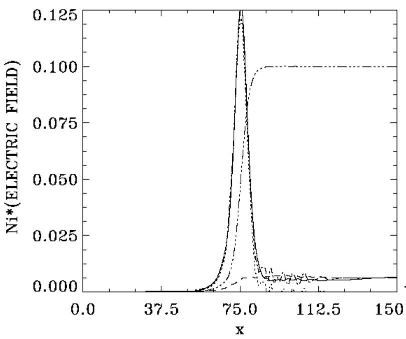
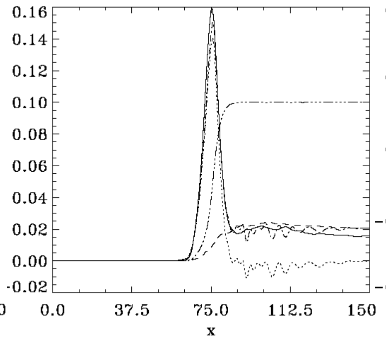
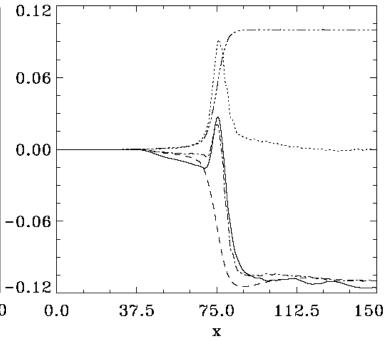
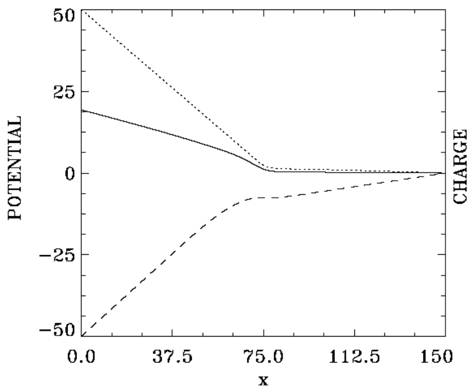
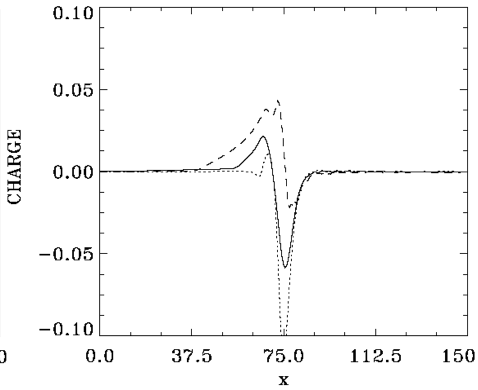




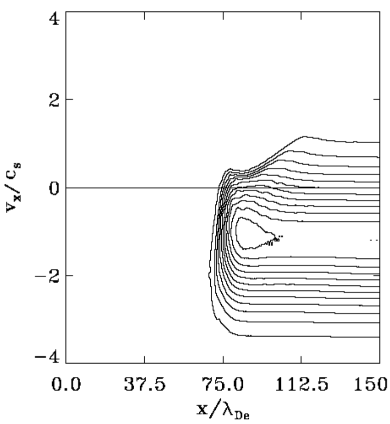


. Fig.2a floating potential Fig.2b limiter bias +50 Fig.2c limiter bias -50 .





. Fig.3 Fig.4



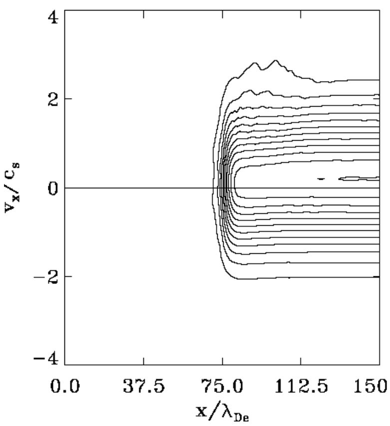


Fig.5 $F_i(x, v_x)$ limiter bias -50 Fig.6 $F_i(x, v_x)$ limiter bias +50