26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 313 - 316

Charge separation at a plasma edge in the presence of impurity ions

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In the presence of a density gradient, the finite ion gyro-radius plays an important role in establishing a charge separation and an electric field at a plasma edge, since in this case the electrons density can change rapidly over an ion orbit size. This effect is important for large values of ρ_i/λ_{De} (ρ_i is the ion gyro-radius and λ_{De} the Debye-length). Adding a small fraction of impurity ions to the mix can increase substantially the charge separation at the edge, due to the fact that impurity ions usually have a much larger gyro-radius than the main plasma ions. In the present work, we use a fully kinetic code for ions (one dimensional (1D) in space, and using the three velocity dimensions) and for impurity ions, to study the problem of the formation of a charge separation with the self-consistent 1D electric field at a plasma edge. Electrons are treated using an adiabatic law. We consider a 1D slab geometry, the y direction representing the radial direction. The 1D Vlasov equation for the main ions distribution function f_i is written in normalized units:

$$\frac{\partial f_i}{\partial t} + v_y \frac{\partial f_i}{\partial y} + \left(\vec{E} + \vec{v} \times \vec{B}\right) \bullet \frac{\partial f_i}{\partial \vec{v}} = 0 \qquad (1)$$

A similar equation holds for the impurity ions. $\vec{B}$ denotes the constant magnetic field situated in the (x, z) plane, which makes an angle $\theta = 89°$ with the x axis (z is the periodic toroidal direction and x is the periodic poloidal direction). $\vec{v}$ is the velocity and the electric field $\vec{E}$ is calculated from: $\vec{E} = -\nabla\varphi$; $\Delta\varphi = -\left(n_i + n_I - n_e\right)$; $n_{i,I} = \int f_{i,I}\, d\vec{v}$. The electron density n_e is calculated from an adiabatic law: $n_e = n(y)\, e^{\phi}$. We normalize time to ω_{pi}^{-1}. Velocity is normalized to the acoustic velocity $C_s = \sqrt{T_e/m_i}$, length is normalized to $C_s\,\omega_{pi}^{-1}$, and potential to T_e/e. We take as initial density $n_i = 0.95\, n(y)$ and $n_I = 0.05\, n(y)$, where $n(y)$ and the temperature in the domain $-80 < y < 80$ are given by:

$$n(y) = 0.5\,\left(1 + \tanh\,\left(y/15\right)\right); \qquad T_i(y) = T_{io}\,\left(0.2 + 0.4\,\left(1 + \tanh\,\left(y/10\right)\right)\right) \qquad (2)$$

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The initial distribution function for the main ions is given by:

$$f_i(y, \vec{v}) = n_i \frac{1}{2\pi\, T_{io}} e^{-(v_x^2+v_y^2)^2/2T_{io}} \frac{1}{(2\pi\, T_i(y))^{1/2}} e^{-v_z^2/2T_i(y)} \qquad (3)$$

and a similar equation for $f_I = (y, \vec{v})$, and $T_I(y) = T_i(y)$. The physical parameters are:

$$T_e/T_{io} = 1; \quad m_i/m_e = 1840; \quad \omega_{ci}/\omega_{pi} = 0.1; \quad \rho_i/\lambda_{De} = \frac{v_{ti}/\omega_{ci}}{\lambda_{De}} = \frac{\sqrt{T_{io}/T_e}}{\omega_{ci}/\omega_{pi}} = 10 \qquad (4)$$

We use $\Delta t = 0.1$, $-4 < v_x, v_y, v_z < 4$, $N_y N_{vx} N_{vy} N_{vz}$ = 160 x 50 x 50 x 50 is the number of grid points. Eq. (1) was solved in [1] using method of fractional steps with a flux conserving scheme which is diffusive, and distorted the charge. In the present work, we use the cubic spline method [2]. In our units, the gyro-period is $2\pi/\omega_{ci} = 62.8$. In the simulation, we see a period of about 56. We show in Fig. 1 the potential over a period from t = 680 to t = 730. The charge ($n_i + n_I - n_e$) is presented in Fig. 2. The electric field in Fig. 3 shows the formation of an oscillating positive bump, while in the edge the profile remains negative. See the accumulation of positive charge at the edge in Fig. 2. Fig. 4 shows the density profiles during the oscillation (full curve for the electrons, broken curve for the main ions, and the dash-dot curve for the impurity magnified by 10). See how the impurity ions extend towards the edge. We present in Fig. 5 for comparison the density profile for the ions obtained with the s ame parameters but without impurity ions. At t = 690 and t = 700 they reproduce approximatly the electron density in Fig. 4. The value $n_i + n_I$ in Fig. 4 reproduces closely the value of n_i without impurity ions for $y > -40$. In Fig. 6, we present the contour plots in (y, v_y) at t = 705 of the distribution functions of the main ions (left) and the impurity ions. See how the positive electric field is pushing the main ions to the right, while the impurity ions extend to the edge. For comparison, see in Fig. 7, 8, 9 the potential, the charge, and the electric field for the case without impurity ($n_I = 0$, $n_e = n(y)$ initially, corresponding to Fig. 5). Note the increase at the edge of the electric field in Fig. 3 compared to Fig. 9, and of the charge in Fig. 2 (with a contribution from n_I at the edge) compared to Fig. 8. Note the oscillation propagating from right to left during the first half period, then as a standing wave during the second half.

References

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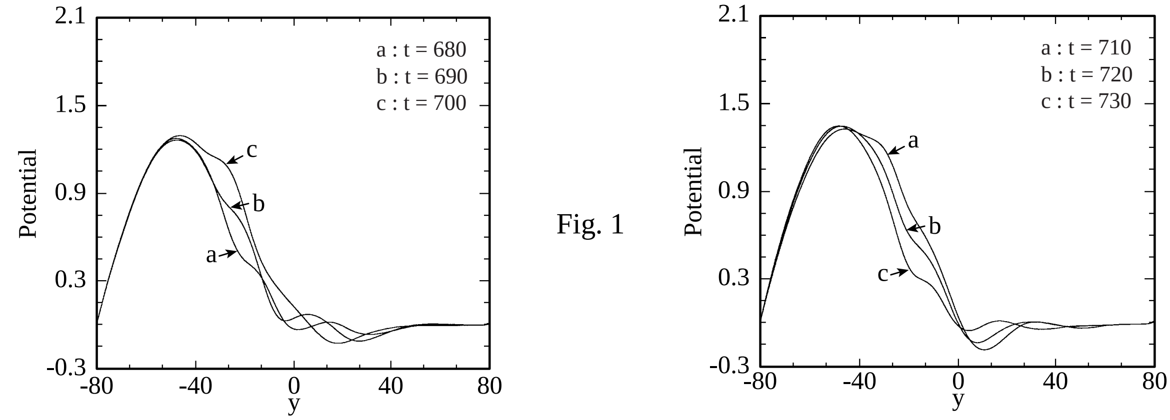

Fig. 1

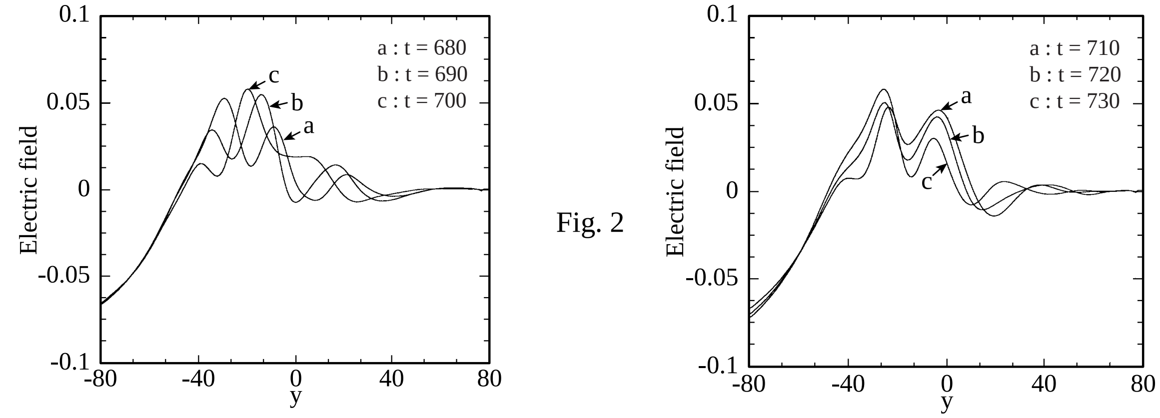

Fig. 2

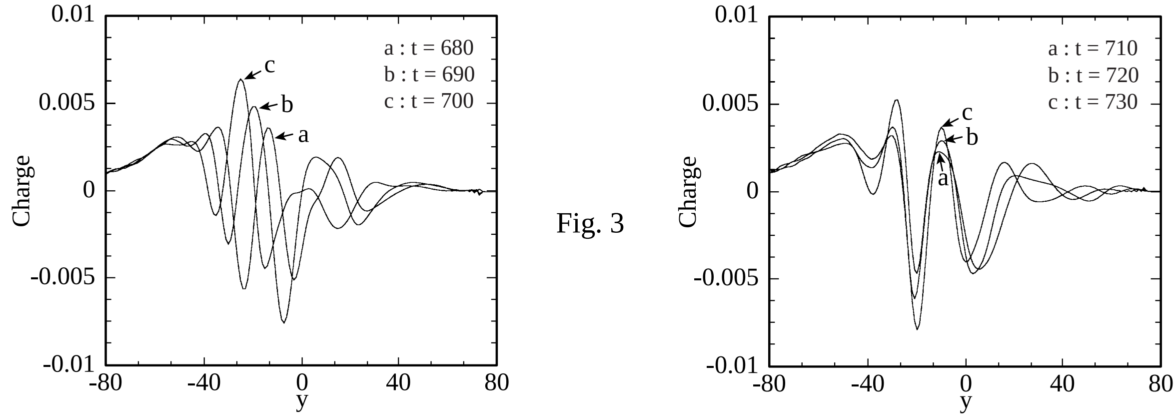

Fig. 3

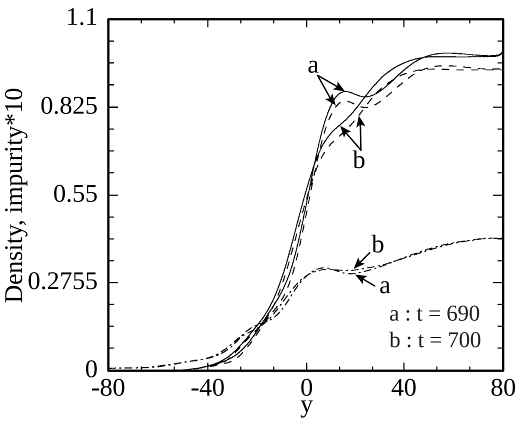

Fig. 4

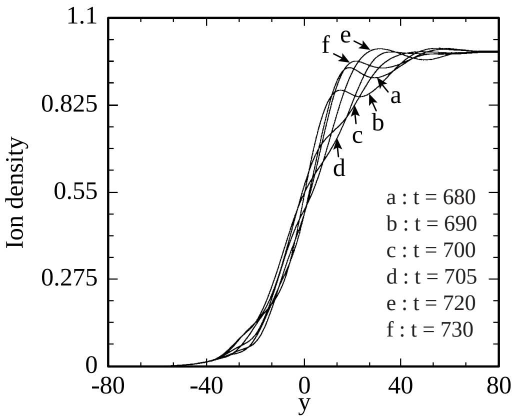

Fig. 5

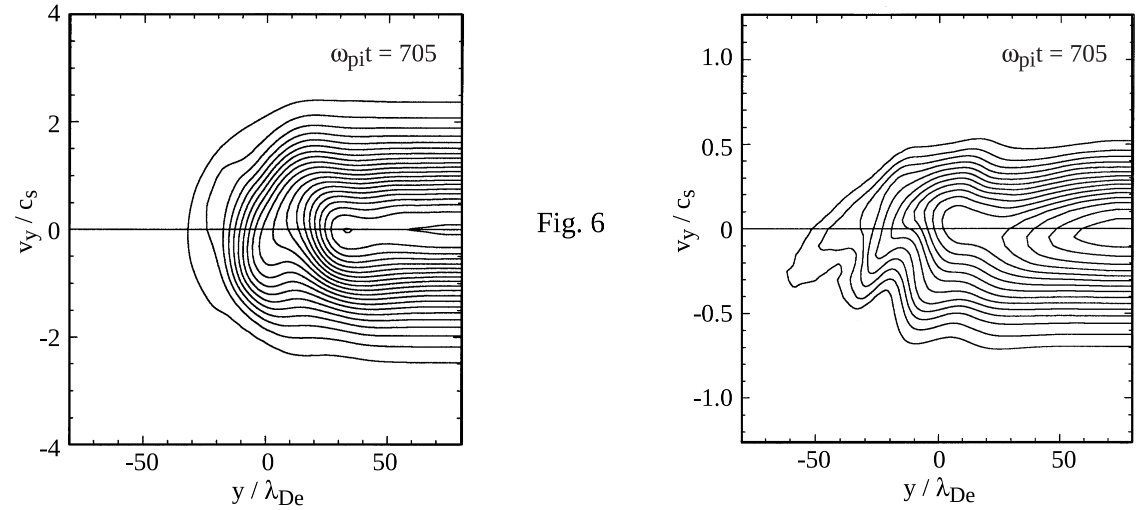

Fig. 6

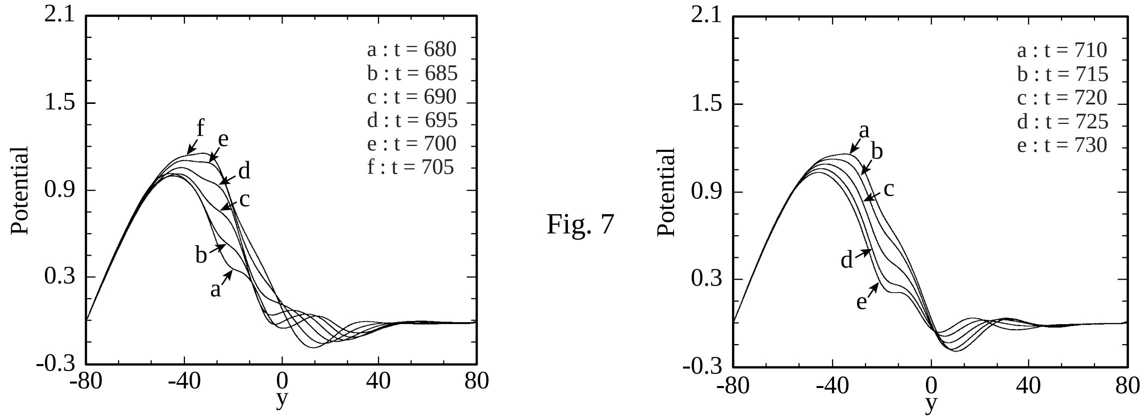

Fig. 7

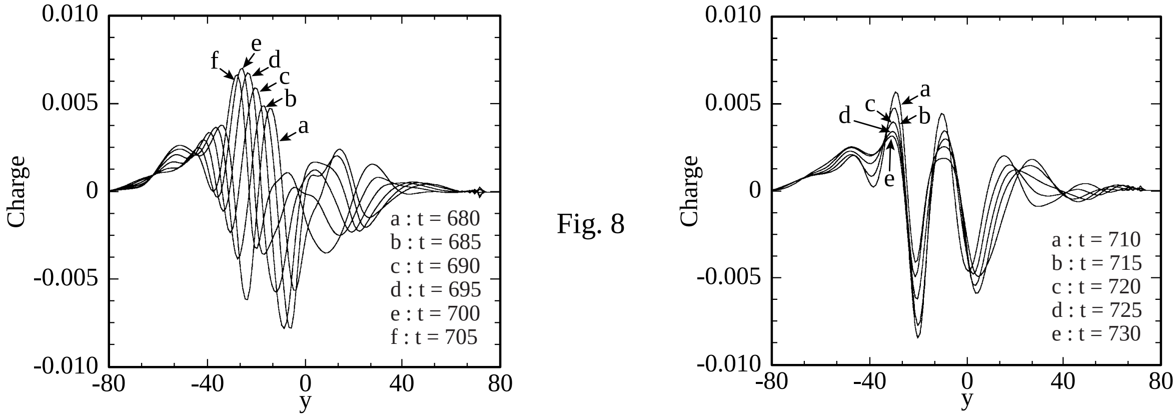

Fig. 8

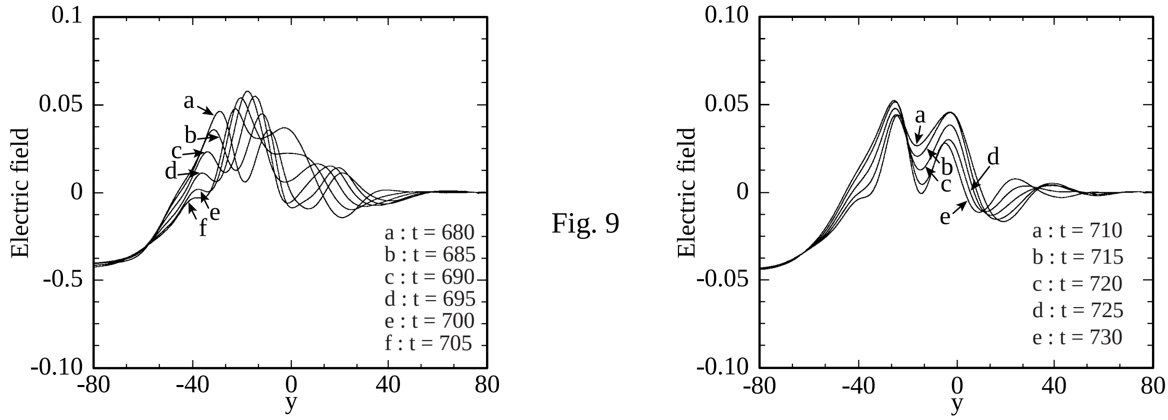

Fig. 9