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Calculation of the electric field at a steep plasma edge in the presence of finite ion orbits

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We present, using a 1 D slab model with an Eulerian Vlasov code, a self-consistent kinetic solution for the problem of the formation of a charge separation and an electric field at a plasma edge, under the combined effect of a large ratio of ρ_i / λ_{DE} (where ρ_i is the ions gyro-radius, and λ_{DE} is the Debye length) and a steep gradient. The ions trajectory are accurately integrated using a fully kinetic Vlasov equation, to calculate accurately the ions orbit. The electrons along the gradient are assumed to be frozen along the magnetic field lines and cannot move across the magnetic field to compensate the charge separation due to the finite ions gyro-radius. Two cases will be studied, the case of a hydrogen plasma, and the case of a deuterium plasma. In the second case, the larger gyro-radius of the deuterium provides a higher electric field at the edge with respect to the case of a hydrogen plasma, for the same density profile and temperature. The 1D slab model presented in Refs. 1 and 2 will be sufficient for our discussion. We keep the same notation and assume a constant toroidal magnetic field directed along the z-direction (which amounts to setting $\theta = \pi/2$ in the equations of Refs. 1, 2), while the inhomogeneous radial direction will be in the y direction. The x coordinate will represent the periodic poloidal direction. We assume in our simulation that the initial profiles at the edge for the initially neutral plasma are given by

$$n_i = n_e = 0.5\,(1 + \tanh\,((y - L/4)/7)) \qquad (1)$$

with an initial Maxwellian distribution for the ions. Length is normalized to the Debye length, velocity to the acoustic speed $C_s = \sqrt{T_e / m_i}$, and time to ω_{pi}^{-1}. The system is solved over a length $L = 150$ Debye lengths. The symbols have their conventional meaning as in Refs [1, 2]. It was pointed out in the analysis of low 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. So it will be sufficient for the purpose of our demonstration to assume that the magnetized electrons are frozen along the magnetic field lines, with a constant profile given by Eq. (1) in the y direction. So the electron density $n_e(y)$ is an invariant [allowing a local variation in the form $n_e(y)e^{\phi}$ as in Refs 1 and 2 did not change the results]. We also note from the two-dimensional (2D) drift kinetic equation used for the electrons in Ref. 2 that any 1D profile $n_e(y)$ is an equilibrium solution for the electrons drift kinetic equation.

The electric field equations are given by:

$$\frac{\partial E_y}{\partial y} = n_i - n_e \quad ; \qquad E_y = -\frac{\partial \phi}{\partial y} \tag{2}$$

with the following parameters for the hydrogen ions case:

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

For the same magnetic field, the same density profile and the same ratio $T_e/T_i = 2$, we have for the case of deuterium ions $\omega_{ci}/\omega_{pi} = 0.1/\sqrt{2}$ and $\rho_i/\lambda_{De} = 10$. Hence the ratio ρ_i/λ_{De} is larger than for the case of hydrogen ions.

Instead of fixing the potential equal to zero at the boundary $y = 0$ as in Refs 1 and 2, we assume in the present calculation that ion particles hitting a wall at $y = 0$ are collected by a floating wall or limiter such that:

$$\frac{\partial}{\partial t} E_y\Big|_{y=0} = -\left(J_{yi}\Big|_{y=0} - J_{ye}\Big|_{y=0}\right) \;; \qquad \text{or} \qquad E_y\Big|_{y=0} = -\int_0^t \left(J_{yi}\Big|_{y=0} - J_{ye}\Big|_{y=0}\right)\, dt \tag{4}$$

($J_{ye}\big|_{y=0}$ is negligible, the frozen electrons along the magnetic field lines have essentially a negligibly small constant density at the wall and no motion normal to the wall). Integrating Eq. (2) over the domain (0, L); we get:

$$E_y\Big|_{y=L} - E_y\Big|_{y=0} = \int_0^L \left(n_i - n_e\right)\, dy = \sigma \tag{5}$$

We assume the plasma ions can circulate at the right boundary, i.e. for ion particles leaving the domain with a positive velocity, the point next to the boundary point is identic to the boundary point, and similarly for ion particles entering the domain with a negative velocity. So the plasma remains Maxwellian at the right boundary and $E_y\big|_{y=L} = 0$. It follows from

Eqs. (4), (5) that the charge collected at the floating edge at $y = 0$ must be equal to the charge σ appearing in the system in Eq. (5), a result verified by the numerical code up to the third decimal point.

We have run the code for sufficiently longer time than in Ref. 3, to be essentially at a steady state. Figure 1 shows the charge n_i-n_e at the edge (full curve for the deuterium, broken curve for the hydrogen), at $t = 500$. We see a more important accumulation of charge at the edge for the case of deuterium ions (full curve). This translates in Fig. 2 and Fig. 3 into a more important potential and electric field respectively for the case of deuterium ions (full curve). Although the maximum charge separation at the edge is only about two percent, this translates into an important potential due to the large ratio of ρ_i/λ_{De} (which is larger for the deuterium). Figure 4 shows the density profiles for the deuterium ions (full curve) and for the electrons (Eq. (1), given by the broken curve). Figure 4 and Fig. 3 shows how the electric field is increasing along the density gradient and reaching a peak at the bottom of the gradient. It is the combined effect of the large ratio ρ_i/λ_{De} with the steep gradient which causes the steep rise of the electric field. The steeper the profile, the steeper the rise in the electric field. This rise of the electric field extends over a length of about to two to three gyro-radii and is independent of how far is the left boundary from the plasma. If the boundary is put further away from the plasma, this will results in a smoother decay of the electric field towards the boundary, without affecting the rapid rise. There is experimental evidence that the power threshold for the excitation of the H-mode for a hydrogen plasma is higher than for a deuterium plasma [4]. This is qualitatively in agreement with the present results which shows the electric field at a plasma edge for the case of a deuterium plasma is higher than for the case of a hydrogen plasma.

To conclude, using a 1D slab model [1, 2], we have presented a self-consistent kinetic solution for the problem of the formation of a charge separation and an electric field at a plasma edge, under the combined effect of a large ratio ρ_i/λ_{DE} of and a steep gradient, when the electrons which are bound by the magnetic field cannot compensate along the gradient the charge separation due to the finite ions gyroradius. The larger the ratio ρ_i/λ_{DE}, the larger the electric field due to a given charge. This underlines the importance of small fractions of impurity ions which, due to their large gyroradii, can increase the charge in regions at the edge for away from where the main ion species can reach, and can substantially increase the electric field [1, 2]. We note finally that a 2D code used in Ref. [2] to study this problem did confirm the existence of the 1D solution, *i.e.*, along a gradient and with guiding center motion of the electrons across the magnetic field, ions with finite gyroradius establish a 1D charge separation.

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References

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