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Journal of Nuclear Materials 266–269 (1999) 873–876

journal of nuclear materials

Charge separation at a plasma–wall transition due to the finite ion gyro-radius

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Abstract

An Eulerian Vlasov gyrokinetic code is developed for the investigation of a plasma in $\vec{E}\times\vec{B}$ flow. The charge separation at a plasma–wall transition due to finite ion gyro-radius is studied. The model is two-dimensional in space and consists of a two-component collisionless plasma slab.

Keywords: Plasma facing material; Numerical simulation

1. Introduction

For edge plasma parameters typical for current tokamaks as well as ITER, the applicability of plasma fluid models is usually violated (especially in 'detached divertor' regimes characterized by the steep plasma parameter profiles [1]). The ratio of the charged particle Coulomb mean free path, λ, to the magnetic field line connection length in the scrape off layer (SOL), L, is not small enough for the Spitzer–Harm (SH) theory of plasma heat conductivity to be applied (typically λ/L is of the order of 10^{-1} while for SH theory to be valid this parameter must be less than 10^{-2}). The kinetics of the collisional plasma transport along the magnetic field lines have been recently a matter of intensive investigation [2]. Using a 1D-2V Fokker Planck code ALLA, it has been shown that the plasma distribution functions in the SOL plasma of tokamaks are non-Maxwellian [2]. The non-Maxwellian tail strongly effects common plasma diagnostics, parallel plasma heat conductivity, plasma–neutral and plasma–impurity interactions, and all the physics and diagnostics associated with the SOL.

Perpendicular plasma transport ($\vec{E}\times\vec{B}$ drift in particular) can lead to enhanced suprathermal tails in the SOL plasma due to the radial gradient of the plasma temperature. These enhanced tails can significantly affect the energy fluxes along and across field lines, neoclassical effects such as plasma rotation, ion losses from the torus etc., which might be related to L–H transitions. Moreover, it was shown theoretically in Ref. [3] that due to the influence of the shear of the self consistent $\vec{E}\times\vec{B}$ drift affecting the inertia term in the plasma momentum balance, a strong drop of the total plasma pressure $P_\Sigma = MnV_\parallel^2 + nT$ along the magnetic field lines can be supported in a manner similar to that observed in detached divertor plasma experiments without any influence of plasma neutral interactions. The required typical radial scale length of plasma parameter (n, T, ϕ) variations for these regimes is of the order of the poloidal ion gyroradius. The goal of this paper is to present a preliminary model of an Eulerian Vlasov gyrokinetic code developed for the investigation of a divertor plasma in $\vec{E}\times\vec{B}$ flow. The model consists of a two-component collisionless plasma slab, with a fixed wall, to simulate a plasma divertor. The model is two-dimensional in space and makes use of the gyro-kinetic approximation for both species in the plane perpendicular to the magnetic field. Kinetic effects parallel to the magnetic field lines are taken into account [4]. It also

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includes the possibility of biasing the fixed wall to a given potential. The Vlasov codes have proven to give very good results in plasma simulation, being capable of description correctly the phase space distribution function even in regions of low density [2].

2. The Pertinent equations and results

We work in a two-dimensional slab geometry, x being the periodic coordinate and y the non-periodic one. The plasma is supposed to be uniform in the z direction. A constant magnetic field $\vec{B}$ lies in the y, z plane and makes an angle θ with the y axis. The two-component electron and ion plasma is supposed to be collisionless. The motion of a plasma, when immersed in a strong magnetic field is generally dominated by the $\vec{E}\times\vec{B}$ drift perpendicular to the magnetic field lines. Since this drift is charge and mass independent, important physical phenomena related to charge separation are lost if we only retain the $\vec{E}\times\vec{B}$ motion in the model. A first attempt to take into account effects due to the polarization drift and the finiteness of the ion Larmor radius (both of which can induce a charge separation) has been done in previous publications [5]. The gyro-kinetic Vlasov equations are written with the drift $\vec{v}_{\mathrm{D}}$ and the polarization drift $\vec{v}_{\mathrm{p}}$:

$$\frac{\partial f_{\mathrm{i,e}}}{\partial t}+\nabla_{\perp}\cdot\left(\vec{v}_{\perp}f_{\mathrm{i,e}}\right)+\vec{v}_{\parallel}\cdot\nabla_{\parallel}f_{\mathrm{i,e}}\pm\frac{q}{m_{\mathrm{i,e}}}\vec{E}^{\,*}_{\parallel}\cdot\frac{\partial f_{\mathrm{i,e}}}{\partial\vec{v}_{\parallel}}=0$$

$$\vec{v}_{\mathrm{D}}=\frac{\vec{E}^{\,*}\times\vec{B}}{B^2};$$

$$\vec{v}_{p_{\mathrm{i,e}}}=\pm\frac{m_{\mathrm{i,e}}\,\mathrm{d}\vec{E}^{\,*}_{\perp}}{qB^2\,\mathrm{d}t}=\pm\frac{m_{\mathrm{i,e}}}{qB^2}\left[\frac{\partial\vec{E}^{\,*}_{\perp}}{\partial t}+\left(\vec{v}_{\parallel}+\vec{v}_{\mathrm{D}}\right)\cdot\nabla\vec{E}^{\,*}_{\perp}\right] \tag{1}$$

and $\vec{v}_{\perp}=\vec{v}_{\mathrm{D}}+\vec{v}_{\mathrm{p}}$. Indices i.e denote ions and electrons respectively. The positive sign is for ions and the negative sign is for the electrons. The star over the electricfield denotes an integral operator that accounts for the finite Larmor radius $\rho_{\mathrm{i,e}}$ effects. This operator is a convolution in ordinary space, and can therefore more easily be written in Fourier space. For example, for a quantity $a(r)$ we have

$$a^*(r)=\int G(r-r')a(r')\,\mathrm{d}r' \tag{2}$$

and in Fourier space

$$a_k^*=G_k\cdot a_k;\quad G_k=\mathrm{e}^{-\frac{1}{2}k_\perp^2\rho_{\mathrm{i,e}}^2}. \tag{3}$$

In our geometry, $k_\perp^2=k_x^2+k_y^2\sin^2\theta$ [4]. The electrostatic potential Φ obeys the equation

$$\Delta\Phi=-\frac{q}{\varepsilon_0}\left(n^*_{\mathrm{i,e}}-n^*_{\mathrm{e}}\right), \tag{4}$$

where $n_{\mathrm{i,e}}=\int f_{\mathrm{i,e}}\,\mathrm{d}v_\parallel$. The wall is supposed to be parallel to the (x, z) plane and intersecting the y axis at the point $y=0$. The magnetic field therefore hits the wall, making an angle θ with its normal [4]. We choose an initial condition that reproduces the profile of the plasma near a wall, with the density profile decreasing towards the wall and attaining some constant value towards the bulk of the plasma. Our initial conditions are the following:

$$\begin{aligned}&f_{\mathrm{e}}\left(x,y,v_\parallel,t=0\right)\\&=\frac{N(y)}{\sqrt{2\pi T_{\mathrm{e}}(y)}}\mathrm{e}^{-v_\parallel^2/2T_{\mathrm{e}}(y)}\;n_{\mathrm{e}}(x,y,t=0)=N(y)\\&=\tanh\,(y/2);\quad T_{\mathrm{e}}(y)=T_{\mathrm{e}}(0.2+0.8\,\tanh(y/2)).\end{aligned} \tag{5}$$

A perturbation of the form $\varepsilon(\sin k_0x+\sin 2k_0x+\sin 3k_0x)$ is added to the initial density of the species. Space is normalized to the electron Debye length λ_{De}, time is normalized to the electron inverse plasma frequency $\omega_{\mathrm{pe}}^{-1}$, and velocity to the electron thermal velocity $V_{\mathrm{Te}}=\lambda_{\mathrm{De}}\omega_{\mathrm{pe}}$. In the simulation: $L_x=24$; $\theta=87°$; $\varepsilon=0.002$; $m_{\mathrm{i}}/m_{\mathrm{e}}=1840$; $T_{\mathrm{i0}}=T_{\mathrm{e0}}=1$.

$$\begin{aligned}&\frac{\omega_{\mathrm{ci}}}{\omega_\pi}=\frac{\omega_{\mathrm{ce}}}{\omega_{\mathrm{pe}}}\sqrt{\frac{m_{\mathrm{e}}}{m_{\mathrm{i}}}}=1\ \text{ and}\\&\frac{\rho_{\mathrm{i}}}{\lambda_{\mathrm{De}}}=\frac{V_{\mathrm{Ti}}/V_{\mathrm{Te}}}{\omega_{\mathrm{ci}}}/\omega_{\mathrm{pe}}=\frac{\sqrt{T_{\mathrm{io}}/T_{\mathrm{eo}}}}{\sqrt{\omega_{\mathrm{ci}}/\omega_{\mathrm{pi}}}}=1.\end{aligned} \tag{6}$$

We have for the initial normalized ion distribution function ($T_{\mathrm{i}}\ (y)=T_{\mathrm{e}}(y)$)

$$f_{\mathrm{i}}\left(x,y,v_\parallel,t=0\right)\frac{N(y)}{\sqrt{2\pi T_{\mathrm{i}}(y)}}\sqrt{\frac{m_{\mathrm{i}}}{m_{\mathrm{e}}}\frac{T_{\mathrm{e0}}}{T_{\mathrm{i0}}}}e^{-\frac{m_{\mathrm{i}}T_{\mathrm{e0}}}{m_{\mathrm{e}}T_{\mathrm{i0}}}v_\parallel^2/2T_{\mathrm{i}}(y)}. \tag{7}$$

The numerical parameters are $N_x\ N_y\ N_v=32\times128\times128$ and the time step $\omega_{\mathrm{pe}}\Delta t=0.05$. For the boundary condition on the potential, we allow it to change its value at the left boundary (the wall), while it is maintained equal to zero at the right boundary (indeed, only the potential difference has a physical meaning). The value of the potential at the left boundary is obtained by imposing that the electric field E_y, averaged over the x direction has opposite values at the two boundaries, i.e.

$$\int_0^{L_x}\mathrm{d}x\,E_y\,(x,y=0)=-\int_0^{L_x}\mathrm{d}x\,E_y(x,y-L_y). \tag{10}$$

With this boundary condition, a charge away on either side of the non-neutral slab, will experience the same electric field. We take initially $n_{\mathrm{e}}=n_{\mathrm{i}}$. At the right boundary of the domain, particles are allowed to flow across the boundary, while at the left boundary density is set equal to zero outside the domain. Even though the ion and electron profiles are the same in Eqs. (7) and (5), the quantity n_{i}^* as calculated from Eq. (2) is different from n_{i} (see profiles in Fig. 1). This results in an initial charge separation in Poisson's equation, Eq. (4). Fig. 1 shows the electron density n_{e} (solid line) and the smooth

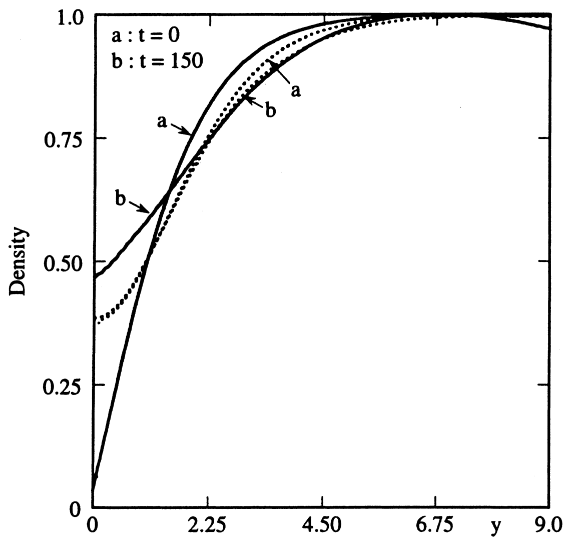

Fig. 1. Electron density n_e (solid line) and the smooth ion density n_i^* (dotted line) averaged over the periodic direction x.

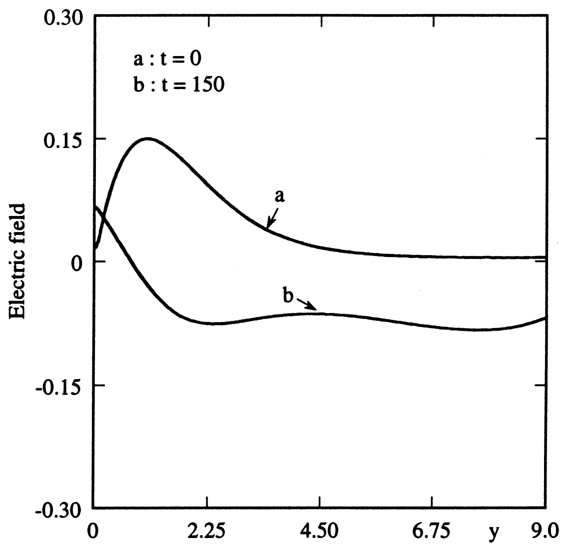

Fig. 3. Electric field E_y averaged over x.

ion density n_i^* (dotted line) averaged over x. Fig. 2 shows the charge $n_i^* - n_e$ (dotted line) and the corresponding potential (solid line). We let these initial profiles evolve to an equilibrium. The profile of the ions evolves very little during the simulations. The electrons profile evolves more rapidly, moving close to the profile of the smoothed ion density n_i^*. The potential, averaged over x, shows an evolution towards a shape close to a straight line, distorted close to the wall at $y = 0$ (Fig. 2, solid curve). The electric field, averaged over x, reaches a shape close to a constant in Fig. 3, with a distortion close to the wall due to the charge accumulation seen in Fig. 2 at $t = 150\omega_{pe}^{-1}$. The final equilibrium remains essentially uniform in the x direction, the initial perturbation damping away. At the final equilibrium, the spatially averaged electron distribution function is strongly distorted, with the electron population moving towards negative velocities (see Fig. 4). Meanwhile, the spatially averaged ions distribution function evolves little. The equilibrium of a plasma in the presence of a

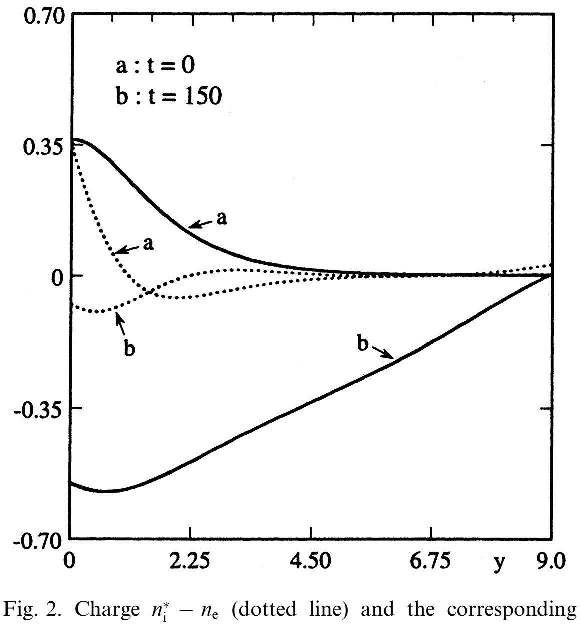

Fig. 2. Charge $n_i^* - n_e$ (dotted line) and the corresponding potential (solid line).

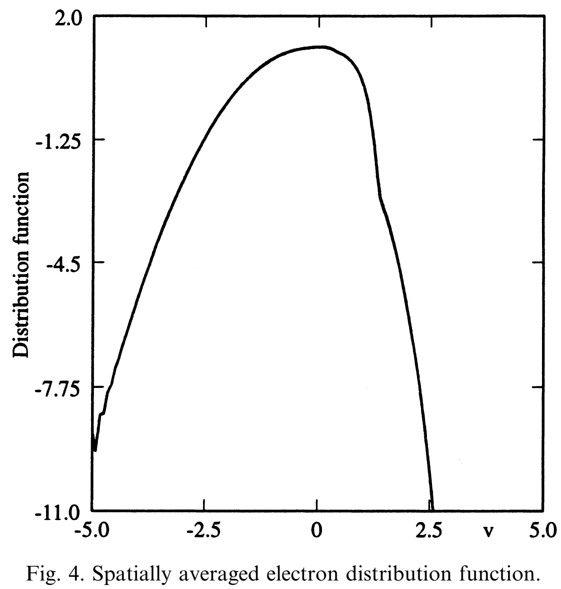

Fig. 4. Spatially averaged electron distribution function.

boundary wall is a phenomenon that typically occurs in many physical situations. In the present work, we have presented a gyro-kinetic Vlasov code to investigate the existence of an equilibrium in a two-component plasma slab, in the presence of a fixed wall. The present results show a rapid motion of the electrons in a few hundred time units ω_{pe}^{-1} towards a shape close to the smoothed ion density n_i^*, reaching a final equilibrium which is only function of y.

Acknowledgements

The CCFM is financed by Hydro-Québec and the Institut National de la Recherche Scientifique. Work supported by DOE contract No. DE-FG02-97-ER-54392 at Lodestard and DE-FG02-91-ER-54109 at MIT.

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