Kinetic modeling and numerical simulation of plasma-wall interactions in magnetic fusion devices

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Physical model

In this work we apply a $1D3V$ kinetic model to the study of plasma wall-interactions relevant to magnetic fusion devices such as Tokamaks. The base physical model describes a plasma in contact with one or two parallel planar material walls, standing for divertor targets plates in the two examples considered here. The direction $\mathbf{e}_x$ normal to the plate(s) is the only one taken into account, while the system is considered invariant in the $(\mathbf{e}_y, \mathbf{e}_z)$ plane. In addition to the self-consistent electric field along $\mathbf{e}_x$, particles are subject to the action of a uniform external magnetic field $\mathbf{B}_0 = B_0(\sin\alpha\mathbf{e}_x + \cos\alpha\mathbf{e}_y)$ tilted with respect to the wall surface. For a given species of mass m_s and charge q_s, the evolution of the distribution function $g_s(t,x,\mathbf{v})$ in the $4D$ phase space is driven by the Vlasov equation

$$\partial_t g_s + v_x \partial_x g_s + \frac{q_s}{m_s}(-\partial_x \phi \mathbf{e}_x + \mathbf{v} \times \mathbf{B}_0) \cdot \nabla g_s = \mathscr{C}_s(g_s) + \mathscr{S}_s, \quad (1)$$

where the self-consistent electrostatic potential ϕ is obtained by the Poisson equation $\partial_{xx}\phi = -(1/\varepsilon_0)\sum_s q_s n_s$ and $(\mathscr{C}_s, \mathscr{S}_s)$ stand respectively for the contribution of collisional processes and external sources. From a computational point of view, the specificity of our approach is the use of fully Eulerian schemes in our computational codes: the particle distribution function is sampled over a $4D$ phase-space grid. Smooth and accurate solutions can be obtained even in low density regions without the need for any additional smoothing procedure.

Stationary sheath and magnetic presheath for grazing incidence of the magnetic field

We analyse here the magnetic pre-sheath (MPS) and Debye sheath (DS) transition for a stationary deuterium plasma, in a regime of separation between electrostatic, magnetic and collisional scales, i.e. $\lambda_D \ll \rho_i \ll l_{coll}$. In that framework, the dynamics in both MPS and DS is described by a collisionless model without source ($\mathscr{C}_s = \mathscr{S}_s = 0$ in eq. (1)). The ion mean velocity at the entrance of the MPS is aligned with the magnetic field and at least sonic, following the Bohm-like Chodura stability criterion $\langle v_\parallel \rangle \geq c_s$. In [2], using a fluid model in the MPS, it was shown that below a critical value α_c of the magnetic incidence angle, a stationary state could be reached without the need for the average ion flow normal to the wall $\langle v_x \rangle$ to reach supersonic

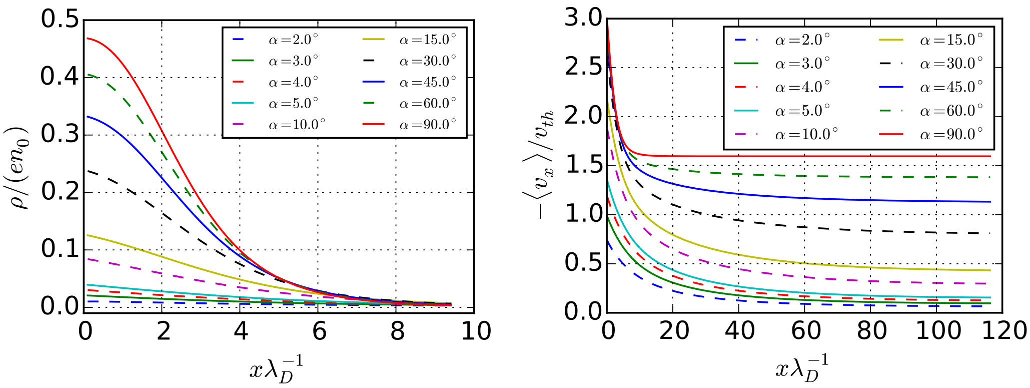

Figure 1: Stationary state for a D^+ magnetized plasma for various values of α; charge density profile near the wall (left) and mean ion velocity profiles normal to the wall over the whole MPS+DS region.

values. In the context of this quasi-neutral model, this implies that no DS should form. The underlying phenomenon is the limitation of the wall electronic current by the magnetic field : the electron flow remains field-aligned up to a few electron Larmor radii from the wall, whereas the alignment of the ion flow with the field is progressively broken in the far larger (a few ρ_i wide) MPS. For near grazing incidence angles ($\alpha \sim 1° - 5°$), the electronic current limitation is strong enough to obtain an ambipolar flow at the wall without the need for a DS to form. In order to check the predictions of [2] in a kinetic context and without imposing quasi-neutrality, we compute with a $1D3V$ Vlasov code [1] the stationary state of a D^+ plasma in contact with a unique wall at $x = 0$ (see [3]). The plasma state at the MPS entry ($x = 120\lambda_D \approx 6\rho_i$) is prescribed to be compatible with the Bohm-Chodura criterion. The ion population is described kinetically, while a Boltzmann model is used for the electrons, with $T_{e0} = T_{i0}$.

Our numerical results confirm for a large part the predictions of [2]. For the lowest values of α ($2 - 5°$) we observe indeed a significant lowering of charge density near the wall (Fig.1 left), down to a few % of the plasma density at the MPS entry, and a limitation of $\langle v_x \rangle$ to subsonic values from $0.9c_s$ to $0.5c_s$ (Fig.1 right). The transition from the MPS entry to the wall can indeed be considered quasi-neutral. With decreasing α, the electric field amplitude is lowered but reaches significant values farther from the wall, which may notably impact the prompt redeposition processes of sputtered neutrals ionized in the MPS.

Following up on this study, we are computing stationary states for $[D^+ + C^{Z+}]$ mixes under similar conditions. The $3D$ velocity distribution functions at the wall for D^+ ions and carbon impurities will provide useful input for sputtering models.

ELM Dynamics

The so-called Edge-localized-Modes (ELMs), characterized by strong variations of plasma quantities at the edge of magnetic fusion devices, are a subject of concern for their safe operation. They induce large power loads on the plasma facing components, reduce their lifetime and also endanger the stability of the discharge due to the sputtering of high-Z impurities. The study of the onset of such events is typically approached using large scale MHD models. Here we consider the ELM event as a given and focus on its fast transport along magnetic field lines up to the divertor target plates. In this simplified geometric model, the tilt angle between the magnetic field and the divertor plates is neglected ($\alpha = 90°$) so that the direction $\mathbf{e}_x$ is aligned with $\mathbf{B}_0$. If one neglects perpendicular drifts and collisional processes, the parallel and perpendicular dynamics are completely decoupled, leading to a $1D1V$ kinetic model in the parallel direction. Such a model was used in [5, 4] to analyse the propagation of an ELM event, modeled as a plasma source localized in the mid plane ($x = 0$) between the target plates localized at $x = \pm L$, with L standing for the connection length. In [4] , it was shown using the PIC code BIT1 that energy transfers from the perpendicular velocity to the parallel one due to Coulomb collisions may impact the plasma parallel expansion and the fluxes reaching the target plates. In order to examine this process, we extend the $1D1V$ kinetic model with a fluid one for the perpendicular temperature [3]. We consider a separable ansatz for the distribution function $g_s(t,x,v_x,\mathbf{v}_\perp) = f_s(t,x,v_x)\exp[-m_i v_\perp^2/(2T_\perp(t,x))]$. The ELM growth is modeled using a source $\mathscr{S}_s = s(t)N(x)F_s(v_x)H_s(v_\perp)$ where N is a Gaussian spatial profile of width σ_0 characterizing the ELM parallel extension, F_s and H_s are Maxwellian velocity distributions with identical temperatures $T_\parallel^0 = T_\perp^0 = T_{ELM}$. The time envelope $s(t) \sim t^2\exp[-(t-t_0)^2/(2\sigma_t^2)]$, with $\sigma_t = 0.7\tau_i, t_0 = 1.4\tau_i$ describes the ELM growth and decay. The collisional coupling is modeled by a BGK relaxation operator driving the distribution towards a Maxwellian $f_{M,s} = f_{M,s}(n_s, u_{x,s}, T_s, v_x)$ with the same density and velocity as f_s but with the total temperature $T_s = [T_{\parallel,s} + 2T_{\perp,s}]/3$. Under those assumptions we obtain the coupled system

$$\begin{cases} \partial_t f_s + v_x\partial_x f_s + \dfrac{qE_x}{m}\partial_{v_x} f_s = s(t)N(x)F(v_x) + \nu_s(f_{M,s} - f_s) \\ \partial_t T_{\perp,s} + u_{x,s}\partial_x T_{\perp,s} = \dfrac{s(t)N(x)(T_\perp^0 - T_{\perp,s})}{n_s(t,x)} + \dfrac{\nu_s}{3}(T_{\parallel,s} - T_{\perp})_{,s} \end{cases}$$

This hybrid model has been added to the VESPA code [5]. For the two species $H^+ + e^-$ plasma considered here, the temperature istropisation rate $\nu_s, s \in \{e,i\}$ has to be estimated. Let us note $\tau_s = L/v_{ths}$ the flight time for a given species. Using estimates of ν_s from [6], we have $\nu_e\tau_e = \nu_i\tau_i = \nu\tau \approx 0.15$ for typical pedestal plasma parameters ($T_e = T_i = 1.5$ keV, $n = 5\times10^{19}$ m^{-3} and $L = 30$ m). In our simulations we scan values of $\nu\tau$ from 0 to 0.2. The time scale of the

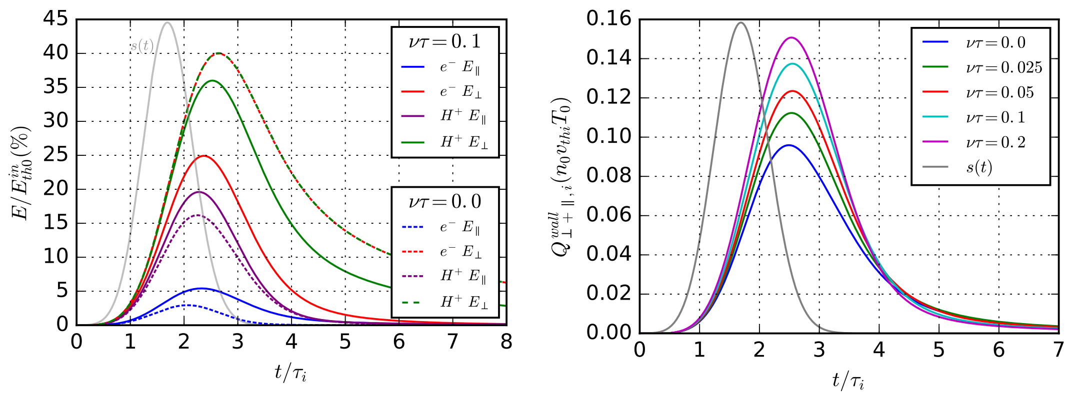

Figure 2: ELM study. Evolution of the space integrated kinetic energy content with time, normalized to the total energy injected (left). Ion energy flux at the wall (right).

overall ELM transit up to the plates is close to the ionic one $t_{ELM} = L/c_s \sim \tau_i$ and so we have $t_{ELM}\nu_i = \nu\tau$, $t_{ELM}\nu_e = \sqrt{m_i/m_e}\nu\tau$. The electron-electron collisional process is a priori the prominent one, which is confirmed by our simulation results. The plasma expansion leads to a fast decrease of ion and electron parallel temperatures. The resulting electron temperature anisotropy $T_{\parallel,e} \ll T_{\perp,e}$ induce a transfer from the perpendicular to the parallel electron kinetic energy. Some of this additional parallel energy is then transferred from the electrons to the ions through the electric field. The overall process is clearly visible in the evolution of the partition of kinetic energy among the species and the parallel and perpendicular directions (Fig.2 left). The net result is a significant increase of the ion particle and power flux peaks (Fig.2 right) at the target plates. While the total energy received by the plates is independent of $\nu\tau$, collisions modify both the power deposition time profile and the balance between ion and electron fluxes.

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