PLASMA FLOW IN A COLLISIONAL PRESHEATH REGION

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ABSTRACT

Plasma flow from a source to an absorbing wall is studied in an 1-d kinetic particle model with Fokker-Planck collisions. The sheath forming in front of the wall in order to preserve ambipolar particle flow affects the heat flux in the upstream presheath region. Flow profiles and electron velocity distributions in the presheath are calculated for different collisionalities. Electron heat flux for different mean-free-path lengths is compared with values from classical Braginskii heat conductivity.

1. INTRODUCTION

In most fusion devices the plasma edge is in contact via magnetic field lines with a material wall, e.g. limiter or divertor plate. Plasma diffusing outward from the core into or generated within this scrape-off zone flows predominantly along field lines to the plate and is neutralized there. A schematic and simplified view of the scrape-off layer is a 1-d stationary flow between a plasma- and energy-creating source and an absorbing wall. The flow is determined by the properties of the source (which includes interactions with the background neutral gas), by the transport properties of the plasma and by the absorption properties of the wall. If the source generates equal amounts of positive and negative charges, the flow to the wall is ambipolar. Since ions and electrons have different mobilities, ambipolarity must be maintained by an electrostatic sheath in front of the wall which reflects all incoming electrons whith energies lower than the potential drop to the wall. Thus, the electron distribution in the sheath is truncated: reflected electrons with energies higher than the potential difference to the wall are lacking. In a region upstream of the sheath the untruncated electron distribution is restored by collisions. This region is called the presheath.

The sheath and presheath regions have characteristic dimensions which are respectively much smaller and comparable to the mean-free path length of plasma particles. It is, therefore, necessary to treat these regions by a kinetic model including collisions, i.e. by a Fokker-Planck model [1, 2].

2. MODEL

The numerical model consists of an 1-d electrostatic particle code including velocity changes by collisions. The coefficients of dynamical friction $\langle \Delta v_{\|} \rangle_{\alpha\beta}$ and diffusion $\langle (\Delta v_{\|})^2 \rangle_{\alpha\beta}$, $\langle (\Delta v_{\perp})^2 \rangle_{\alpha\beta}$ of a particle α are determined from the local moments of the distribution f_β of the collision partners β under the assumption of nearly Maxwellian f_β. The source is assumed to be well separated from the wall such that there is no particle and energy production within the presheath and sheath region. Electrons are generated with a finite temperature T_{e0}, ions as cold. Additionally, the plane of the symmetry $x = 0$ within the source is treated as heat bath: all electrons passing through this plane leave it with a Maxwellian distribution of temperature T_{e0}, thus simulating electron heat conduction from the core plasma. The wall at $x = L$ is assumed to be totally particle absorbing. No magnetic field is taken into account, i.e. the magnetic field is either absent or perpendicular to the wall.

Whereas the sheath has a thickness of only a few Debye lengths the presheath has an extension of the mean-free path of an electron with energy of about the sheath potential, which is for realistic cases by 3–4 orders of magnitude larger. In order to treat sheath and presheath with the same model, the latter had to be reduced to a comparable size by artificially enlarging the collision rate.

3. RESULTS

Figure 1 shows profiles of particle flux

$$\Gamma = \int f_{e,i} v_x d^3v,$$

ion flow velocity $V_i = \Gamma/n_i$, where n_i is the ion density, electron energy flux

$$Q_e = m_e/2 \int f_e v^2 v_x d^3v,$$

electron heat flux

$$q_e = m_e/2 \int f_e (\mathbf{v} - \mathbf{V}_e)^2 (v_x - V_{ex}) d^3v,$$

and potential ϕ. The space coordinate x is normalized to $\lambda_D = \lambda_D(n_0, T_{e0})$, the Debye length at n_0 and T_{e0} where T_{e0} is the temperature of electrons generated in the source and $n_0 = \Gamma_0/v_{te0}$ with Γ_0 the total electron production per time of the source and $v_{te0} = (T_{e0}/m_e)^{1/2}$. C_0 is the ion sound speed at $T_{e0}, C_0 = (T_{e0}/m_i)^{1/2}$. The collisionality of the flow is indicated by the mean-free path length λ for 90° deflection of an electron with energy $3/2T_{e0}$ by collisions with other electrons of density n_0 and the same temperature.

Electron flux Γ_0 crossing the sheath and being absorbed at the wall consumes more energy than that being transported convectively, i.e. $\delta T_{es}\Gamma_0, \delta = 2 + e(\phi_s - \phi_w)/T_{es}$ as compared to $5/2T_{es}\Gamma_0$ (index s and w for sheath edge and wall respectively). The additional energy flux demand must be transported conductively from the source, i.e. by heat flux q_e. Far upstream from the wall q_e is maintained by a twist in the elctron distribution due to the temperature gradient (Fig. 2a). Less than a relaxation length in front of the wall the electron distribution becomes a Maxwellian with a truncated upstream wing due to the lack of the wall-absorbed electrons (Fig. 2b). This relaxation length is determined by the diffusion length λ_{Diff} of reflected electrons into the truncated tail of its velocity distribution,

$$\lambda_{Diff} = v_c(\Delta v)^2/\langle(\Delta v_{\|})^2\rangle_{ee}$$

with Δv the diffusion interval, $v_c^2 = 2e(\phi_s - \phi_w)/m_e$, and $\langle(\Delta v_{\|})^2\rangle$ the coefficient of parallel diffusion at $v_e = v_c$. In case of Fig. 1,

$$\lambda_{Diff} = 1.9(\Delta v)^2/v_{te}^2\lambda$$

As shown in Fig. 3, the collisional heat flux q_e is nearly independent of x. Figure 4 shows the collisional heat flux for different ratios of mean-free-path length λ to system length L with n_0 fixed. For comparison the same relation is plotted for the classical Braginskii heat conductivity $\kappa = \kappa_0 T^{5/2}$, $\kappa_0 \propto \lambda$ [3]. Under the assumption of spatially constant q_e determined by the edge value $q_e = (\delta - 2.5)\Gamma_0 T_{es}$, $\delta = 4.4$, q_e is given by

$$[\frac{q_e}{(\delta - 2.5)\Gamma_0}]^{7/2} + \frac{7}{2}\frac{L}{\kappa_0}q_e = T_{e0}^{7/2}.$$

The Fokker-Planck curve is shifted toward lower q_e values indicating a heat flux limitation [4] at large mean-free-path lengths.

References

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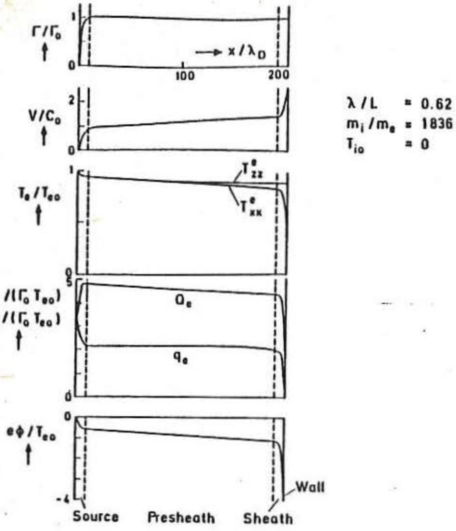

Fig. 1 Profiles of particle flux Γ, ion flow velocity V_i, total energy and heat flux of electrons Q_e and q_e, and potential ϕ.

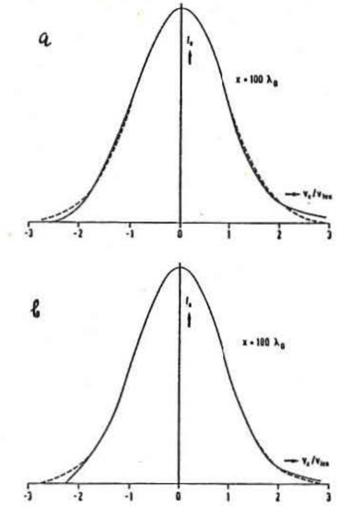

Fig. 2a,b Electron distribution functions in the collisional and non-collisional region.

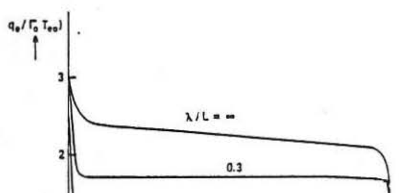

Fig. 3 Profiles of electron heat flux $q_e(x)$ for different mean-free-path lengths λ.

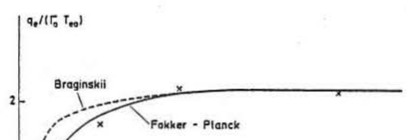

Fig. 4 Electron heat flux q_e for different ratios of mean-free-path length λ to system length L.