KINETIC MODELLING OF PLASMA NEAR THE NEUTRALIZER PLATE IN A TOKAMAK DIVERTOR

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An electron kinetic code is used to simulate longitudinal transport and recycling near the neutralizer plate in a divertor plasma. In addition to the standard features, such as e-e and e-i Coulomb collisions, transport, ion motion, and a self-consistent electric field, the code now accounts for ionization, excitation, and recycling of hydrogen near the plate. Ions and neutrals are treated as fluids. The kinetic results are compared with those of a one-dimensional, two-temperature fluid code. Some implications of these results for recycling and impurity control in tokamaks are also discussed.

INTRODUCTION

Several analytical and numerical approaches have been used to study the basic processes of divertor plasmas. Most approaches are based on a fluid description of the plasma [1-3]. In a divertor, the temperature gradient scalelength $L_T = T/(dT/dx)$ is known to be only a few times the collisional mean-free path λ_{col}. Under these conditions, heat transport is in the so-called flux-limited regime, and the particle distribution function is not expected to be Maxwellian. In the following we consider kinetic simulations of the plasma near the neutralizer plate. The simulations are based on a modified version of the FPI 'Fokker-Planck International' code [4], originally written to model laser-plasma interactions [4,5], and recently used to simulate electron heat transport in the 'AURORA' microwave-driven plasma experiment [6]. Results obtained with a two-temperature fluid code are also presented and compared with results obtained under similar conditions with the kinetic code.

MODEL

Geometry

For simplicity, transport is considered along a single spatial coordinate, parallel to the magnetic field. A given plasma flux is assumed on the left boundary, at $x = 0$, and a perfectly absorbing plate is assumed on the right, at $x = L$. In the kinetic model, the electron distribution function depends on two velocity components $v_\parallel$ and $v_\perp$, respectively parallel and perpendicular to the magnetic field.

Electron kinetic model

The equation governing the electron distribution function is:

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial x} - \frac{e}{m} E \frac{\partial f}{\partial v_x} = C(f) + A(f). \qquad (1)$$

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The first term on the right hand side stands for Coulomb collisions of electrons with ions and with other electrons handled in a Fokker-Planck manner. A(f) is a Boltzmann-type operator which accounts for excitation and ionization of neutral hydrogen atoms.

Fluid model

In addition to the electron kinetic model just described, a simple fluid simulation code is also used in which all particles species (including electrons) are treated in the fluid approximation. Specifically, the code solves for a single density, single velocity, and two temperatures (T_e and T_i) as a function of time. The ion thermal conductivity and viscosity have the standard Braginski values [7]. The electron heat flux in the moving fluid is calculated as the harmonic mean between the Spitzer flux q_{SH} [7] and a limited free streaming flux;

$$q_e = q_{SH} \left[1 + \frac{|q_{SH}|}{f N_e T_e v_e}\right]^{-1} \qquad (2)$$

where $v_e = (T_e/m_e)^{1/2}$ and f is the so-called flux limiter. From earlier work [4,5] we have chosen f to be 0.2.

Atomic physics

The atomic physics processes accounted for in the simulations include ionization and excitation of the hydrogen atom from the ground state. The cross-sections used in the kinetic code and the rates used in the fluid code are taken from reference [8].

Boundary conditions

i) Electron kinetic code

Plasma is assumed to be flowing from the left (x = 0) with given electron and ion density, drift velocity and temperature. The neutralizer plate at the right boundary (x = L) is modelled as follows. All incident ions are absorbed by the plate. Drawing on the results for Vlasov sheath, incoming electrons with a longitudinal velocity above a certain velocity v_o are absorbed as well. Electrons with $v_x \leq v_o$ are reflected specularly. The velocity v_o is adjusted so as to give a zero net current at the plate. This boundary condition models the pre-sheath and avoids having to resolve the sheath itself.

ii) Fluid code

As in the kinetic code, given plasma flux, density and temperatures (both ionic and electronic) are prescribed on the left boundary. On the right boundary, all incoming plasma is assumed to be absorbed. The ion energy flux there is $Q_i = 3.5\ \Gamma_i T_i$, [3,9], where Γ_i is the ion particle flux. For the electron energy flux at the plate, we have used two formulae. The first one can be found elsewhere in the literature [9]; it is

$$Q_e = 2\ \delta\ \Gamma_e T_e. \qquad (3)$$

In what follows we consider results obtained with $\delta = 3$ [3] and $\delta = 2$ (which seems to fit other results [9]). The second expression is obtained by assuming a truncated Max-

wellian electron distribution at the plate [10,11], i.e.:

$$f(v_x,v_\perp) = \frac{2\,N_e}{1 + \mathrm{erf}(x_o)} \left(\frac{m_e}{2\pi T_o}\right)^{3/2} \exp\left(\frac{-m_e(v_x^2 + v_\perp^2)}{2\,T_o}\right) H\,(v_o + v_x) \qquad (4)$$

where $x_o = v_o/v_{tho}$, $v_{tho} = (2\,T_o/m_e)^{1/2}$. From this, the electron particle and energy fluxes are found to be:

$$\Gamma_e = \frac{N_e\,v_{tho}}{\sqrt{\pi}\,(1 + \mathrm{erf}x_o)} \exp\,(-\,x_o^2) \qquad (5)$$

and

$$Q_e = \Gamma_e\,T_o\,(2 + x_o^2) \qquad (6)$$

We note that the parameter T_o appearing in these expressions is not the temperature T_e produced by the code which is the mean energy in the drift frame. The relation between T_o and T_e is:

$$\frac{T_e}{T_o} = 1 - \frac{2\,x_o \exp\,(-\,x_o^2)}{3\,\sqrt{\pi}\,(1 + \mathrm{erf}x_o)} - \frac{2\exp\,(-\,2x_o^2)}{3\,\pi\,(1 + \mathrm{erf}x_o} \qquad (7)$$

In practice, x_o is calculated from Eqs. (5) and (7), for a given particle flux and a given electron density and temperature at the plate.

Recycling

Hydrogen recycling at the plate is simply modelled in this early work by assuming a constant profile of hydrogen neutrals localized near the plate. This distribution of neutral is prescribed a priori and it is not allowed to vary in time; i.e. when a neutral hydrogen atom is ionized, it is assumed to be replaced instantly by another neutral.

Initial conditions

In the fluid simulation code, for simplicity, all profiles are assumed to be uniform at time t = o. However, to reduce the computer load, the initial conditions used in the electron kinetic code correspond to the stationary solution already found with the fluid simulation.

RESULTS AND DISCUSSION

The results considered were obtained with the following parameters: at x = 0 the imposed electron and ion densities are 3×10^{13} cm^{-3} and both ion and electron temperatures are equal to 50 eV and the ion drift velocity is $v_i = 0.3\,C_s$, with $C_s = ((T_e + T_i)/m_i)^{1/2}$. The neutralizer plate is assumed to be at L = 15 m, with the boundary condition discussed above.

The electron density and v_i/C_s profiles computed with the kinetic code are shown in Fig. (1). These profiles are close to the corresponding profiles computed with the fluid code. We note that the flux of particles outside the divertor (recycling region) is uniform with a Mach numbers ~ 0.3. In this region the pressure is uniform. The pressure gradient is responsible for the acceleration of ions to a velocity close to C_s near the divertor plate. The electron temperature profiles computed with both codes are shown in Fig. (2). For the fluid simulation, results are presented for four possible expressions of the electron heat flux at the plate. These are: A) $f = .2$, $\delta = 3$ in Eq. (3), B) $f = .2$, $\delta = 2$ in Eq. (3), C) $f = .2$ and Eq. (6), D) $f = \infty$ and Eq. (6). The latter case corresponds to an unlimited Spitzer heat flux. We note that the temperatures predicted by the fluid model with these different parameters are always larger than that computed kinetically except for case D near the plate. This general overestimate of the electron temperature in the fluid code is believed to be due to non local effects involving the left hand boundary which are not correctly treated in the fluid approximation.

The ion production rates $s_n = N_e N_n \langle v_e \sigma \rangle_{ion}$ calculated in the kinetic and the fluid (for case C only) codes are shown in Fig. (4). The difference between the two rates is due to the difference in the electron temperature profile predicted by the two codes rather any difference in the form of the distribution from Maxwellian. (In the fluid code, $\langle v_e \sigma \rangle_{ion}$ is calculated by averaging the ionization cross section over an assumed Maxwellian electron distribution function.)

The ion temperature profiles are shown in Fig. (6). The kinetic calculation yields a T_i which is less than that calculated in the fluid model outside the recycling region. The opposite is true inside the recycling region. This is caused in part by the larger value of s_n computed in the fluid model with its larger temperature. Also, the smaller electron temperature computed in the kinetic model tends to lower the ion temperature away from the plate. The electrostatic potential energy $e\phi$ calculated from the kinetic code is presented in Fig. (7). The electron distribution function $f_e(v_x)$ vs v_x calculated from the kinetic code is shown in Fig. (8).

CONCLUSION

This kinetic modelling of the divertor plasma has shown that the simpler fluid models perform quite well as far as macroscopic quantities such as density and drift velocity are concerned. However, the temperature and heat transport are not well modelled by the fluid code variants (even though the non Maxwellian nature of the electron distribution is not important here). This has significant effects on ionization and excitation rates.

ACKNOWLEDGEMENT

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FIGURE CAPTIONS

Fig. 1. Profile of the electron density N_r and v_i/C_s calculate from the kinetic code.

Fig. 2. Profile of the electron temperature T_e (kinetic code —. Fluid code: -·-· f = .2, δ = 3 in Eq. (3); -···- f = .2, δ = 2 in Eq. (3); --- f = .2 and Eq. (6); -·- f = ∞ and Eq. (6)).

Fig. 3. Profile of the electron heat flux q_e (kinetic code——. Fluid code: -·- f = .2, δ = 3 in Eq. (3); -···- f = .2 in Eq. (3); --- f = .2 and Eq. (6); -·-· f = ∞ and Eq. (6)).

Fig. 4. Profile of $s_n = N_n N_n \langle v_e \sigma \rangle_{ion}$ (a: Kinetic code, b: Fluid code: f = .2 and Eq. (6).

Fig. 5. Contour lines of $\ln f_e(v_x)$ calculated from the kinetic code as a function of v_x and x. The truncation of $f_e(v_x)$ at the plate is clearly seen from this figure.

Fig. 6. Profile of the ion temperature T_i (Kinetic code ——, Fluid code ---).

Fig. 7. Profile of the electrostatic potential eϕ calculate from the kinetic code.

Fig. 8. The electron distribution function $f_e(v_x)$ calculate from the kinetic code vs v_x and x.

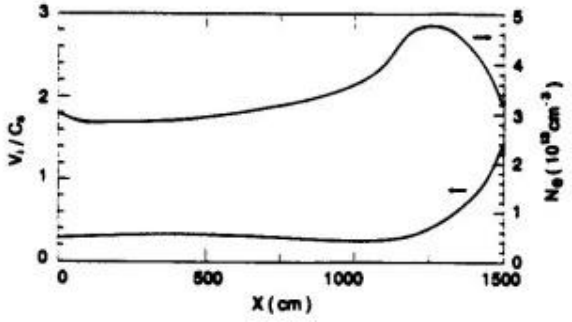
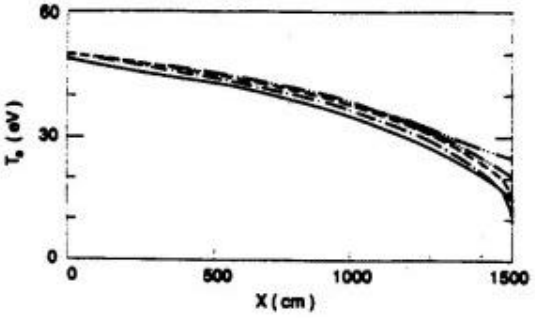


FIGURE 1



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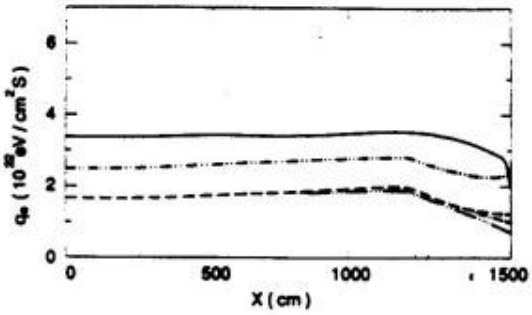

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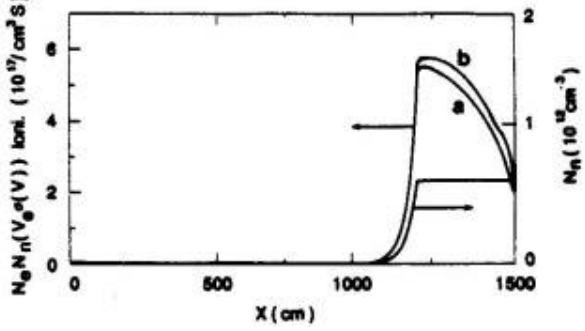


FIGURE 4

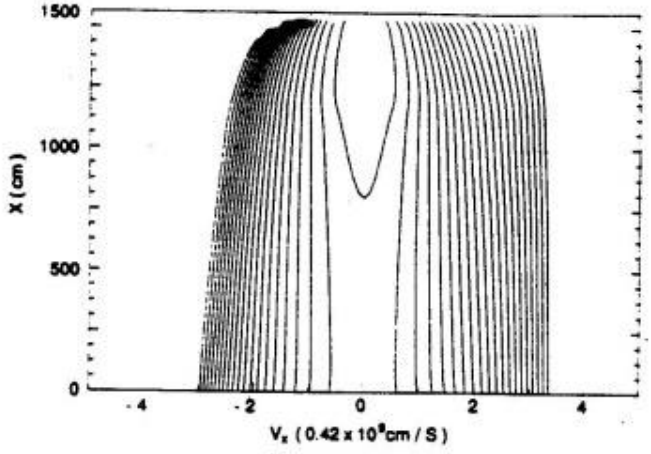
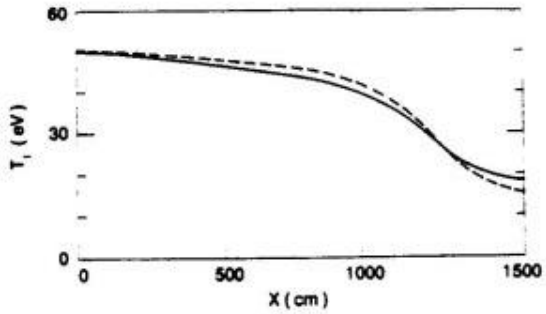


FIGURE 5



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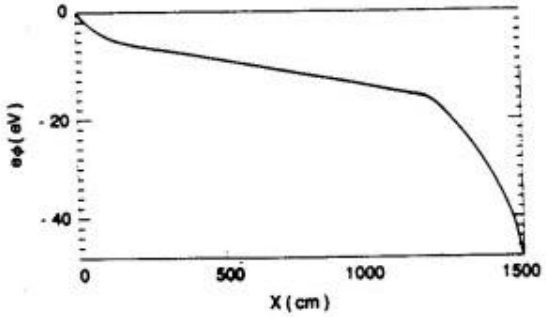

FIGURE 7

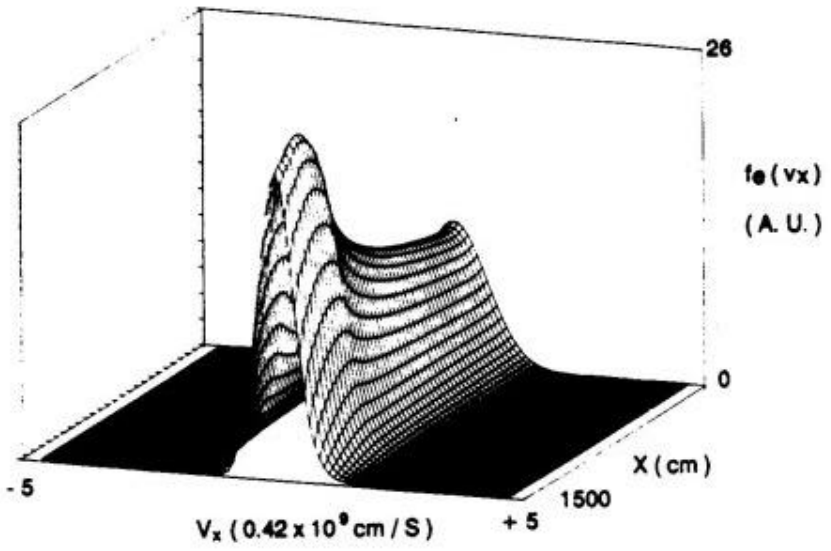

FIGURE 8