Fokker-Planck Modelling of Edge Plasma Near the Neutralizer Plate in a Tokamak

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We have modelled the transport of particles and energy through a tokamak SOL near the neutralizer plate. The electron kinetic/ion fluid code FPI and a two-fluid code were employed for this study. Because of the electron time scale, it would take a very long time to reach steady state with the kinetic code. We have therefore developed a hybrid technique, using both codes in alternation, to reach a full equilibrium compatible with electron kinetics. When it is used in the stand-alone mode, the two-fluid code's results are closest to FPI if a heat flux limiter f=0.2 is used. The electron distribution function is very non-Maxwellian near the plate.

I. Introduction

In the edge plasma of a tokamak the particle and power fluxes are directed more or less along the magnetic field line in the Scrape-Off Layer SOL to the divertor chamber and then to the neutralizer plate. This plate neutralizes the incoming plasma ions and reemits most of them as atoms or molecules and these are re-ionized by in-streaming plasma electrons. This causes the plasma particle flux to be amplified, and the temperature to fall. Most of these processes occur in the pre-sheath, which is in the divertor chamber, where there are gradients in the plasma density, temperatures, drift velocities and electrostatic potential. The physics of the pre-sheath thus plays a dominant role in determining the flow of particles and power to the solid surface.

As the conduction along field lines is dominant, we have used a one dimensional model, in which plasma is injected at one end, with fixed density, velocity and temperature, and it flows towards the neutralizer plate [1]. An kinetic electron/ion fluid code FPI [2,3,4] has been used for this modelling. However, as the electrons'time-scale is much faster than the ions', it would be prohibitive to run the kinetic code until full equilibrium is reached. We have therefore also written a two fluid code (electrons and ions) which can be used either alone, or in conjunction with the kinetic code (to obtain the correct electron thermal conductivity). This hybrid kinetic/fluid technique makes it possible to arrive at an equilibrium consistent with electron kinetics.

In section II, we present the kinetic and fluid codes. The hybrid fluid/kinetic simulation method is explained in section III. In section IV, results of the fluid model alone, and of the hybrid simulation technique, including displays of the velocity distribution function, will be shown. We give our conclusions in section V.

II. Simulation models

A. Fokker-Planck International Code

The Fokker-Planck International (FPI) code [2,3,4] is one-dimensional in configuration space, but two-dimensional in velocity space (azimuthal symmetry is assumed). This code uses the kinetic model for the electrons and a fluid model for the ions and neutral particles. The FPI code advances the Vlasov-Fokker-Planck equation for the electron distribution function in time. The dependence of the distribution function on the pitch angle is expanded in Legendre polynomials, and it is the coefficients of this expansion that are advanced in time. Thus:

$$f(X,V,t)=f(x,v_x,v_\perp,t)=f(x,v,\mu,t)=\sum_{l=0}^{N} f_l(x,v,t)P_l(\mu) \tag{1}$$

where $v=(v_x^2+v_\perp^2)^{1/2}$, $\mu=v_x/v$ and $P_l(\mu)$ is the l th Legendre polynomial. We have used N=3 in the simulations. The kinetic equation for the electrons is given by :

$$\frac{\partial f}{\partial t}+v_x\frac{\partial f}{\partial x}+\frac{eE}{m_e}\frac{\partial f}{\partial v_x}=\left(\frac{\partial f}{\partial t}\right)_{(e-i,e-e)}+\left(\frac{\partial f}{\partial t}\right)_{(E_n)}+\left(\frac{\partial f}{\partial t}\right)_{(e-n)} \tag{2}$$

The second and third terms in the left hand side of Eq.(2.2) are the advection and the acceleration due to the electric field, respectively. The right-hand side terms in Eq.(2.2) represent respectively electron-ion and electron-electron Coulomb scattering, electron-ion energy exchange and inelastic electron-neutral collisions (ionization and excitation).

B. Two-Fluid Code

A simple, one-dimensional, ambipolar two-fluid code including heat flow has also been developed and used to study the plasma transport in a divertor tokamak. The code solves for a single density, single velocity and two temperatures as a function of time. The basic equations and transport coefficients used in this code are taken from Braginskii [5], including ion viscosity and heat flow. In our fluid model we limit the electron conduction heat flux by using the harmonic mean between the Spitzer-Härm and the flux-limited fluxes [6]:

$$Q^e_{cond.}=q_{SH}\left[1+\frac{|q_{SH}|}{fnT_e v_e}\right]^{-1} \tag{3}$$

where $v_e=\sqrt{T_e/me}$, m_e is the mass of the electron and f is the so called flux limiter, which is assumed to be f=0.2.

C. Boundary Conditions

1. Electron Kinetic code (FPI)

Plasma is assumed to be flowing in from the left, $x=0$, with given plasma density n_0, drift velocity v_0, and electron and ion temperatures ($T_e=T_i=T_0$). The electron distribution function on the left is adjusted in accordance with the hot wall technique explained in reference [1]. The neutralizer plate at the right boundary ($x=L$) is modelled as follows: all incident ions are absorbed by the plate, incoming electrons with a longitudinal velocity above v_R are absorbed as well and others are reflected. The velocity v_R is adjusted so as to give a zero net current at the plate. This boundary condition removes the need to simulate the sheath itself. The ion and neutral dynamics are the same in the electron kinetic code as in the two-fluid code.

2. Two-Fluid Code:

As in the kinetic code, plasma density, velocity and temperatures are prescribed on the left boundary. At the neutralizer plate, we assume that the incoming plasma is absorbed. The drift velocity is assumed to be equal to or higher than the ion sound velocity, i.e,

$$v \geq c_s=\sqrt{(T_e+T_i)/m_i} \tag{4}$$

The ion and electron heat flux at the plate are taken as [7]:

$$Q_i=3.5T_i nv \; ; \; Q_e=6T_e nv \tag{5}$$

D. Neutral Particles

The neutral density n_n decays according to:

$$\frac{\partial}{\partial t}n_n+v_n\frac{\partial}{\partial x}n_n=-n_n n_e\langle v\sigma\rangle_I \tag{6}$$

where v_n is the neutral velocity and it is assumed to be constant in time and space. The ionization rate $\langle v\sigma\rangle_I$ is obtained from an integral over the actual distribution function in the kinetic code, while the Maxwellian rate is used in the two fluid code. The boundary condition at the plate for the neutral density is calculated by assuming that the neutral flux at the plate is given by:

$$n_n v_n \sin\theta=Rn_i v_i \tag{7}$$

where θ is the angle between the plate and the magnetic field lines, we used $\theta = 5^\circ$. Here we have assumed that the recycling factor is $R=0.8$. For the neutral velocity v_n, we assume $m_i v_n^2/2=3\ eV$, corresponding to the Frank-Condon energy.

III. Fluid and Fokker-Planck Hybrid Iteration

The FPI code is too slow to run until equilibrium, while the two-fluid code does not calculate electron heat flow correctly. In order to obtain a fully electron kinetic/ion fluid equilibrium solution we alternate the two codes, using FPI code to determine correctly the fluid code's temperature and local heat transport, while using this locally modified fluid code for the ion dynamics to provide the ion profile for FPI. In the locally modified fluid code we use the T_e profile which is calculated from the FPI code and also force the local electron conducting heat flux, q_e, to agree with that of FPI by correcting it at each grid point with the following correction factors:

$$CFQ = q_{e\text{-}FPI}/q_{e\text{-}fluid}(T_{e\text{-}FPI}) \tag{8}$$

We iterate this two-code alternation cycle until no further significant change occurs. We thus arrive at an equilibrium completely consistent with electron kinetics but at a tiny fraction of the cost of doing so with the FPI code alone. We have found that two cycles were sufficient.

IV. Parameters and Results

The physical parameters used in this simulations are listed in table (1). Density, temperature, and drift velocity, are assumed to be uniform at t=0.

Table 1 Simulation parameters.

System length: L = 300 cm
Electron source temperature: T_{e0} = 30 eV
Ion source temperature: T_{i0} = 30 eV
Plasma source density: n_{e_0} = 3×10^{13} cm^{-3}
Ion drift velocity: v_{i0} = 0.10 Cs, C_s=7.6×10^{6} cm/sec
m_i/m_e = 1836
Recycling factor: R = 0.8

The fluid results of the plasma with high recycling, near the divertor plate are presented in Figs. (1) and (2). In Fig. (1) we plot the profiles of the plasma density $(n=n_i=n_e)$, drift velocity v_i, electron and ion temperatures (T_e,T_i). The profiles of the plasma particle flux $(n_i v_i)$, neutral density n_n, ionisation and excitation rates (S_{ion},S_{exc}) are plotted in Fig. (2). From these figures we see that the back flow of the neutral particles from plate collides with the hot plasma electrons. Because of the ionization of the neutral particles, the neutral density decreases. The density and the decay length of the neutrals are, of course, consistent with the recycling at the plate and with the ionisation rates. Far from the plate, in the hot, low recycling region, the total thermal pressure and the particle flux are nearly uniform. The drift velocity is subsonic in this region, and has low Mach number, around 0.10. In the high recycling region, near the plate, the neutral density is high and the electron and ion temperatures decrease, because of the ionisation and excitation processes. The plasma density increases as we approach the plate and it reaches its maximum value at around 20 cm from the plate. In the cold, high recycling region the total thermal pressure decreases and the gradient causes the ion drift velocity to increase. The combination of decreasing temperature and increasing velocity gives a high local Mach number and it reaches a value ≥1 at the plate sheath edge.

The equilibrium solution of the kinetic electron/fluid ion simulation is obtained by using the hybrid iteration scheme between the fluid and FPI codes as described in the previous section. The profiles of the electron temperature, T_e, and of the electron conduction heat flux, q_e, obtained from FPI, from the FPI/fluid calculations and from the original fluid code, are plotted in Figs. (3) and (4) respectively. From Fig. (3) we see that the electron temperature calculated from the original fluid code is above that from the FPI calculation. By modifying q_e in the fluid code by using the local correction factor (CFQ), we obtain profiles of q_e and T_e which match those of the FPI calculation. In Fig. (4) we also plotted the profile of q_e calculated from the FPI profile of T_e, by using the classical formula, Eq. (3), with f=0.2. This calculation disagrees significantly with the FPI/fluid calculations, and the discrepancy is worse if a value of the flux limiter f different from 0.2 is used.

In Fig. (5) we plotted the electron distribution function $f_e(v_x)$ vs x and $(v_x/|v_x|)E$, $E=m_e v_x^2/2$, and in Fig. (6) we plotted the contour line of $f_e(v_x)$ vs x and $(v_x/|v_x|)E$, calculated from FPI code. From these figures we see the deviation of the electron distribution from Maxwellian everywhere in the SOL plasma. On negative v_x side, the truncation of the electron distribution function near the plate is clear from these figures. This is due to the absorption of high energy electrons by the plate. The tail of the electron distribution near the hot plasma source has been filled up by electron-electron and electron-ion collisions. In all positions we see a strong deviation of the electron distribution from Maxwellian, especially in the tail, where are more energetic electrons with $v_x>0$ in the FPI calculation than in the Maxwellian: this is due to non-local electron transport in the SOL plasma. These high energy electrons can have a strong effect on the atomic physics of the impurities which may exist in SOL.

V. Summary and Conclusion

Fluid and kinetic equilibrium solutions of a model divertor plasma with high recycling were obtained. The fluid-FPI hybrid iteration technique has been shown to be effective. The equilibrium solutions show the following features: (i) Far from the plate, in the low recycling region, the drift velocity, the thermal pressure, the energy and particle fluxes remain uniform. (ii) In the high recycling region, near the plate, the Mach number becomes higher due to the temperature gradient and to the ion acceleration by the gradient of the thermal pressure. (iii) The plasma density increases due to the ionization and then drops close to the plate because of acceleration. (iv) The particle flux increases monotonically between the source and the plate. On the other hand, the energy fluxes drop near the plate because of radiation cooling. (v) The profiles of T_e, q_e, calculated from the fluid code do not agree with those of the FPI calculation. (vi) The classical theory of the electron heat flux even with an f=0.2 limiter does not work very well in SOL Plasma near the plate with high recycling. The electron energy distribution function calculated from the FPI code is not Maxwellian due to the non-local transport of the high energy electrons and to the absorbtion of some of these by the plate.

VI. Acknowledgement

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VII. References

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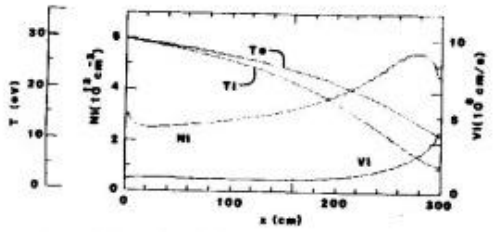

Figure 1 Fluid equilibrium solution of edge plasma near the plate with high recycling: Profiles of T_e, T_i, n_i, and v_i.

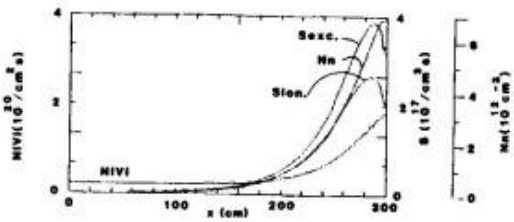

Figure 2 Fluid equilibrium solution of edge plasma near the plate with high recycling: Profiles of n_iv_i, n_n, $S_{exc.}$, and $S_{ioni.}$.

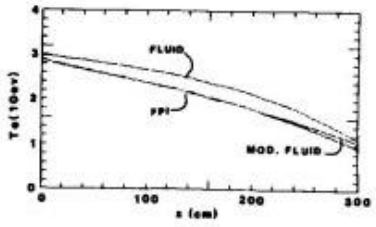

Figure 3 Fluid and Fokker-Planck hybrid simulations: Profiles of T_e from FPI, Mod. fluid, and original fluid calculations.

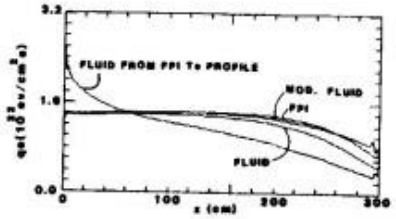

Figure 4 Fluid and Fokker-Planck hybrid simulations: Profiles of q_e from FPI, Mod. fluid, and original fluid calculations.

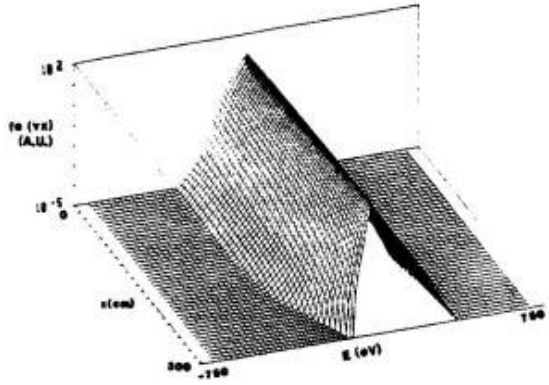

Figure 5 Fokker-Planck calculation: $f_e(v_x)$ vs x and sign $E=1/2m_e v_x^2$.

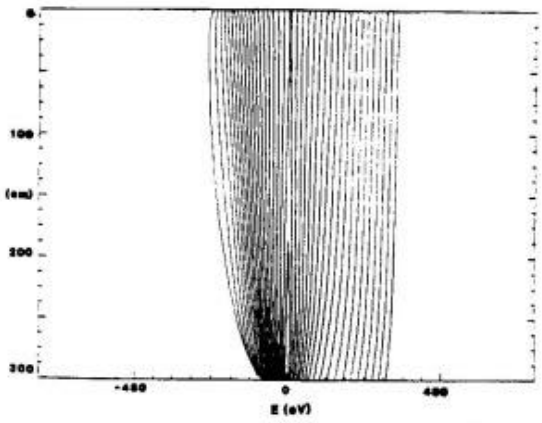

Figure 6 Fokker-Planck calculation: the contour lines of $f_e(v_x)$ vs x and sign $E=1/2m_e v_x^2$. The truncation of $f_e(vx)$ at the plate is clearly seen from this figure.