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Fokker-Planck Simulation of Coupled Plasmas and Neutral Particles Parallel Transport in the SOL of TORE-SUPRA During LH Current Drive

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Introduction

We apply the Fokker-Planck code ALLA [1] to study the transport along magnetic field lines in the SOL of Tore-Supra of collisionally coupled electrons, ions and neutral atoms, during LH current drive. The model includes some of the most important collisional processes in SOL plasmas, such as electron-electron, electron-ion and ion-ion coulomb collisions, elastic neutral-neutral collisions, neutral-atom ionization and excitation by electron impact, and ion-neutral charge exchange. Tore-Supra operates at a density of 0.5 x 10**13/cm**3 and Te=15eV in the SOL. During LH current drive, with power density of 25 Mw/m**2, significant departure of the distribution functions from a Maxwellian takes place, especially suprathermal electrons which affect the Spitzer-Harm conductivity and the plasma-neutral particles interaction rates. As shown in Fig.1, the suprathermal electrons [2,4] carry most of the heat flux along the magnetic field. The formation of hot spots around the strike points during LH heating (M. Goniche et al.,Nucl. Fusion 28,919(1998)), suggests that a significant amount of power can be deposited directly into the electrons in the SOL plasma causing a rise of its temperature, and thus making it less collisional. All these important but quite complex phenomena can be studied correctly only with a time dependent kinetic model. The code [3] studies the kinetic of both plasma and neutral particles during transient regime in a one-space two-velocity dimensionality, during LH current drive in the SOL of Tore-Supra.

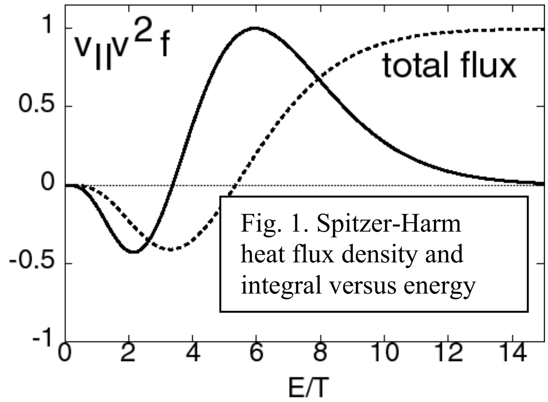

Fig. 1. Spitzer-Harm heat flux density and integral versus energy

Kinetic model description

We numerically simulate 1D2V plasma and gas flows along an open magnetic line (x≡S), as indicated the Fig.2. A half of the connection length is actually simulated because of the symmetry plane condition used at s=L. At the other end of the simulation domain (s=0) a 100% recycling of plasma is imposed: $\Gamma_N^+ = b\Gamma_i^- + \Gamma_N^-$, where $b = \sin\beta$ - an angle between magnetic field and the plate, Γ_N^+, Γ_N^- – outcoming and incoming neutral fluxes, respectively, Γ_i^- - the incoming ions flux. The distribution function is properly defined in the spherical axisymmetrical corrdinates {v,μ} [3]. We apply reflective conditions at x=L to all species, while at x=0 the logical floating sheath and recycling conditions are adopted:

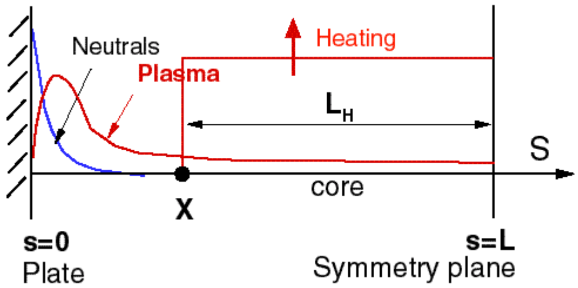

Fig. 2. 1D simulation domain with boundary condition and heating section.

$$f_e(0,v,\mu) = \begin{cases} f_e(0,v,-\mu), & v\mu \le V_F \\ 0, & V_F < v\mu < +\infty \end{cases}$$

$$\left. \begin{aligned} & f_i(0,v,\mu) = 0 \\ & f_N(0,v,\mu) = F_M^N(T = T_N) \end{aligned} \right\} \quad ,\forall \mu > 0$$

The recycled neutrals assumed to have low ~1eV temperture and half-Maxwellian energy distribution. The magnitude of the sheath potential, $\Delta\Phi = mV_F^2/2e$ (here V_F is the specific velocity) is calculated self-consistently from the logical sheath boundary condition [6]:

$$\Gamma_i^-(t) = \int_{-1}^{0}\int_{0}^{+\infty} v^3 \mu f_i(x=0) dv d\mu = \int_{-1}^{0}\int_{0}^{V_F} v^3 \mu f_e(x=0) dv d\mu = \Gamma_e^-(t)$$

The system of coupled plasma-neutrals kinetic equations is rather complex.

$$\begin{cases} \dfrac{\partial f_e}{\partial t} + v_{||}\dfrac{\partial f_e}{\partial x} - \dfrac{e}{m}E_{||}\dfrac{\partial f_e}{\partial v_{||}} = C_{ee}^C + C_{ei}^C + EX_e + I_e + H_e - R_e \\ \dfrac{\partial f_i}{\partial t} + v_{||}\dfrac{\partial f_i}{\partial x} + \dfrac{e}{M}E_{||}\dfrac{\partial f_i}{\partial v_{||}} = C_{ii}^C + CX_i + I_i + H_i - R_i \\ \dfrac{\partial f_N}{\partial t} + v_{||}\dfrac{\partial f_N}{\partial x} = C_{NN} + CX_N - I_N + R_N + S_N \end{cases}$$

It includes plasma transport, ambipolar field, various elastic and inelastic collisions, RF-heating. The LH heating term is simulated by the localized diffusion of the perpendicular to B component of the kinetic energy [6]. The e-e- and i-i Coulomb terms C_{ee}^{C} and C_{ii}^{C} are taken in the full form, and utilize actual non-linear Rosenbluth potentials:

$$C_{\alpha\beta}^{C} = \sum_{\beta=e,i} \frac{L^{\alpha/\beta}}{v^2}\left\{\frac{\partial}{\partial v} v^2\left[\frac{m_\alpha}{m_\beta}\frac{\partial\varphi^\beta}{\partial v} f^\alpha - \frac{\partial^2\psi^\beta}{\partial v^2}\frac{\partial f^\alpha}{\partial v} - \frac{1-\mu^2}{v^2}\left(\frac{\partial\psi^\beta}{\partial v\partial\mu} - \frac{1}{v}\frac{\partial\psi^\beta}{\partial\mu}\right)\frac{\partial f^\alpha}{\partial\mu}\right] + \right.$$
$$\left.\frac{\partial}{\partial\mu}\left(1-\mu^2\right)\left[\frac{m_\alpha}{m_\beta}\frac{\partial\varphi^\beta}{\partial\mu} f^\alpha - \left(\frac{\partial^2\psi^\beta}{\partial v\partial\mu} - \frac{1}{v}\frac{\partial\psi^\beta}{\partial\mu}\right)\frac{\partial f^\alpha}{\partial v} - \left(\frac{1}{v}\frac{\partial\psi^\beta}{\partial v} + \frac{1-\mu^2}{v^2}\frac{\partial^2\psi^\beta}{\partial\mu^2} - \frac{\mu}{v^2}\frac{\partial\psi^\beta}{\partial\mu}\right)\frac{\partial f^\alpha}{\partial\mu}\right]\right\}$$

while for electron-ion interaction we retain only symmetric part of the term. Other elastic collisions include important ion-neutral charge-exchange in the full form:

$$CX_i = \int \sigma_{CX}\left|\vec{v}-\vec{u}\right|\left[f_N(\vec{v}) f_i(\vec{u}) - f_i(\vec{v}) f_N(\vec{u})\right] d\vec{u}$$

$$CX_N = \int \sigma_{CX}\left|\vec{v}-\vec{u}\right|\left[f_i(\vec{v}) f_N(\vec{u}) - f_N(\vec{v}) f_i(\vec{u})\right] d\vec{u}$$

and neutral-neutral collisions, C_{NN}, for which BGK approximation [7] is adopted. The non-elastic collisions include 3-body recombination, R3, (apparently is not important for the Tore-Supra SOL), excitation, EX, and ionization, I, which could be reduced in the energy space in the zero electron-neutral mass ratio limit to the following expression:

$$I_e = N(t,x)v\left\{\begin{matrix}-\sigma_I(v) f_e(v,\mu) + \\ \sigma_I(a_I v) a_I^3 f_e(a_I v,\mu)\end{matrix}\right\}, \quad V_I \le v < \infty$$
$$I_e = N(t,x)v\left\{\sigma_I(a_I v) a_I^3 f_e(a_I v,\mu)\right\}, \quad 0 < v < V_I$$

where σ is a corresponding cross-section [5], a is the phase volume conservation factor [2].

Results of Fokker-Planck simulation

We simulate Tore-Supra SOL plasma heating for ~0.15 msec. The evolution of electron temperature and density profiles with time is presented in Fig.3ab. For comparison we plot

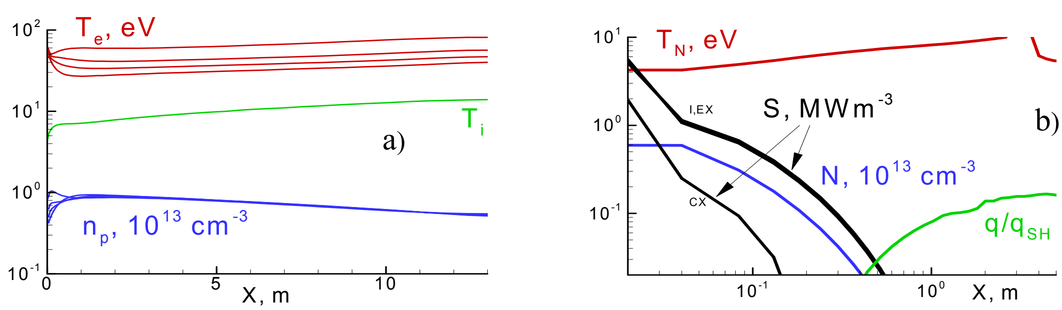

Fig. 3. Calculated plasma profiles at t=0.15msec: a) electron and ion temperatures and density, and b) neutral T and N, energy sinks, S, and ratio of the heat flux to the classical SH-value.

the ion temperature in Fig.3a. As one can see electrons and ions are thermally de-coupled. Electron temperature exceeds 40eV, which suggest that the tokamak operates in the attached regime; the neutral density does not exceed plasma density (Fig.3b). From Fig.3b (plotted up to 5m) impact ionization and excitation are the main energy sinks, while charge-exchange losses may comprise ~20% of a total loss. Because neutral temperature has inverse profile, at some distance from the plate CX becomes a local source of energy. Interestingly enough, the flux-limit factor is about 0.1 at the midplane (Fig.3b), and reduces to ~0.01 in the symmetry plane and limiter region. This is different from our previous simulations of C-Mod and DIII-D machines because of relatively shallow temperature profile and much lower Coulomb Knudsen number observed in Tore-Supra. The degree of the non-local transport dominance of the simulated regime could be illustrated by the calculated distribution functions (Figs.4).

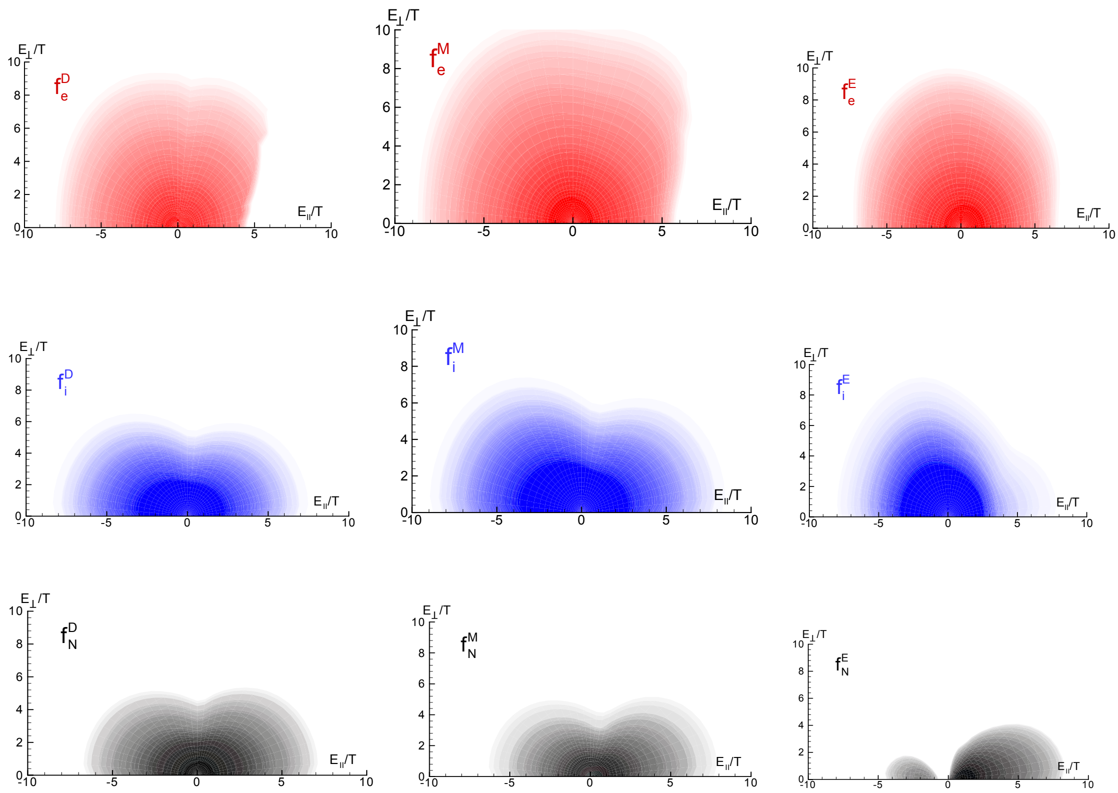

Fig. 4. Calculated distribution function of plasma and neutrals at three spatial locations, which are marked by a superscript: D-limiter, M-midplane, E-symmetry plane.

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