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COMPUTATION OF TRANSPORT AND NEUTRAL BEAM INJECTION IN TOKAMAKS*

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I. Introduction

This paper presents a description of a simulation code which is being used to study tokamak experiments. The emphasis in the model is on computational simplicity, so that we may attain some understanding of the interaction between the major plasma and atomic physics processes in a real experiment. The code we use is modular, so that more sophisticated treatments of any constituent process may be readily adapted. While other papers at this meeting will deal with basic plasma physical processes, we will proceed with semi-empirical models where necessary.

The code solves one-dimensional, time dependent fluid equations for protons, electrons and impurity ion species and the electromagnetic fields. The balance of neutral gas is treated by solving a 1-D space, 2-D velocity neutral kinetic equation. Fast injected ions are treated with a 1-D space, 2-D velocity time-dependent Fokker-Planck equation. The code incorporates rate equations for the stripping of carbon and oxygen impurities, and corona equilibria for impurities with atomic charge up to 28. The beam ion deposition profile is calculated by averaging birth distributions over the fast ion trajectories in the toroidal and poloidal fields.

II. Plasma Transport, Neutral Atoms, Impurities

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Plasma Transport Models

The equations comprising the basic plasma and field transport module are:

$$\frac{\partial}{\partial t} N_e\,(r,t) + \frac{1}{r}\frac{\partial}{\partial r}(rN_eV) = N_oN_e\,\langle\sigma v(T_e)\rangle_{ion} + \Sigma_{imp}\,(N_e,\,T_e) \qquad (1)$$

where N_e: electron density, N_o: neutral hydrogen atom density, $\langle\sigma v\rangle_{ion}$: rate coefficient for ionization by electron impact, Σ_{imp}: source of electrons from impurity stripping, V: diffusion velocity

$$\frac{3}{2}\frac{\partial}{\partial t}(N_eT_e) = -\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(q_e + \frac{3}{2}N_eVT_e\right)\right] - 3\,\frac{m_e}{mp}[z]N_e\,\frac{T_e-T_p}{\tau_e} + E_zj_z \qquad (2)$$
$$- Q_{RAD} + Q_e$$

where T_e,T_p: electron, proton temperatures, q_e electron heat flux, E_z: longitudinal electric field, j_z: longitudinal current density, m_e, m_p: electron, proton masses

$$\tau_e = \frac{3\sqrt{m_e}\,T_e^{3/2}}{4\sqrt{2\pi}(\ln\Lambda)e^4N_e}\ ;\quad \text{electron-proton collision time}$$

Q_e: source of energy from injection, Q_{RAD}: loss of energy to impurities

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$$\frac{3}{2}\frac{\partial}{\partial t}(N_p T_p) = -\frac{1}{r}\frac{\partial}{\partial r}[r(q_p + \frac{3}{2}N_p V T_p)] + 3\frac{m_e}{m_p}N_p\frac{T_e - T_p}{\tau_e} - Q_{cx} + Q_p \quad (3)$$

N_p: proton density, q_p: proton heat flux, Q_p: proton energy source from injection, Q_{cx}: charge exchange energy loss.

The field equations solved are:

$$\frac{\partial B_\theta}{\partial t}(r,t) = \frac{\partial E_z}{\partial r} \quad (4.a)$$

$$j_z = \frac{1}{r}\frac{\partial}{\partial r}(r\, B_\theta) \quad (4.b)$$

$$E_z = \eta(j_z - j_B) \quad (4.c)$$

B_θ: poloidal magnetic field, η: resistivity, j_B: beam current

The transport model is solved with an implicit, linearized Crank-Nicholson scheme.[1] The physical problem is specified by defining the diffusion velocity, heat fluxes and resistivity. A variety of models have been treated; neoclassical, pseudoclassical, trapped-particle and MHD turbulence processes may be relevant for experiments.

Neutral Atoms

The kinetic equation for neutral atoms is reduced to a one-dimensional integral equation for the spatial density, which is solved by functional iteration. The fast neutral distribution is then

$$f_{hot}(x,V,\theta) = \frac{\langle\sigma v\rangle_{cx}}{v\cos\theta}\begin{cases}\int_{-a}^{x} dx'\, f^p_{max}\, N_o e^{-R(z,z')} \\ \int_{-x}^{a} dx'\, f^p_{max}\, N_o e^{R(z',z)}\end{cases}$$

where $R(x,y) = \int_x^y dz\,[\langle\sigma v\rangle_{cx} N_p + \langle\sigma v\rangle_{ion} N_e]$

$\langle\sigma v\rangle_{cx}$: Rate coefficient for charge exchange. It is used to compute the emergent neutral spectrum and impurity sputtering. The ion loss (Q_{cx}) from charge exchange is also calculated from f_{hot}.

Impurity Ions

The code solves rate equations for stripping of carbon and oxygen impurities, and computes spatial diffusion with transport coefficients calculated by Moore and Hinton.[2] Alternatively, coronal equilibrium solutions given by Jordan[3] are used to determine the impurity spatial distribution of C, O, Si, Ne, N, Mg, Fe or Ni. The dynamic calculation gives nonequilibrium radiative rates for Q_{RAD} in equation (2), while the coronal equilibrium rates are used in the latter case.

III. Fast Ions

Neutral beam trapping by proton impact ionization, impurity impact ionization, charge exchange and electron impact is included, and the average over fast ion drift orbits computed to obtain a deposition profile. The moments formulation of Callen, et. al.[4] or, alternatively, the solution of the Fokker-Planck equation for the fast ions, are done

at many radial positions to couple the beam and transport calculation. The Fokker-Planck equation assumes the fast ions are all untrapped, and incorporates the loss-regions due to unfavorable drift orbits discovered by Rome, et. al.[5]

The fast ion Fokker-Planck equation we solve is

$$\frac{\partial f_b}{\partial t} = \frac{1}{\tau_s}\Bigg\{\Bigg(\underbrace{-\frac{\tau_s}{\tau_{cx}}}_{(1)} + 3\Bigg)f_b + \frac{\partial f_b}{\partial v}\Bigg[\underbrace{\frac{eE^*}{m_b}\zeta\tau_s}_{(2)} + \frac{\overset{(a)}{v^3}+\overset{(b)}{v_c^3}}{v^2}\Bigg] + \frac{\partial^2 f}{\partial v^2}\Bigg[\frac{1}{2}\frac{v_e^2 m_e}{m_b} + \frac{v_c^3 v_i m_i}{2v^3 m_b}\Bigg]$$

$$+ \frac{1}{2}\frac{m_i}{m_b}\frac{\langle Z\rangle}{[Z]}\frac{v_c^3}{v^3}\underbrace{\frac{\partial}{\partial\zeta}\Bigg[(1-\zeta^2)\frac{\partial f_b}{\partial\zeta}\Bigg]}_{(4)} - \underbrace{\frac{eE^*}{m_b}\frac{(1-\zeta^2)}{v}\frac{\partial f_b}{\partial\zeta}\tau_s}_{(5)}\Bigg\} \qquad (6)$$

where

$$\langle Z\rangle \equiv \sum_{\substack{\text{IONS}\\ \text{IMPUR}}} Z_k^2 \frac{n_k}{n_e} \qquad [Z] \equiv \sum_{\substack{\text{IONS}\\ \text{IMPUR}}} Z_k^2 \frac{n_k}{n_e}\frac{m_i}{m_k}$$

$$v_c \equiv \left[\frac{3}{4}\pi\frac{m_e}{m_i}[Z]\right]^{1/3} v_e \qquad E_c \cong 14.8\, T_e \qquad \tau_s \equiv \frac{4\pi\epsilon_o^2 m_b v_c^3 m_i}{n_e e^4 \ln\Lambda Z_b^2 [Z]}$$

(1) Charge Exchange Loss
(2) E-Field Acceleration
(3) Force of Dynamical Friction, a)electrons, b) Ions, Impurities
(4) Pitch-Angle Diffusion
(5) E-Field Distortion of f_b

f_b is the fast ion distribution function, τ_{cx} the charge exchange lifetime, ζ the pitch-angle, E^* the effective electric field. The equation is solved independently for each of the radial positions. This equation is solved by successive over-relaxation, or alternatively, by a strongly implicit technique.[6]

IV. Discussion

The code is used to interpret ORMAK injection experiments, where velocity-space loss region effects are an important factor in the energy balance. We have also examined the beam-trapping instability in large tokamaks.

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