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INTERACTION OF NEUTRAL HYDROGEN AND PLASMA INCLUDING WALL REFLECTION

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Abstract: We solve the kinetic equation for the neutral hydrogen in a hot plasma taking into account gas feed, Franck-Condon neutrals, wall absorption and re-emission of neutrals, electron impact ionization and charge exchange reactions. Steady state neutral profiles are obtained showing the effect of neutral hydrogen on the ion momentum and energy balance.

The presence of neutral hydrogen in Tokamak reactors is unavoidable (refuelling, outgassing) as well as desirable (wall protection, plasma profile control). Combined with the choice of wall reflection properties, one can achieve control of boundary conditions for the plasma, extending some depth into the plasma. The full problem entails the simultaneous solution of the coupled kinetic equations for the proton and the neutral hydrogen distribution functions. In this paper we assume the proton distribution function given and using a simple model, address the steady state kinetics of the various neutral components, shown schematically in Fig. 1. f_{H2} is the source distribution of molecular hydrogen producing the distribution f_{FC} of Frank-Condon neutrals, F_W describes the net amount of atomic hydrogen reflected off the wall and f_o describes warm charge exchange neutrals born inside the plasma. In the figure, the superscripts + and - refer to the direction with respect to z, the slab model equivalent of the radial coordinate. We assume the mean free path of a neutral against charge exchange (CX) to be much smaller than a, and

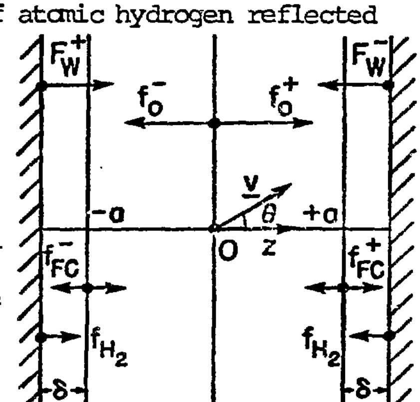

Fig. 1 Slab model

that of a proton against charge exchange smaller or equal to a. The distance δ << a in Fig. 1 characterizes the source of the Frank-Condon neutrals, whose location depends on the shape of the plasma temperature profile near the edge.- The kinetic equation for f_o is [1]

$$v_z \frac{\partial f_o}{\partial z} = n_W \langle \sigma_{cx} v\rangle_i f_i - n_e \langle \sigma_{ion.} v\rangle_e f_o + n_o \langle \sigma_{cx} v\rangle_o f_i - n_i \langle \sigma_{cx} v\rangle_i f_o \quad (1)$$

n is the density. The indices on the density w, e, o, and i stand for neutrals born outside the plasma region, electrons, neutrals born inside the plasma region and ions (protons). The first term is gain from CX of a wall neutral with a proton, the second loss due to electron impact ionization, the third gain from CX of an "interior" neutral with a proton, the fourth loss of interior neutrals due to CX with protons. A more rigorous CX collision operator has been given elsewhere [2]. This simplified operator allows the analytic solution

$$f_o = (\overline{\sigma v}/\mu v) \int_{-a}^{z} dz' f_i (n_o + n_w) \exp - A(z', z) \ldots \mu > 0 \quad (2a)$$

$$f_o = -(\overline{\sigma v}/\mu v) \int_{z}^{a} dz' f_i (n_o + n_w) \exp + A(z, z') \ldots \mu < 0 \quad (2b)$$

Here,

$$A(z_1, z_2) = \int_{z_1}^{z_2} dz'' n_i \overline{\overline{\sigma v}} / v\mu \quad (3a)$$

$$\mu = \cos\Theta, \quad \overline{\sigma v} = \langle \sigma_{cx} v\rangle_o, \quad \overline{\overline{\sigma v}} = \langle \sigma_{cx} v\rangle_i + \langle \sigma_{ion.} v\rangle_e \quad (3b)$$

To keep the theory analytically tractable, we choose the model for the proton distribution function

$$f_i = n_i \,\delta(v - \alpha_i)\,(1 + 3 v_x u_i/\alpha_i^2)/4\pi v^2 \quad (4)$$

a finite temperature "Maxwellian" containing a toroidal flow velocity u. (We have in mind the neoclassical pressure gradient driven ion flow [3,4].)

One obtains

$$n_o = \frac{1}{2} \int_{-a}^{a} dz' (n_o + n_w) n_i \sigma_{cx} E_1 [|\bar{A}(z', z)|] \quad (5)$$

where

$$\bar{A}(z', z) = \int_{z'}^{z} dz'' n_i \overline{\overline{\sigma v}} / \alpha_i(z') \quad (6)$$

and E_1 is the first exponential integral.

If the density of wall originating neutrals n_W is assumed given, Eq. 5 can be solved straightforwardly numerically for $n_o(z)$, which inserted in Eq. 2

completes the problem [1]. However, as can be concluded from Fig. 1, $n_W = n_{FC} + n_R$ where n_{FC} is the density of Frank-Condon neutrals and n_R the density of neutrals reflected from the wall. n_R is therefore dependent on n_o, the density of energetic neutrals originating inside the plasma, and a further integral equation for n_W must be found. Motivated by a detailed study of the wall absorption and re-emission problem of warm CX neutrals, we assume that on re-emission the neutrals have a flat distribution in energy $(0 \leqslant E' \leqslant E)$ and in angle $(0 \leqslant \theta' \leqslant \frac{\pi}{2})$. Introducing a reflection transfer function R (E, μ) [where (E, μ) describes the neutral before absorption and (E', μ') after], one finds for the distribution of reflected neutrals

$$f_R(v', \mu') = \left(\sqrt{m/2}\,/v'\right) \int_{E'}^{\infty} dE\, E^{-\frac{1}{2}} \int_0^1 d\mu\, R(\mu, E)\, f_o(\mu, E, z = \pm a) \quad (7)$$

This distribution is attenuated as the reflected neutrals penetrate into the plasma, so that the neutral distribution due to wall reflection becomes, at point z

$$F_W^{\pm} = f_R(v, \mu) \begin{cases} \exp - A(-a, z) \ldots \mu > 0 \\ \exp\ A(z, a) \ldots \mu < 0 \end{cases} \quad (8)$$

with A as defined in Eq. 6. A similar equation describes the Frank-Condon distribution f_{FC}^{+-} within the plasma. Thus, the total density of wall originated neutrals is given by

$$n_W = \sum_{+-} \int d^3v \left(F_W + f_{FC} \right) \quad (9)$$

and the total density of all neutrals becomes $n_T = n_o + n_W$, where n_o has been given in Eq. 5. This completes the formulation of the problem. Combining the integral equations 5 and 9

$$n_W = \int_{-a}^{a} dz'\, K_1(z', z)\, n_T + S_{FC}\ ; \quad n_T = \int_{-a}^{a} dz'\, K_2 + S_{FC}^{*} \quad (10)$$

where the kernels $K_{1,2}$ are similar to that shown in Eq. 5 and S_{FC}, S_{FC}^{*} are Frank-Condon source terms. Numerical solutions are in progress. A simple case results by omitting the contribution of wall reflected neutrals (i.e., setting R $(E, \mu) = 0$, $n_W = n_{FC}$). After solving for n_o, f_o we calculate the moments $n_o u_o = \int d^3v\, v_x f_o$ and $n_o E_o = \int d^3v\, \frac{mv^2}{2} f_o$, the toroidal flow velocity and heat content of "interior" neutrals. Typical results are shown in Figs. 2,3,4. Particularly noteworthy is the fact that one deduces from Fig. 3 a finite friction $R_{cx} = - m\, n_i\, \nu_{cx}\, (u_i - \ldots)$ between the toroidal ion flow

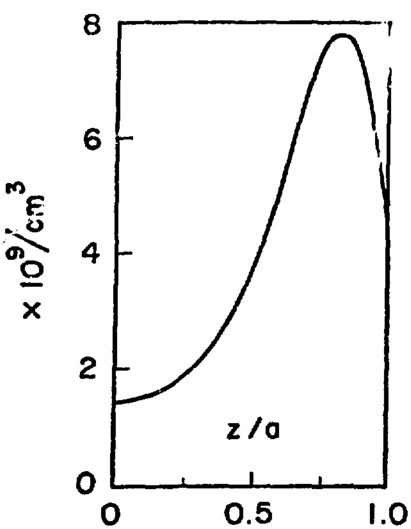

Fig. 2 Neutral density n_o

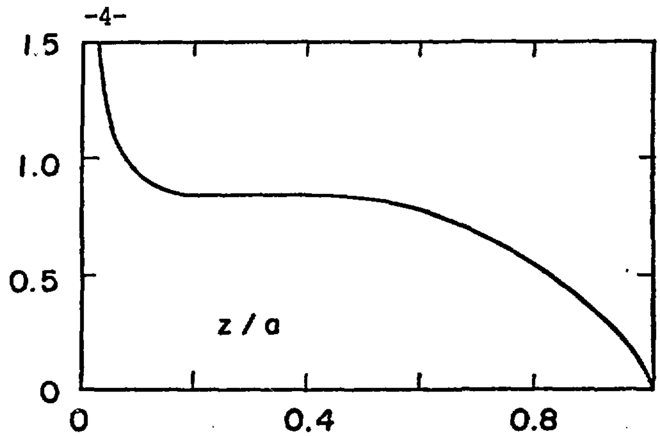

Fig.3 Ratio $n_o u_o / n_i u_i$

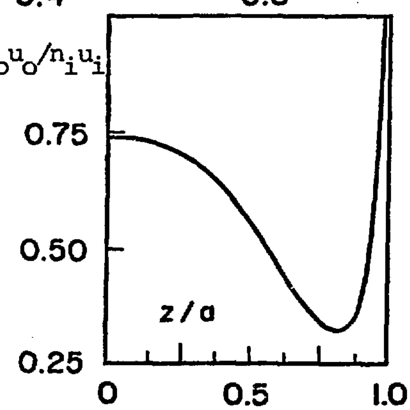

Fig. 4 $n_o E_o / n_i T_i$

velocity u_i and the neutral flow velocity u_o which reverses over the plasma radius owing to momentum transport from neutrals originating in the outer region. This friction leads to non-ambi-polar ion diffusion [2,4]. From Fig.4, the ion energy loss $Q_{cx} = - m_i n_i \nu_{cx} (T_i - E_o)$ by CX is seen to be reduced by the finite neutral energy in the plasma core and reversed near the edge where the fast neutral energy exceeds the ion temperature. These effects will be explored parametrically, allowing the ratio of neutral and proton CX mean free path over device size to vary.

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References: [1] J.T. Hogan and J.F. Clarke, Proceedings, Journal of Nucl. Materials 53, 1 (1974).

[2] D.J. Sigmar and J.F. Clarke, ORNL-TM-4606, to be published in Physics of Fluids.

[3] M. Rosenbluth, R. Hazeltine, and F. Hinton, Phys.Fl. 15 (1972) 116.

[4] D. Sigmar, J. Clarke, R. Neidigh, K. Vander Sluis, Phys. Rev. Lett. 33 (1974), 1376.

[5] M.T. Robinson, paper presented at 3rd Intl. Conf. Atomic Collisions with Solids, Kiev, U.S.S.R., Oct. 1974.