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TITLE: INTERACTION OF THE NEUTRAL DEUTERIUM FLUX WITH A FIELD-REVERSED CONFIGURATION

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AUTHOR(S): Donald J. Rej

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INTERACTION OF THE NEUTRAL DEUTERIUM FLUX WITH A FIELD-REVERSED CONFIGURATION

Donald Rej

Los Alamos National Laboratory, Univ. of California, Los Alamos N.M. 87545

I. INTRODUCTION: Recycling effects arising from the penetration of cold neutrals into a hot plasma has been known to contribute to confinement properties of tokamaks, mirrors, RFPs, and spheromaks. To date, however, ionization and charge exchange processes associated with the possible influx of neutrals have been neglected in FRC transport models, or their effects have been found negligible for experiments with short lifetimes (< 20 µs). These processes are also neglected when ascertaining the experimental particle confinement time $t_N$.

As experimental FRC lifetimes have recently been extended to record values (>300 µs), these effects on transport may no longer be negligible. Furthermore, these losses can be enhanced when FRCs translate at axial speeds much greater than the thermal speeds of the neutrals. The purpose of this analysis is to examine the interaction of neutral deuterium with an FRC. In Sec. II, the relevant atomic and molecular processes are reviewed. A simple, steady-state, multi-species 1-D (radial) neutral transport model is described in Sec. III and applied to FRC plasma parameters similar to those observed in the FRX-C experiment. In Sec. IV, estimates of the power loss due to these neutrals are made for both stationary and translating plasmas.

II. ATOMIC AND MOLECULAR PROCESSES: At the FRC edge, one might expect to find many species of deuterium: $D_2^0$, $D^0$, $D_3^+$, $D_2^2$, $D^+$. Listed in Table I are the reactions these constituents make with the FRC and each other.

In this analysis, charge neutrality is assumed and impurities are ignored. Photoionization processes appear unimportant and are thereby neglected. For each reaction we define the collision frequency, $\nu = n<\sigma v>$, where $n$ is the density of particles with which a given deuterium species interacts, and $<\sigma v>$ denotes the Maxwellian averaged reaction rate coefficient which depends on the temperatures of the reacting particles.

Values of $\nu$ for cold $D_2$, $D$, $D_3^+$ reactions with FRC deuterons and electrons have been computed for $n$, $T_e$, and $T_i$ radial profiles (shown in Fig. 7, normalized to the separatrix radius $r_s$) somewhat similar to those encountered for 5-mtorr conditions in the FRX-C experiment. The results are plotted in Fig. 2. Electron impact ionization of $D_2$ is most probable for radii $r \leq 1.25r_s$. Outside these radii, it is about equally likely that the $D_2$ molecule

![Table 1: Deuterium reaction rates considered.](image)

![Fig. 1: 1-mtorr FRX-C profiles used in these calculations.](image)
will dissociate or charge exchange with the 500 eV FRC deuterons which could extend into this region. At every location, almost all of the $D_2^+$ ions will dissociate while the $D$ atoms will charge exchange. The collisional-radiative recombination rates for $D_2^+$ are negligibly small ($\lesssim 10^3 \text{s}^{-1}$) even at the cold outer edge of the FRC.

Calculations have also been performed for 20 mtorr FRX-C conditions (average plasma parameters: $n_e = 5 \times 10^{15} \text{ cm}^{-3}$; $T_i = T_e = 100$ eV). At all radii the dominant reactions are: $D_2^+$ ionization, $D_2$ dissociation, and $D$ charge exchange.

III. NEUTRAL DIFFUSION MODEL: The penetration of a constant radial $D_2$ influx at the edge of an FRC is considered. For each deuterium species $j$ there exists the continuity equation

$$\frac{\partial n_j}{\partial t} + \nabla \cdot \mathbf{v}_j n_j = \sum_{k=1}^{N} \sum_{m=1}^{M} \sum_{q=1}^{Q} n_k n_m \sigma_{jm\,q} <\sigma v> n_q \quad \text{(1)}$$

where the summations include the $N$ possible reactions with each of the $M$ species. The integer $i \in \{1\,\text{to}\,Q\}$ is the number of particles lost or gained from a single reaction. stead-state solutions ($\partial n_j/\partial t = 0$) of Eq. (1) are sought.

Elongated FRCs (with separatrix length $L_s > r_s$) similar to those observed experimentally are considered; therefore, radial effects are neglected (i.e., $\partial/\partial z = 0$). Each species is assumed to penetrate the plasma at constant radial speed $v_r$. Eq. (1) subsequently reduces to four coupled ordinary differential equations for the $D_2$, $D$, $D_2^+$, $D^+$ radial density profiles. Forward boundary condition it is assumed that at radius $1.3 r_s$ the $D_2$ density is the constant $n_0$, while the $D$, $D_2^+$, $D^+$ densities are zero. Using the time independent FRC plasma parameters of Fig. 1 as input, the steady-state density profiles have been computed numerically assuming $r_s = 10 \text{ cm}$, $v_r = 0.3 \text{ cm} / \text{s}$ (for all four species), and $n_0 = 4 \times 10^{14} \text{ cm}^{-3}$. This value of $n_0$ can be considered as an upper bound, consistent with the fraction of initial $D_2$ fill unaccounted for in FRX-C electron inventory measurements. The results appear in Fig. 3. The corresponding reaction rates $\sigma_{jm}\langle\sigma v\rangle$ are plotted in Fig. 4. The $D_2$ molecules are ultimately converted to $D^+$ ions in the narrow band, $1.15 r_s < r < 1.25 r_s$, where $n_e < 10^{14} \text{ cm}^{-3}$. The molecules spend less than 1 s in this region before most of them are ionized. The $D_2^+$ ions dissociate, and the formation of $D^+$ is unimportant. The $D$ atoms promptly charge exchange with the 500 eV FRC ions.

IV. POWER LOSS ESTIMATES: In Sec. III it was shown that upon encountering the FRC edge, most of the $D_2$ molecules are ionized, while the $D$ atoms charge exchange with the hot FRC deuterons. The resulting hot neutrals that flow radially inward will again charge exchange well before they penetrate to the FRC center. (The average charge exchange mean free path is 0.21 cm for FRX-C...
5 mtorr conditions and 0.05 cm for 20 mtorr, values much less than r_s.)
Therefore, the energy from most of these hot neutrals is directed towards the containment vessel wall.

The cold ions that result from charge exchange or ionization reside on open field lines. These ions can be heated by the core plasma to nearly the bulk ion temperature by classical cross-field thermal conduction. This heating can occur before the ion is lost due to free streaming along the open field lines. Therefore, for the remainder of the analysis, it is assumed that each D_2 molecule incident onto the plasma surface is indirectly responsible for an energy loss 3T_i from the FRC. For a given D_2 influx \Gamma_0, the associated power loss P_o for the elongated, stationary FRC is

\[ P_o = 6 \pi n_e^2 \Gamma_0 \tau_0 \]

A confinement time, associated with P_o, can be defined,

\[ \tau_0 = E_p/\Gamma_0 = n_T r_s (1+T_e/T_i) /4 \Gamma_0, \]

where E_p is plasma kinetic energy within the separatrix. A total power loss P_T=300 MW is inferred from 5 mtorr FRX-C data. For charge exchange to contribute 10% to these losses, a critical D_2 density n_0(cm^3) = 5x10^{13}/T_0 is necessary (T_0 = D_2 temperature in eV). For 20 mtorr conditions (where P_T=100 MW), the corresponding n_0 is 8x10^{13}/T_0(cm^3).

The D_2 flux can increase substantially when FRCs translate at speed v_z >> v_D. The surface area across which the plasma sweeps up these neutrals, however, is reduced by r_s/2^1/2. The additional loss incurred because of the translation P_tr is

\[ P_tr = 3 \pi n_0^2 v_z T_i \]

Axial speeds v_z = v_A/2 are typically measured in FRX-C/T experiments. The corresponding critical D_2 densities of 3x10^{13} and 1.3x10^{14} cm^3 for 5 and 20 mtorr conditions, respectively, are necessary for P_tr to account for 10% of P_T.

In the CTR reactor study, an FRC with r_s=0.95 m, r_T=1.5x10^{19} cm^{-3}, T_i=15 keV, T_e=10 keV, \tau_T=0.1 s, is envisioned to translate at speed v_z = 30m/s. For this situation one finds that both D_7 molecules and D atoms are most likely to charge exchange with the FRC deuterons. For P_o to contribute 10% of P_T (i.e., \tau_0=10\tau_T), n_0 values of 3x10^{11}/T_0 cm^{-3} are necessary.
V. DISCUSSION: As a result of this analysis, the following conclusions can be made: (1) Cold D$_2$ molecules incident upon the plasma are ultimately converted to $D^+$ ions outside the separatrix; (2) Cold D atoms are most likely to charge exchange with the hot FRC ions that extend beyond $r_s$; (3) The resulting hot D atoms can undergo further charge exchange but eventually all of their energy is directed to the containment vessel wall; (4) For $T_0 = 1$ eV, D$_2$ densities outside the plasma exceeding 10-30% of the initial fill density are required for $P_0$ to account for 10% of the global energy confinement in TE-C; (5) The additional losses incurred by plasma translation at speed $v_p > n_D$ are of the same order as $P_0$ for the stationary FRC (because of the reduced surface area that the increased flux crosses). For all temperatures, ionization of D atoms occurs less frequently than does charge exchange, provided $T_e < T_1$. D$_2$ molecules are most likely to be ionized, provided $T > 5$ eV. Electron temperature measurements at the low density FRC edge ($r = 1.2 r_e$) have never been made. If $T_e$ in this region is less than 5 eV, then dissociation of D$_2$ is more probable. For sufficiently large $T_0$, D$_2$ ionization should be considered when ascertaining $T_e$. In the FRC-C experiment D and D$_2$ densities outside the plasma have never been measured; however, electron inventory measurements indicate that the plasma comprises more than 80% of the initial D$_2$ inventory inside the 8-pinch coil. Therefore, $P_0$ could not contribute more than about 10% to $v_e$ for D$_2$ temperature of 1 eV. Moreover, the contributions of D$_2$ ionization in the inferred $T_e$ is also less than 10%. In experiments, the scaling $v_e / v_p$ (for constant $v_p$) is observed. Therefore, charge exchange losses can become increasingly significant for larger sized devices since the ratio $v_e / v_p$ will decrease with $r_e$.

The purpose of this analysis has been to identify the important reactions that neutrals undergo upon encountering an FRC and to assess the impact of these processes on the confinement properties. These results are preliminary. Future work will concentrate on a much needed improvement of the neutral diffusion model. One-dimensional transport codes will be used to include self-consistent diffusion coefficients and the effects of neutrals absorbed, emitted, and reflected from the containment vessel walls. These effects will then be coupled with other energy loss mechanisms such as thermal conduction to calculate self consistent radial plasma profiles.

VI. REFERENCES:

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