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Deuterium recycling, confinement and limiter flux in TFTR

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The neutrals code DEGAS and the transport code SNAP were used to model recycling during steady state phases of Ohmic and neutral beam-heated discharges in TFTR. The flux of deuterium from the inner limiter is calculated to be 15–45 times the total D_α emission rate, with $\approx 2/3$ of the deuterium flux resulting from D^+ flow in the scrape off to the limiter, and $\approx 1/3$ resulting from D^0 scattering off the limiter. The total D^+ ionization rate in the core plasma is 6–24 times the total D_α emission rate, and is larger than the total neutral beam fueling rate. The D_α emission rate, limiter flux, and core ionization rates scale approximately as the square of the volume averaged electron density.

1. Introduction

Recycling of ions between the limiter (or divertor) and the plasma is an important and poorly understood source of fueling for tokamak discharges. Early in the discharge, deuterium trapped in the limiter is released by the intense bombardment from the plasma. As the discharge evolves towards a steady state, the rate of deuterium release approaches the rate of deuterium flux to the limiter. The plasma profiles are strongly coupled with the recycling.

It is important to understand recycling for several reasons: 1) The ion flux to the limiter is related to the heat flux to the limiter, which causes limiter erosion and impurity generation. 2) For tritium operation, the ion flux to the limiter will determine the tritium wall loading. 3) Fueling by recycling is usually the dominant fueling mechanism. Fig. 1 shows that even for one of the best supershots [1] in TFTR, the local recycling source, averaged over poloidal angles, is larger than the beam fueling source from the half-radius to the edge. Thus recycling is important for transport analysis in this region (D, χ, etc). 4) Limiter conditioning improves the quality of discharges (e.g., allows the occurrence of supershots), and lowers recycling. Analysis of recycling helps evaluate the limiter performance, and should lead to an understanding of the connection between discharge quality and recycling. 5) Particle confinement times, which are inversely related to the recycling flux, effect the concentrations of impurities and He ash.

This paper uses the DEGAS neutrals code [2] and the SNAP transport code [3] to calculate deuterium recycling in TFTR discharges. From the D_α emission measurements [4], the ionization rate, S_W, the fraction of the deuterium ionization from recycling occurring within the last closed flux surface, f_{co}, and the flux of deuterons (D^0 and D_2) emitted from the limiter, Γ_{lim}^{out}, are calculated. From these, the deuteron flux to the limiter, Γ_{lim}^{in}, and the deuterium confinement time can be inferred.

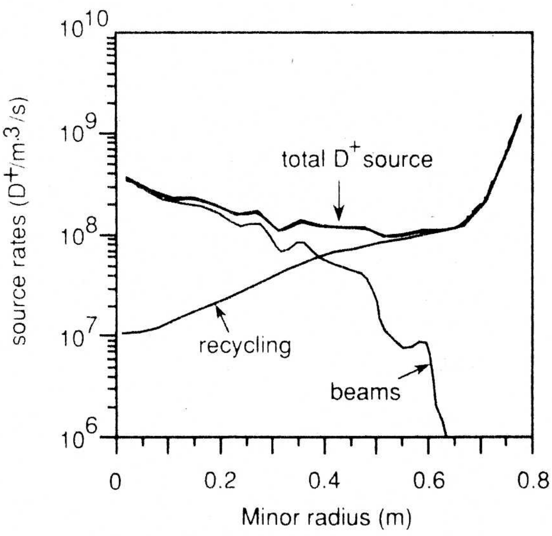

Fig. 1. An example of the D^+ source rates from neutral beam injection and recycling, as computed by TRANSP for a supershot with 22 MW beam power. The recycling contribution dominates beam fueling from the half radius to the edge.

2. Definitions

Local conservation of the deuteron density n_D is given by:

$$dn_D/dt = s_w + s_v - \nabla \cdot \gamma \quad (1)$$

with s_w being the wall source (from recycling and gas fueling), s_v being the volume source (from neutral beam injection and pellets), and γ being the local outward flux. The volume-integral of eq. (1) within the flux surface x ($= r/a$ for circular discharges with minor radius a) is

$$dN_D(x)/dt = S_w(x) + S_v(x) - \Gamma(x),$$

with $N_D(x) = \int n_D \, dV$ = the total number of deuterons within the flux surface x, $S(x) = \int s \, dV$ = the total source rates within the flux surface, and $\Gamma(x) = \int \gamma \, dA$ = the total flux out of the flux surface. If γ is poloidally and toroidally symmetric, then $\Gamma(x) = A(x) \gamma$, with $A(x)$ = the area of the flux surface.

The local deuterium particle confinement time is defined as

$$\tau(x) \equiv N_D(x)/\Gamma(x)$$

and the global deuterium confinement time is $\tau_D \equiv \tau(x = 1)$. In the rest of this paper, we concentrate on steady state portions of discharges with $x = 1$. Thus

$$\tau_D = N_D/(S_w + S_v).$$

N_D is determined from measurements of n_e and Z_{eff}, and S_v is given, roughly, by the D^0 injection rate of the neutral beams.

The DEGAS calculation gives the recycling fueling

$$S_w = mD_\alpha = f_{co}\Gamma_{lim}^{out},$$

where m is a conversion factor from the total D_α emission inferred from measurements (which was shown in ref. [5] to be roughly constant), f_{co} is the fraction of the recycled D ionized within $x = 1$ (i.e., excluding the scrape off), and Γ_{lim}^{out} is the total flux of deuterons leavin the limiter.

The total flux of deuterons hitting the limiter, Γ_{lim}^{in}, is related to Γ_{lim}^{out} by

$$\Gamma_{lim}^{out} = R_w \Gamma_{lim}^{in}$$

where R_w is the recycling coefficient of the limiter. R_w is time-dependent and is less than 1 when the limiter emits less deuterons than it absorbs, and can be greater than 1 in certain circumstances such as in the case where the limiter is saturated or heated. The more commonly used definition of the recycling coefficient is

$$R_a \equiv S_W/\Gamma_{lim}^{out}.$$

This is the recycling coefficient at the last closed flux surface ($r = a$), and is related to the density decay time τ^*:

$$\frac{\tau^*}{\tau_D} = \frac{1}{1 - R_a}.$$

The fluxes Γ and recycling coefficients R are related by conservation of deuterons in the scrape off:

$$\Gamma + (1 - f_{co})\Gamma_{lim}^{out} = \Gamma_{lim}^{in},$$

$$R_a[1 - R_w(1 - f_{co})] = R_w f_{co}.$$

The ionization rates are calculated from the measured D_α emission rates. We define the ratio of ionizations to spectral emission in three regions: the total vacuum vessel, ϵ_{tot}, the core ($x < 1$), ϵ_{co}, and the scrape off ($x > 1$), ϵ_{so}. These are related to the previously defined quantities by:

$$\epsilon_{tot} \equiv (D^+)_{tot}/D_\alpha = \Gamma_{lim}^{out}/D_\alpha = m/f_{co},$$

$$\epsilon_{co} \equiv (D^+)_{co}/(D_\alpha)_{co} = f_{co}\Gamma_{lim}^{out}/(D_a)_{co}, \quad \text{and} \quad (2)$$

$$\epsilon_{so} \equiv (D^+)_{so}/(D_\alpha)_{so} = (1 - f_{co})\Gamma_{lim}^{out}/(D_\alpha)_{so}.$$

From eqs. (2), we can derive the relation

$$1/\epsilon_{tot} = f_{co}/\epsilon_{co} + (1 - f_{co})/\epsilon_{so}.$$

This paper discusses computed values of Γ_{lim}^{out}, m, f_{co}, ϵ_{tot}, and S_w, based on experimental values for D_α, for a wide range of discharges.

3. Measurements of D_α emissions in TFTR

The combined signals from D_α (656.1 nm) and H_α (656.3 nm) emission have been measured along five poloidal sight lines at one toroidal location in TFTR with the HAIFA diagnostic [4]. Spectroscopic analysis indicates that most of the light is from D^0 and not H^0 for the deuterium discharges [6] we studied.

A typical example of the measured D_α profiles for a discharge are given in fig. 2a. The measurements have been integrated to estimate the total D_α emission in TFTR as a function of the volume-averaged electron density, which are shown in fig. 3. They were also used to calibrate the DEGAS model, as discussed below.

4. DEGAS model

DEGAS uses a three dimensional model of the geometry of the TFTR vacuum vessel and inner limiter, along with the measured plasma profiles, symmetrized by the one dimensional transport code SNAP, to simu-

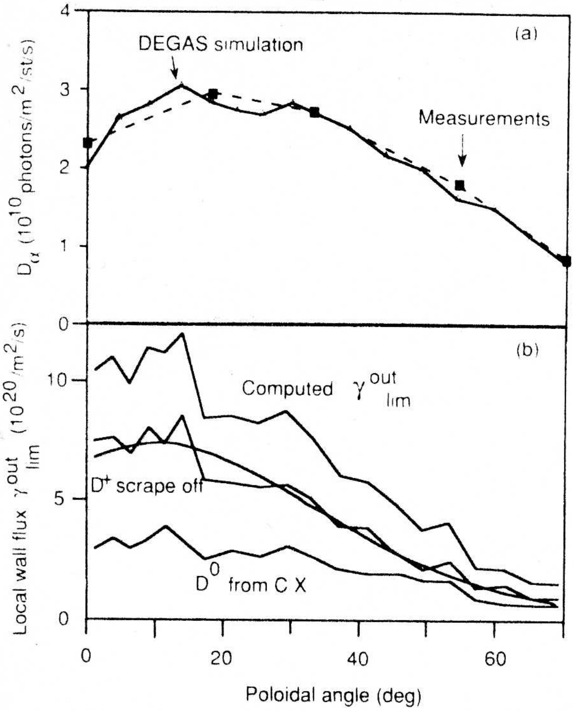

Fig. 2. (a) Poloidal D_α profile measured by HAIFA and simulated by DEGAS; (b) Limiter flux, Γ^{out}_{lim}, computed by DEGAS, showing the contributions due to D^+ (from scrape off D^+ flow to the limiter) and D^0 (from D_2 dissociation and charge-exchange). The smooth curve in (b) is determined by the parameters λ and δ and the D^+ scrape off curve is the Monte Carlo sampling of that distribution.

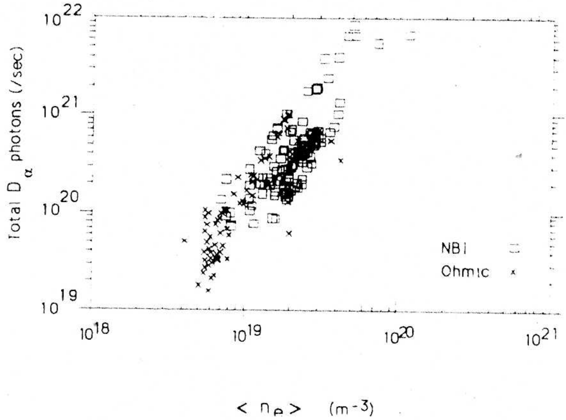

Fig. 3. Total D_α emission from measurements vs the volume-averaged electron density.

late flights of neutrals emitted from the limiter. An example of the geometry and of a test flight is shown in fig. 4. The shape of the ion limiter flux, γ^{out}_{lim}, which is used as a source term in DEGAS, is parametrized by two parameters, λ and δ. The parameter λ specifies the assumed exponential decrease of the parallel D^+ flow in the scrape off to the limiter, and δ specifies a perpendicular diffusion needed to increase the flow near the midplane (where the parallel flow is zero, c.f. [7]).

These parameters are adjusted to get agreement between the shape of simulated D_α profile and the measured D_α profile, as described in ref. [5]. An example of such an agreement is shown in fig. 2a. The ratio of the measured to calculated poloidal averages is used to scale the computed profile, limiter particle flux, and ionization rate. An example of Γ^{out}_{lim} is shown in fig. 2b.

The DEGAS results are also integrated over the toroidal and poloidal angles and radial zones $x \le 1$ to get the global core quantities S_W, f_{co}, m, and ϵ_{co}, and over zones $x > 1$ to get the global scrape-off quantities Γ^{out}_{lim} and ϵ_{so}.

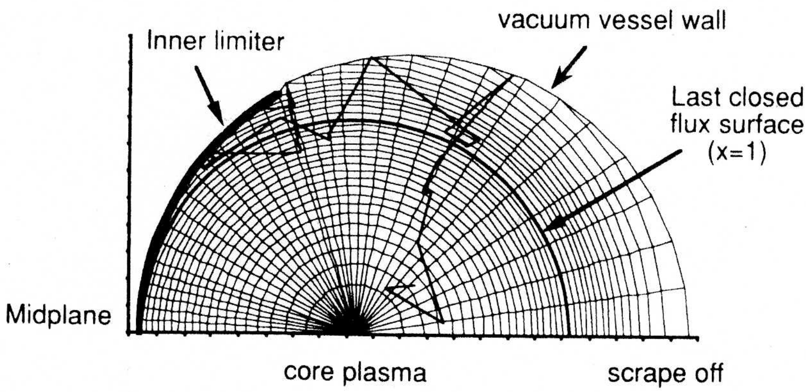

Fig. 4. Geometry used for the DEGAS calculations and an example of a Monte Carlo test flight of $D_2 \rightarrow 2D^+$.

5. Atomic physics

DEGAS calculates the ionization rate along with the D_α rate. The ratios of deuteron ionizations to D_α emission used in the calculation are shown in fig. 5. Emission due to atomic excitation from electron impacts varies both with electron temperature, T_e, and density, n_e. At the plasma core where T_e is above 1 keV, there are few deuterium molecules, so all photons come from atomic excitation. In this case the ratio ϵ_D is relatively constant, as shown in fig. 5a.

At the plasma edge, however, a contribution from molecular processes must be included [8]. There are two processes which may produce significant D_α emission:

$$e^- + D_2^0 \rightarrow e^- + 2D^0,$$

$$e^- + D_2^0 \rightarrow e^- + D^0 + D^+.$$

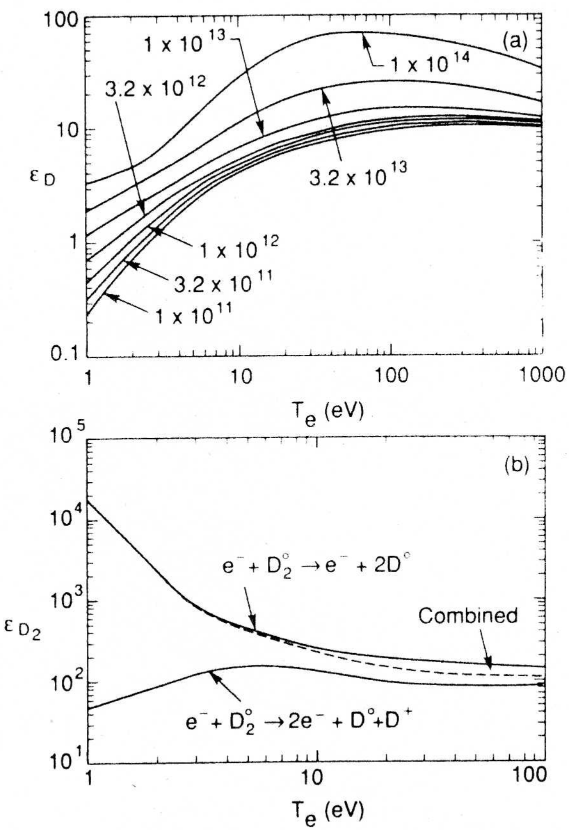

Fig. 5. Ratios of ionizations per D_α photon from a) D^0 excitation at various electron densities (cm^{-3}), and b) D_2 breakup: $e^- + D_2^0 \rightarrow e^- + 2D^0$ and $e^- + D^0 + D^+$.

The ratios ϵ_D for each reaction is shown in fig. 5b, along with the cumulative ratio where their reaction rates are taken into account. The ratios ϵ_D are larger than ϵ_D for $1 < T_e < 100$ eV.

When both atomic and molecular processes are included, ϵ varies significantly from the edge to the core. In the discharge shown in fig. 2, for example, $\epsilon_{so} = 24.9$, $\epsilon_{co} = 17.1$, and $\epsilon_{tot} = 19.9$.

6. Results

DEGAS analysis has been done for 250 TFTR discharges with a wide range of plasma conditions. The results were iterated with the SNAP transport analysis to give a self-consistent analysis, and the results from both DEGAS and SNAP were combined using the TFTR database [9].

Results for Γ_{lim}^{out} ($= \epsilon_{tot}\ D_a$) are plotted in fig. 6a. Results for S_w are shown in fig. 6b. A plot of m vs f_{co} fig. 7 over a wide range of f_{co} shows a factor of 3 variation in m. Values for the ratio ϵ_{tot} ($= m/f_{co}$) vary from 15 to 45. The values for ϵ_{tot} that have often been used in the past used [10] are ≈ 15, with only D_α from atomic deuterium considered.

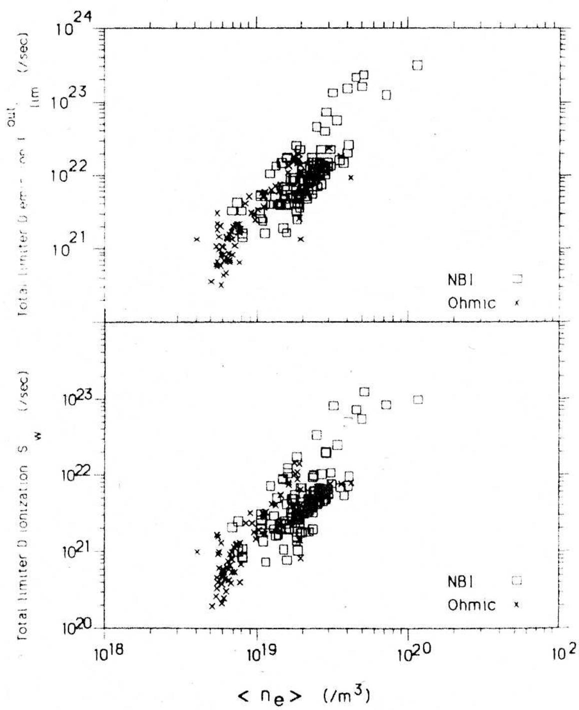

Fig. 6. DEGAS results for a) the limiter flux Γ_{lim}^{out}, and b) S_w vs the volume-averaged electron density.

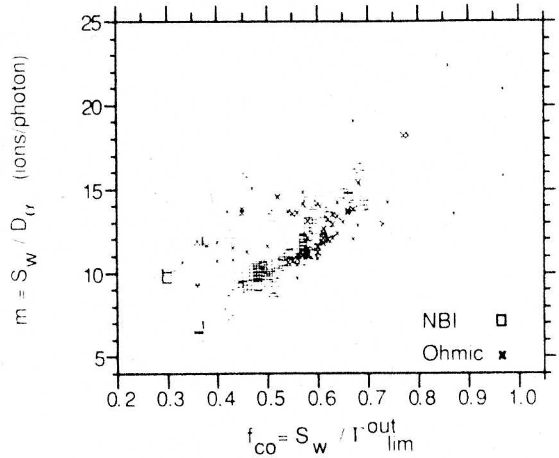

Fig. 7. The core quantities m vs f_{co}.

Most of the excitation and ionization occurs near the edge (both inside and outside), so ϵ_{tot} depends mainly on edge conditions. The lowest values for ϵ_{tot} we found were for q-mode discharges [11], which have a low edge T_e due to islands in the edge. Discharges with the highest values were pellet fueled discharges, with high n_e. These results are are consistent with fig. 5. The values for ϵ_{co} and ϵ_{so} bracketed those for ϵ_{tot}, and were found to be roughly

$$\epsilon_{tot} \approx 2\epsilon_{co}^{2/3}\epsilon_{so}^{1/3}.$$

We studied the dependence of these quantities on plasma parameters, and found that both f_{co} and m decrease weakly with the edge values $n_e(a)$, $T_e(a)$, and the parameter λ, whereas ϵ_{tot} increases weakly with $T_e(a)$ and decreases weakly with λ.

The ratio S_w/S_v was found to have a wide range, varying between 2 and 200 for beam-heated discharges. The higher values were for to L-mode discharges when the limiter was poorly conditioned. For good, high beam-power supershots, this ratio is about 5. The ratio of the deuterium condinement time to the energy confinement time of the thermal deuterium was found to vary between 0.5 and 1.5, with the ratio being close to 1 for good superhots.

7. Discussion

Our simulations indicate that the variation of the ratio of the total D^+ ionizations to D_α emission is large (15–45). Combined with the D_α measurements, this indicates large values for S_W, relative to S_v, so that recycling is the dominant overall fueling mechanism in TFTR.

The scaling of D_α with $\langle n_e \rangle^{1.7}$ (fig. 3) is similar to the scaling derived earlier in TFTR (ref. [4]), but contrasts with the results found even earlier in TFTR discharges on the moveable-limiter [12]. There, D_α emission near the limiter was found to scale as the line-averaged density cubed. Our results that Γ_{lim}^{out} and S_w also scale approximately as $\langle n_e \rangle^{1.7}$ suggest that recycling will remain the dominant fueling mechanism in experiments in future tokamaks at higher density and beam power.

Acknowledgements

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