EVOLUTION OF TFTR SCRAPE-OFF PLASMAS WITH NEUTRAL BEAM INJECTION*

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ABSTRACT

Langmuir probe radial scans were achieved for several types of neutral-beam-heated 0.8 MA discharges in TFTR. The $I(V)$ characteristics were analysed to derive n_e and T_e profiles and extrapolated to infer the global particle confinement time $\tau_p(t)$. A one-dimensional edge model was used to infer transport coefficients before and during neutral beam injection. The model indicates that ionization in the scrape-off increases the ion flux to the limiter by a factor ~ 2 and alters the profiles.

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1. INTRODUCTION

Information about the plasma scrape-off region is needed for the design of limiters and divertors since these objects must extract heat while causing minimal harm to the confined plasma. As more auxiliary heating is applied to the plasma, more heat flows into the scrape-off, making limiter and divertor design problematic, and making it harder for probes to survive in the scrape-off.

During neutral beam injection, the electron density in the scrape-off increases. This could be caused by increases in central density, recycling, impurity release from the wall or limiter, and ionization in the edge, or by decreases in central particle confinement.

Langmuir probe data were analysed to determine how the scrape-off changes with neutral beam injection, and an edge model was used to investigate the causes of these changes.

2. SCRAPE-OFF MEASUREMENT

A double Langmuir probe with thick, stubby graphite electrodes was used to obtain the data [1]. The probe was biased with a sinusoidal voltage at 60 Hz and the current and voltage signals were recorded. The $I(V)$ characteristics were reconstructed from the recorded signals and analysed using a standard double probe model [2] with

$$I_{\text{sat}} = \frac{1}{2} e n_e v_s, \quad (1)$$

$$v_s = \sqrt{k(T_i + T_e)/M_i}.$$

To fit $I(V)$, $T_i = T_e$ was assumed, and a curve-fitting program [2-3] was used.

Plasma conditions during the neutral-beam-heated TFTR discharges for which radial probe scans exist are given in Table I. These discharges were formed on the moveable limiter, and had an atypically low plasma current, I_p , which flat-topped at 0.8 MA. Their line-averaged density, $\bar{n}_e$, was constant in the ohmic heating phase (OH) just before the start of the neutral beam injection (NB), and rose steadily during NB. The "long, thin" plasmas had a large major radius R , small minor radius a , and moderate line-average density $\bar{n}_e$. The "high T_i " plasmas had a smaller major radius, larger minor radius, lower $\bar{n}_e$, and for one case, chromium gettering.

A summary of the probe results is being published [4]. Examples of the n_e fits to the probe data at several distances, δ , outside the last closed flux surface are given in Figs. 1a and 2a. The values of n_e were roughly constant in the OH phase just before the start of NB injection. They rose linearly in time after the start of injection for a time interval t_1 , then flat-topped, or continued to rise more slowly. At the end of injection they fell linearly during an interval $t_2 > t_1$. These intervals are approximately the particle confinement times computed below.

Exponentials were fitted to the $n_e(\delta, t)$ and $T_e(\delta, t)$ profiles at each $I(V)$ sweep to determine how the scrape-off lengths, λ_n and λ_{T_e} , varied with time, with the result that λ_n rises and λ_{T_e} dropped slightly during NB. These fits also provided extrapolations of n_e and T_e to the last closed flux surface. The extrapolations, $n_e(0)$, shown in Figs. 1a and 2a, rose by a factor of 2-5 during NB, and came to a constant level. $T_e(0)$, shown in Figs. 1b and 2b, also rose during NB, but by a much smaller factor. Results are summarized in Table II.

Extrapolations of the probe measurements can be used to estimate the global particle confinement time, $\tau_p = N_e/\dot{N}_{SO}$, where N_e is the total number of

electrons within the last closed flux surface, and $\dot{N}_{SO}$ is the rate for electrons entering the scrape-off. If ionization in the scrape-off is negligible, then $\dot{N}_{SO} = \dot{N}_{Lim}$, the rate for electrons hitting the limiter. If the electron flux is exponential,

$$\Gamma(\delta) = n_e(\delta) v_{||}(\delta) = \Gamma(0) \exp\{-\delta/\lambda_F\}, \quad (2)$$

then the rate of flow to the four edges of the moveable limiter is

$$\dot{N}_{Lim} = 4 \sqrt{2\pi a} \Gamma(0) \lambda_F^{3/2}. \quad (3)$$

Results for τ_p , assuming $v_{||} = F_{Mach} v_s$ with $F_{Mach} = 1/2$ are given in Figs. 1c and 2c. The value for τ_p dropped significantly during NB. The intervals t_1 and t_2 are approximately τ_p during the NB and OH phases, respectively.

3. EDGE MODEL

The scrape-off region was modeled using a modification [5] of a one-dimensional plasma and neutral transport computational model [6]. Impurity and gas fueling effects in the scrape-off are ignored. Neutral transport is simulated using SPUDNUT [7].

The parallel flows to the limiter are determined by the parallel confinement time, $\tau_{||} = L_{||}/v_{||}$, with the parallel connection length, $L_{||}$, written as f_{Lim} times the connection length for a full poloidal limiter, πR . An estimate for f_{Lim} is given by the ratio of the particle fluxes to a full poloidal limiter and to the moveable limiter [Eq.(3)], i.e.,

$$f_{Lim} = \sqrt{\frac{\pi a}{2\lambda_F}}. \quad (4)$$

The values for f_{Lim} , given in Table III, are relatively constant for the plasmas studied. There is uncertainty about $r_{||}$ due to lack of measurements. For the fits, $F_{Mach} = 1/2$ was assumed.

The radial flows are determined by the transport coefficients: χ_e , χ_i , and $D_{||}$. The boundary conditions for the power and particle flow into the scrape-off from the last closed flux surface, P_{SO} and $\dot{N}_{SO}$, and for the density and temperatures at the vacuum vessel wall: $n_e(VV)$, $T_e(VV)$, and $T_i(VV)$ were assumed.

The transport coefficients and boundary conditions were adjusted to fit the probe measurements of n_e and T_e for the six cases in Table I. The measured profiles of n_e are exponential. When $D_{||}$ is constant, the modeled profiles are exponential for most of the scrape-off region. At large δ , the modeled n_e profiles depend on the boundary conditions chosen at the vacuum vessel wall ($\delta = 20$ cm), and could deviate from exponential. Probe data for this region are sparse, and the probe signal is small.

The model predicts that the temperature profiles collapse at large δ unless χ_e and χ_i increase with δ . A form which does not collapse is $\chi_e \sim \chi_i \sim 1/n_e$. There is uncertainty about $T_i(\delta)$ and thus χ_i due to scarcity of data, but $\chi_i = \chi_e/2$ gave plausible $T_i(\delta)$ profiles.

Results from the model are given in Table III. Profiles of n_e , T_e , and T_i for the long, thin, and ungettered high T_i plasmas just before and during NB are shown in Figs. 3 and 4.

In view of the various uncertainties and difficulties modeling three-dimensional phenomena with a one-dimensional model, these results are qualitative, and are intended to provide a self-consistent, but not a unique edge model. Examples of the ambiguities in the modeling are the scaling with

F_{Mach} of $\bar{n}_{\text{SO}}$, P_{SO} , x_e , and D_1 , and the trade-off between P_{SO} and x_e .

4. DISCUSSION

The model implies that ionization in the scrape-off has a significant effect on the scrape-off profiles. The amplification factor for flux to the limiter, $\bar{n}_{\text{Lim}}/\bar{n}_{\text{SO}}$, given in Table III, is large for the plasmas studied. This factor implies that the estimates for τ_p given in Section 2 should be increased by about 2. This ionization significantly alters the values of the transport coefficients which fit the measurements.

The measured T_e profiles are approximately exponential, but to fit them, the model gives nonexponential profiles, exhibiting an upturn near $\delta = 0$ where probe measurements do not exist. This implies shorter scrape-off lengths at small δ than are predicted by the probe data at larger δ . This is consistent with the shorter scrape-off lengths inferred for $0 < \delta < 2$ cm from the measurements of the moveable limiter infrared emission [8] as well as those of the rotatable limiter on PLT [9]. Also a higher $T_e(0)$ is more in line with extrapolations of the Thomson scattering data for $T_e(r)$.

Higher T_e at small δ also implies larger heat flow ($\sim T_e^{3/2}$) and particle flow ($\sim T_e^{1/2}$) to the limiter than predicted by exponential extrapolation of the probe data. This implies a smaller τ_p than would naive extrapolations of Langmuir probe data, and counters the correction caused by the flux amplification factor. The results for τ_p given in Table III are higher than the probe extrapolations in Table II. Both methods for estimating τ_p indicate its value decreases during NB, and is lower for the high T_i plasmas. It scales with $\bar{n}_e$ to the -2 power for the high T_i plasmas, as was observed with D_0 measurements [10]. It is independent of $\bar{n}_e$ for the long, thin plasma, suggesting that these plasmas have sufficiently high $\bar{n}_e$ for saturation.

The values of $x_e(0)$ are low compared with typical values [11], and $D_\perp$ is low even compared with Bohm diffusion, except for the ungettered high T_i plasma. The ratio $x_e(0)/D_\perp$ is constant (0.9 - 1.4). Also, $x_i \sim 1/n_e$ leads to relatively large values at large δ . These differences suggest that either transport in the scrape-off plasma on open field lines is different from that in the plasma on closed field lines, that the plasmas considered here are atypical (low I_p , and large R , small a , or low $\bar{n}_e$), or that the model is too simple. Due to uncertainties in the parallel flows, the model is more reliable in estimating the ratio of perpendicular to parallel transport, so if the parallel loss is too low, the perpendicular transport will be low also.

Comparison of the results for pre-NB and NB phases of the discharges shows that the ratio P_{SO}/P_{tot} increases 20 - 40%, and the energy per ion, $P_{SO}/\bar{N}_{SO}$, increases more. The flux amplification, $\bar{N}_{Lim}/\bar{N}_{SO}$, also increases. Thus P_{SO} is roughly proportional to P_{tot} , and $\bar{N}_{SO}$ rises slower than P_{SO} , but faster than N_e .

Comparison of the results for the three plasma cases shows that the ratio of P_{SO} to P_{tot} is about 10 - 33%. Power balances for these plasmas are not available; however, limiter temperature measurements indicate that low amounts of power flowed to the moveable limiter during high T_i discharges [8].

Striking differences in the fits for the ungettered and gettered high T_i plasmas are that $D_\perp$ and the scrape-off lengths are smaller for the gettered case. One caveat in comparing these plasmas is that they were probed from different toroidal locations.

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TABLE I. Plasmas with Neutral Beam Injection and Probe Radial Scans

Plasma	Ungettered long, thin		Ungettered high T_i		Gettered high T_i	
I_p (MA)	0.8		0.8		0.8	
R/a (cm)	300/58		255/83		258/81	
q_{Lim}	2.4		7		6.8	
	<div>pre-NB NB</div>		<div>pre-NB NB</div>		<div>pre-NB NB</div>	
$\bar{n}_e$ ($10^{13}/\text{cm}^3$)	2.2	3.7	0.72	1.1	0.9	1.1
$N_e = \bar{n}_e \times \text{Vol}$ (10^{20})	4.4	7.4	2.5	3.7	3.0	3.7
P_{OH} (MW)	1.8	1.2	0.8	0.4	0.6	0.3
P_{NB} (MW)	0.0	2.0	0.0	3.6	0.0	3.7
P_{tot} (MW)	1.8	3.2	0.8	4.0	0.6	4.0
P_{Rad} (MW)	1.0	1.5	0.5	1.4	0.3	1.2

TABLE II. Summary of Fits and Extrapolations Based on the Langmuir Probe Data

Plasma	Ungettered long, thin		Ungettered high T_i		Gettered high T_i	
Probe location	Bay E		Bay A		Bay E	
δ range (cm)	1 - 8		3 - 19		9 - 14	
	pre-NB	NB	pre-NB	NB	pre-NB	NB
λ_n (cm)	2.1	2.2	7.5	5.5	3.2	4.4
$n_e(0)(10^{12}/\text{cm}^3)$	7.0	14	1.0	4.5	3.5	5.5
λ_{T_e} (cm)	5	4.5	9	7.5	10	8
$T_e(0)$ (eV)	40	55	35	50	15	45
τ_p (msec)	200	140	180	60	150	60

TABLE III. Transport Parameters and Results from the Scrape-off Model

Plasma	Ungettered long, thin		Ungettered high T_i		Gettered high T_i	
	pre-NB	NB	pre-NB	NB	pre-NB	NB
f_{Lim}	9.7	9.5	6.0	7.1	8.8	8.6
P_{SO} (kW)	240	500	73	510	170	1300
N_{SO} ($10^{20}/s$)	16	30	14	46	19	53
D_L (cm^2/s)	620	500	12500	6000	1600	2400
x_e ($10^{15}/n_e/cm/s$)	4	11	13	40	8	16
$x_e(0)$ (cm^2/s)	590	720	13800	8200	1900	2100
P_{SO}/P_{tot}	0.13	0.16	0.09	0.13	0.28	0.33
N_e/N_{SO} (msec)	275	247	179	80	157	70
P_{SO}/N_{SO} (keV)	0.94	1.04	0.33	0.69	0.56	1.53
N_{Lim}/N_{SO}	2.2	2.8	1.7	2.5	2.2	2.5
$\lambda_{n_e}(0)$ (cm)	1.96	1.92	6.70	5.46	2.95	3.10
$\lambda_{T_e}(0)$ (cm)	0.91	1.00	3.68	2.59	1.54	1.21
$\lambda_{T_i}(0)$ (cm)	0.97	1.04	4.16	2.77	1.65	1.30

FIGURE CAPTIONS

Fig. 1. Probe results for the ungettered long, thin plasmas. (a) Histories of $n_e(\delta)$ measured with the probe located at various distances, δ (cm), from the last closed flux surface. The result for $n_e(0)$ was extrapolated assuming an exponential scrape-off and averaging over 5 $I(v)$ sweeps; (b) the extrapolated $T_e(0)$; and (c) the estimated global particle confinement time τ_p . The drop in $T_e(0)$ and the rises in $n_e(1.06)$ and τ_p after $t = 2.8$ sec were probably caused by the probe becoming overheated.

Fig. 2. Probe results for the ungettered high T_i plasmas.

Fig. 3. Edge model results for the ungettered long, thin plasmas compared with the probe data for OH phase 0 and NB phase *.

Fig. 4. Edge model results for the ungettered high T_i plasmas.

Fig. 1

Fig. 2

Fig. 3

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Fig. 4

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