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COLLECTOR PROBE MEASUREMENTS OF OHMIC CONDITIONING
DISCHARGES IN TFTR

By

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COLLECTOR PROBE MEASUREMENTS OF OHMIC CONDITIONING DISCHARGES IN TFTR

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Abstract

Special limiter conditioning techniques using low density deuterium or helium discharges have produced enhanced plasma confinement in TFTR. Measurements with a rotatable collector probe have been made to increase our understanding of the boundary layer during these conditioning sequences. A set of silicon films behind slits facing in the ion and electron drift directions was exposed to four different D^+ and He^{++} discharge sequences. The amounts of deuterium and impurities trapped in the surface regions of the samples have been measured by different analytical techniques, including nuclear reaction analysis for retained deuterium, Rutherford backscattering spectroscopy for carbon and metals, and Auger electron spectroscopy for carbon, oxygen, and metals. Up to $1.9 \times 10^{17} \text{ cm}^{-2}$ of deuterium was detected in codeposited carbon layers with D/C generally in the range of the bulk saturation limit. Radial profiles and ion drift/electron drift asymmetries are discussed.

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1. Introduction

Several papers [1-5] have documented the ohmic conditioning sequences used routinely in TFTR to produce enhanced confinement discharges with neutral beam heating. They have focused on the strong pumping effect for hydrogenic species induced in the graphite toroidal bumper limiter and on the mechanisms which may produce it. It is currently believed [1] that ohmic conditioning produces a depletion layer in high flux areas of the limiter surface (depleted of its normally saturated supply of deuterium) by ion-induced desorption, primarily via C^{4+} and He^{2+} ions [5]. Limiter pumping in a conditioned machine is then a result of deuterium retention in this non-saturated volume of graphite. Limiter pumping may also occur in the carbon films which build up through C^+/C self-sputtering from the limiter. This carbon tends to accumulate in low flux areas of the limiter and on the vessel walls in a codeposited layer of carbon and deuterium. But over time all areas of the limiter receive a redeposited carbon film. Measurements [6] on TFTR limiter tiles removed after the 1985-87 operations period showed an amorphous carbon layer that ranged in thickness from less than $10\text{ }\mu\text{m}$ on high flux areas to $50\text{ }\mu\text{m}$ on low flux areas. The implications of codeposition for the future in-vessel tritium inventory have been discussed [6].

Collector probes are often used [7-14] to trap incident plasma and impurity ions as a means of studying the plasma boundary layer. In this study a collector probe was inserted in the scrape-off layer to add to our understanding of ohmic conditioning plasmas in TFTR. We looked for

evidence of codeposition and/or ion-induced desorption on a set of collecting strips after a small number of discharges in four different exposure sequences. Exposures were made during both He^{++} and D^+ plasmas. In all cases codeposition of carbon and deuterium was observed. Deuterium, carbon, and metal fluences are reported for each of these exposures. Their radial dependences and asymmetries between the electron and ion drift directions are described. Time-resolved exposures during a deuterium plasma are also studied.

2. Experimental

2.1 Exposures

The TFTR CESEP (Combined Electrical and Sample Exposure Probe) system [15] consists of a translatable probe cylinder which rotates behind slits in an outer housing. The tantalum slits defined apertures 1 mm wide facing into the ion and electron drift directions, corresponding to a time resolution of 210 ms at the rotation speed used. Seven samples, with 2 μm silicon films sputter deposited on thin electropolished molybdenum foils, were wrapped around the probe cylinder (3.8 cm diameter) to collect radial profiles of the impinging particles. The probe enters the TFTR vacuum vessel through a bottom port.

The first of the four exposures was to four identical 1.2 MA D^- discharges run on the inner bumper limiter (as were all these plasmas) with major radius $R = 2.35$ m and minor radius $a = 0.70$ m. These were discharges

in a deconditioned machine with gas puffing to bring the line average electron density to $\bar{n}_e = 3.5 \times 10^{19} \text{ m}^{-3}$. The probe was positioned a distance $d = 28$ cm outside the plasma boundary (last closed flux surface), so that the outermost sample was positioned just inside the structures at the vacuum vessel wall. The second exposure was to four consecutive 1.4 MA He^{++} conditioning discharges, $R = 2.45$ m and $a = 0.80$ m, with the probe at $d = 15$ cm (the outermost sample again just inside the vessel wall structures). They were the first in a cleanup sequence following a series of L-mode beam-heated discharges, and had densities which fell on successive discharges from $\bar{n}_e = 2.4 \times 10^{19}$ to $1.6 \times 10^{19} \text{ m}^{-3}$. (These conditioning discharges were largely deuterium and carbon regardless of the fill gas used.)

The third exposure was an overlaid exposure of D^+ and He^{++} plasmas. It began with four D^+ discharges similar to those described above (but with D pellet injection which increased the density from 1.2×10^{19} to $> 4.6 \times 10^{19} \text{ m}^{-3}$). The probe position was $d = 17$ cm. This same location on the samples was then exposed to four consecutive 1.4 MA He^{++} conditioning discharges at $d = 15$ cm. Again they formed the beginning of a cleanup sequence, and had densities which fell on successive discharges from $\bar{n}_e = 1.4 \times 10^{19}$ to $1.3 \times 10^{19} \text{ m}^{-3}$.

The fourth exposure was a time-resolved exposure which was made during a $R = 2.35$ m, $a = 0.70$ m, 1.6 MA D^+ discharge at $d = 17$ cm, with $\bar{n}_e = 3.1 \times 10^{19} \text{ m}^{-3}$. This plasma was a cleanup shot after a pellet-induced

disruption. The flux from the first 4.5 s of the discharge was accumulated without probe rotation. For $4.5 \leq t \leq 7.5$ s the probe cylinder was rotated to collect the flux from the end of the plasma flat-top phase, the rampdown phase, and the shot termination, which occurred at $t \approx 7.5$ s.

2.2 Analysis

After exposure to these discharges the samples were removed in air and analyzed by several techniques [16]. The areal density of retained deuterium was measured using $^3\text{He}(d,p)^4\text{He}$ nuclear reaction analysis (NRA) with a 700 keV ^3He analyzing beam. The data collection was automated to make a measurement every 0.5 mm along the sample axis (points of constant plasma minor radius) using a dose of 0.5 μCoul . The analysis beam spot size was 0.75x1.5 mm. Rutherford backscattering spectroscopy (RBS) was used to find metallic impurities using a 1 MeV ^4He beam. A narrow resonance in the Rutherford backscattering (RBS) cross section for protons at 1.74 MeV was used to detect carbon with a sensitivity of $1 \times 10^{16} \text{cm}^{-2}$. Auger electron spectroscopy (AES) was also used to determine surface concentrations of C, O, and other impurities, and for depth profiling.

3. Results

3.1 Retained Deuterium

Figure 1 shows the retained deuterium per exposure for the exposures mentioned, both for the ion and the electron drift directions, as a function

of distance from the plasma. The scrape-off lengths, λ , associated with these radial profiles assuming exponential decay are also shown. For clarity, the time-resolved exposure, which has been integrated, is shown separately as Fig. 1b. This exposure will be discussed in more detail in section 3.3. The scrape-off lengths for the D^+ exposure and for the He^{++} exposure in Fig. 1a were short, in the range of 1-2 cm. These exposures were both made near the outer wall, where edge model calculations [17] predict steeply decaying particle fluxes. The overlaid exposure of D^+ and He^{++} had broad radial profiles, with the decay lengths on the two sides between 10 and 19 cm. Note that the probe position for these D^+ discharges was much closer to the plasma and away from the vessel wall. The time-resolved exposure (1.6 MA D^+), made at the same radial location, also had long decay lengths, in the range of 8-16 cm. See Section 4 for further comments on these profiles.

Evidence of local heating was noted for the samples closest to the plasma at the overlaid exposure of D^+ and He^{++} , such as flaking of the Si film. Since the simple He^{++} exposure, with the probe at the same location as during the He^{++} component of this exposure, showed no such evidence, the damage must have been caused by the D^+ plasmas. And since some detrapping of the deuterium must have occurred, those data points give a lower bound measurement. All of the exposed Si on the sample at $d = 19$ cm (averaged distance for the exposure sequence) was missing, yet a large amount of deuterium (and carbon) was detected. Presumably the first D^+ plasma removed the Si (and all collected particles, see error bars) by overheating, but the underlying Mo made an adequate collector for further

deposition.

The fluences for this experiment are reported per exposure and not per discharge, due to the complications in the overlaid exposure, and the steady drop in density on successive He^{++} conditioning shots. However, to make a comparison with Langmuir probe data, one computes the average deuterium fluence to the electron side during one He^{++} discharge at $d = 18$ cm as $4.1 \times 10^{16} \text{D/cm}^2$. With reasonable assumptions this is in agreement within a factor of two with the steady-state ion flux measured with a Langmuir probe for a similar discharge.

The electron side to ion side retained deuterium ratios are shown by sample number in Table 1, with sample II being closest to the plasma. The areal density on the electron side consistently exceeds that on the ion side by factors of at least 2-4, and much higher for the He^{++} exposure. The connection lengths to the limiter (or inner wall) on the electron drift side were ~19-33 m, but only ~2-4 m on the ion drift side. Their ratio was largest for the He^{++} exposure (a combination of lower q and larger minor radius). Thus the lower fluxes to the ion side could be due to the shorter connection lengths.

3.2 Impurities

Carbon deposition as measured by RBS generally paralleled the deuterium deposition features described above, with substantial amounts observed on the inmost samples. Wherever carbon was detected it could be

seen visually as a brownish discolored stripe on the sample. A measurement in the region exposed to He^{++} discharges at $d = 20$ cm on the electron side showed an areal density of $2.4 \pm 0.2 \times 10^{17} \text{C/cm}^2$. On the adjacent sample further from the plasma, the visual discoloration faded away toward the outboard side of the foil, implying a scrape-off length < 1 cm, similar to that reported above for the retained deuterium from these plasmas. The exposure at $d = 18$ cm was very discolored, although the measured areal density was only $1.5 \times 10^{17} \text{C/cm}^2$. An Auger depth profile at this location revealed a well-defined carbon overlayer (see Fig. 2) with an estimated thickness of 18 nm, if a carbon density of 1.8 g/cm^3 is assumed. Applying this density to the RBS result yields excellent agreement between the measurements. (Other measurements [6] on thick codeposited carbon layers suggest slightly lower density values.)

The overlaid D^+ plus He^{++} exposure at $d = 19$ cm (averaged distance) on the electron side had $5.8 \pm 0.1 \times 10^{17} \text{cm}^{-2}$ of carbon (plus whatever was removed with the Si). The scrape-off length calculated from the samples was 1.7 cm. The ion side values were smaller by a factor of ~ 2 -8. The closest sample for the 1.2 MA D^+ exposure ($d = 31$ cm) had approximately $3 \times 10^{16} \text{C atoms/cm}^2$. An Auger depth profile showed there was a 2 nm thick carbon film present.

The metals content ($\text{Cr} + \text{Fe} + \text{Ni}$) in the deposited film from the He^{++} exposure was measured by RBS. The electron side exposure at $d = 20$ cm had an areal density of $7 \times 10^{14} \text{cm}^{-2}$. This is 0.3% of the deposited carbon observed. No metals or oxygen (i.e., < 0.5 at%) were detected by AES in the

He⁺⁺, the 1.2 MA D⁺, or the 1.6 MA D⁺ exposures.

3.3 Time-Resolved Measurement

The time dependence of the flux of deuterium ions to the probe during a 1.6 MA D⁺ discharge shows a modest decay from the current flat-top into the rampdown phase, and a burst at the shot termination, as shown in Fig. 3 for the electron side. The large peak on the left is due to the accumulated flux from the first 4.5 s of the plasma. It likely conceals another peak due to plasma start-up, as observed by other experimenters [14] and by TFTR Langmuir probes [18]. The sloping curves for $t \sim 4.5$ -5.5 s (seen more strikingly on the ion side, not shown) could be due in part to multiple scattering of these low energy ions [19] during a high fluence exposure made adjacent to this one (off scale to the left in Fig. 3). The burst at $t = 7.5$ s is the accumulated flux after the probe stopped rotating and is probably dominated by the outflux of plasma particles that accompanies loss of confinement at the end of a discharge. This also has been observed before [14,18]. A set of AES carbon measurements is overlaid on Fig. 3. They were taken on the electron drift side of sample II at $d = 20$ cm. They show a correlation between the collected amounts of deuterium and carbon. RBS spectra were taken on the $t = 0$ -4.5 s peak and for $t = 4.9$ s at $d = 23.3$ cm. They showed C areal densities of $4.1 \pm 0.8 \times 10^{16}$ and $1.8 \pm 0.8 \times 10^{16}$ C/cm², respectively.

Deuterium flux scrape-off lengths were calculated from the time-resolved data in Fig. 3. The scrape-off length on the electron drift

side varied slowly from ~5 cm to ~3 cm and back to ~5 cm for the period of probe rotation, $4.5 \leq t \leq 7.5$ s. The ion side decay length was considerably larger, generally in the range of 7-10 cm, with a larger uncertainty. The start-up (in the $t = 0-4.5$ s peak) and termination transients had broad radial dependences, with 7 and 11 cm scrape-off lengths on the electron and ion drift sides, respectively, at $t = 0-4.5$ s, and ~20 and >40 cm decay lengths, respectively, at $t \geq 7.5$ s. Therefore, the long scrape-off lengths reported for this exposure on Fig. 1b were dominated by the start-up and termination phases of the discharge.

4. Discussion and Conclusions

Codeposited layers of carbon and deuterium were observed on collecting samples placed in the scrape-off layer during four different exposure sequences. This has also been observed with collector probes recently in JET [20]. Several parameters varied during this experiment, including plasma gas, plasma current, electron density, plasma size, probe position, and degree of limiter conditioning. It would appear that carbon deposition generally occurs on surfaces in the boundary layer during ohmic operation, as it does on the vacuum vessel walls and low flux areas of the limiter.

The scrape-off layer in D^+ or He^{++} plasmas contains significant quantities of deuterium, as is known from other measurements [2]. Deuterium can be held in bulk graphite up to a saturation limit of ~0.44 atoms per atom [21], and perhaps to a similar limit in redeposited films [6].

D/C ratios have been calculated on the electron side from the above measurements at the locations cited in Section 3.2, and they indicate saturated layers in almost all cases. For the D⁺ exposure D/C was approximately 0.9. This, coupled with the small amount of carbon observed (2 nm), suggests that a sizable fraction of the deuterium was trapped in the silicon substrate. It is also possible that chemical effects, including hydrocarbon formation, play a role in the codeposition process. One measurement on the He⁺⁺ exposure region showed D/C = 0.49, while an analysis on the adjacent innermost sample showed a lower amount of carbon ($1.5 \times 10^{17} \text{C/cm}^2$) and D/C = 1.15. For the overlaid D⁺ plus He⁺⁺ exposure several measurements indicated D/C = 0.53-0.64, and a lone ion side analysis yielded 0.62, while the data from the innermost sample which lost the silicon film had a ratio of 0.33 (perhaps having lost additional deuterium by overheating). D/C = 0.5 for $t = 0-4.5$ s on the time-resolved D⁺ exposure, falling to 0.28 during the plasma flat-top ($t = 4.9$ s). Since D/C ratios greater than ~0.44 cannot be explained only by codeposition phenomena, it appears that either deuterium trapping in the silicon substrate or some chemical effect has also occurred in most cases. Trapping in the silicon might occur when the deuterium arrival rate exceeded ~0.44 times that for carbon early in an exposure sequence.

Because in almost every case these carbon films were saturated with deuterium, it must be emphasized that the radial profiles and scrape-off lengths of retained deuterium discussed in Section 3.1 are not accurate representations of the incident deuterium fluences, but of the incident carbon fluences, and should not be compared closely to TFTR Langmuir probe

data. Nevertheless, a discussion of the variation in scrape-off lengths and extrapolations to the vacuum vessel wall structures are appropriate. It would appear that the large variation in the deuterium decay lengths (as seen in Fig. 1) to first order is due to relative probe position in the scrape-off layer. The first two exposures, to D^+ and to He^{++} plasmas, were made near the vessel wall, where the radial profiles were very steep. Only the innermost samples had measurable amounts of carbon and deuterium. The overlaid D^+ plus He^{++} exposure was made near the wall for the He^{++} plasmas, but in the middle of the boundary layer for the D^+ discharges. The resultant profiles (on the electron and ion sides) were quite broad, which seems to reflect a broad carbon profile in the middle of the boundary layer for D^+ plasmas. The contribution of the He^{++} discharges to the deposited films was modest and confined to the innermost samples, and was noticeable only on the overheated sample (note the vertical error bars on that point at $d = 19$ cm). This hypothesis is consistent with the broad radial profiles observed for the time-resolved D^+ exposure, which was also made with the samples in the middle of the scrape-off layer.

From these data the effect of overlaying He^{++} plasmas on top of D^+ plasmas was further codeposition of carbon and deuterium. Some ion-induced desorption of deuterium presumably occurred as well (and in the other exposures), but further studies under more constrained experimental conditions would be required to confirm this.

Extrapolations of carbon areal densities per discharge to the radius of the vessel wall structures were made using the calculated scrape-off

lengths for the deuterium data (see Fig. 1). Only the exposures near the vessel wall (the first two exposures) were considered. This yielded values of $7.1 \times 10^{13} \text{C/cm}^2$ and $5.7 \times 10^{14} \text{C/cm}^2$ for the 1.2 MA D^+ and the 1.4 MA He^{++} discharges, respectively (which averages over the range of plasma densities encountered in the He^{++} exposure). These values are in general agreement with recent measurements [6] of long-term carbon deposition on TFTR wall structures. Stainless steel clips used to mount getter panels at the bottom of the machine were removed and analyzed after being exposed to 9,922 high-power discharges during the 1985-1987 operations period. The areal density of carbon on these clips was $\sim 4 \times 10^{18} \text{C/cm}^2$, or on the average $\sim 4 \times 10^{14} \text{C/cm}^2$ per discharge.

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Figure Captions

Fig. 1 Radial distributions of the retained deuterium per exposure for the various exposures, as determined by nuclear reaction analysis. The time-resolved D^+ exposure is shown separately in (b). The lateral error bars on the overlaid D^+ plus He^{++} exposure show the position of the probe for the D^+ plasmas (right mark) and the He^{++} plasmas (left mark).

Fig. 2 Redeposited carbon overlayer as seen by depth profiling with AES. No other impurities were detected.

Fig. 3 Time-resolved exposure shows the retained deuterium received during plasma flat-top, rampdown, and shot termination at a range of distances, d , from the plasma boundary. The time dependence of the plasma current and line average electron density is shown for comparison. A set of AES carbon measurements is overlaid.

Table I
Electron side/ion side ratios of retained deuterium

Plasma	Sample No.					
	II	III	IV	V	VI	VII
1.2 MA D^+	2.3	2.1	-	-	-	-
1.4 MA He^{2+}	14.1	14.7	> 11	-	-	-
1.2 MA D^+ and 1.4 MA He^{2+} }	-	-	-	-	-	6.2
1.6 MA D^+ , integrated	4.2	3.5	3.2	3.0	2.6	2.9
1.6 MA D^+ , $t = 0-4.5$ s	4.4	3.4	3.6	3.1	3.0	3.6
1.6 MA D^+ , $t = 7.5$ s	3.0	2.6	2.3	2.7	2.1	2.5

Fig. 1

Fig. 3

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