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THE EFFECT OF LIMITER CONDITIONING ON THE TOKAMAK FUSION TEST REACTOR EDGE PLASMA

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ABSTRACT

Measurements by moveable Langmuir probes and edge spectroscopy diagnostics have documented the conditioning effect of low density helium-initiated discharge sequences on the Tokamak Fusion Test Reactor (TFTR) edge plasma. Langmuir probe measurements show in general that the edge electron density n_e decreases by less than a factor of 2 while the edge electron temperature T_e doubles. Radial profiles to the plasma boundary show that the density scrape-off length increases somewhat while the temperature scrape-off length decreases substantially. The particle flux density is unaffected. The spectral emission of C II decreases by a factor of 2, a much smaller change than that exhibited by the D_α signal. These results complement previous accounts of the conditioning technique. Comparisons of these He conditioning measurements are made to edge measurements during a deuterium density scan experiment, showing many similarities, and to an existing edge model of the conditioning process, showing qualitative agreement.

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I. INTRODUCTION

Interactions between the plasma and the axisymmetric graphite bumper limiter on the inner wall of the Tokamak Fusion Test Reactor (TFTR), referred to as the inner limiter, have a strong effect on machine performance, particularly in the areas of impurity and particle recycling and control [1]. With regard to the latter, typical plasma operation with deuterium fueling causes the near-surface region of the limiter to become saturated with hydrogenic species, which results in particle recycling coefficients near unity and limits the range of plasma density control. In 1986, a conditioning technique was found [2] which could remove a large fraction of the trapped gas. It consists of a series (20 - 30) of minimum density helium- (or deuterium-) initiated discharges (each discharge lasting generally 6 - 8 s) which, most likely, removes the hydrogenic species by an ion-induced desorption process [3,4]. By this process the line-average plasma density can be reduced to the recycling limit, $0.9 \times 10^{13} \text{ cm}^{-3}$ for a plasma current, I_p , of 1.4 MA, and the recycling coefficient is reduced to values as low as 0.5. This conditioning process was instrumental in discovering an enhanced confinement mode [5,6] during high power neutral beam injection in which the density profile is highly peaked. He conditioning using 1.4 MA discharges has become a routine procedure for continuing these and other low-recycling experiments on TFTR.

Previous descriptions of limiter conditioning [1-2,7] have reported measurements of the plasma density, edge neutral pressure, D_β emission, and integrated gas output (derived from pressure versus time data after each discharge). This paper focuses on Langmuir probe measurements of ion saturation current density, electron density, and electron temperature up to the plasma boundary and C II emission measurements at the inner wall. Section II gives experimental details, Section III summarizes the results, and Section IV compares these He conditioning measurements to earlier measurements on the scaling of edge quantities with central deuterium density and to an existing edge model.

II. EXPERIMENTAL

The data in this paper come from He conditioning discharges with $I_p = 1.4 \text{ MA}$, $R = 2.45 \text{ m}$, and $a = 0.80 \text{ m}$, which contact the inner limiter. Only a small quantity of He is actually introduced for each discharge, enough for plasma breakdown; this plays no role in the characteristics of the discharge [2]. The discharge is sustained by deuterium and other species

(e.g. carbon) which are removed from the limiter. In between discharges there is a significant amount of gas pumped out of the machine, as has been documented by Ulrickson et al. [7]. A conditioning sequence consists of several consecutive discharges (generally 20 - 30, but depending on the starting condition of the inner limiter and the desired endpoint of the process). Measurements of the plasma loop voltage indicate that the Ohmic power input stays roughly constant during a conditioning sequence.

The Langmuir probe measurements were made with a fast moving probe mechanism [8] (13 cm/s) mounted above the outer midplane, which acquired radial profiles to the plasma boundary in each discharge, and the CESEP (Combined Electrical and Sample Exposure Probe) diagnostic [9], which made stationary Langmuir probe measurements from a location below the plasma column and toroidally displaced by $\sim 50^\circ$ from the fast probe. The Langmuir elements on the fast probe and the CESEP probe were graphite rods 6.4 mm and 2.8 mm in diameter, respectively, and were biased as double probes with a sinusoidal voltage at 60 Hz. In the data analysis [10] it was assumed that the electron and ion temperatures were equal ($T_i = T_e$) and the ion mass was that for deuterium. The latter is generally a good assumption in the confined plasma in the early stages of a conditioning sequence, when the plasma density is high. However, near the end of conditioning, the plasma Z_{eff} is nearly 6 [11,12], being dominated by carbon sputtered from the limiter. We have no measurements of ion temperature, although it has been observed in the range of 2 - 3 times T_e on other tokamaks [13] at low densities. If an average ion mass greater than mass 2 and $T_i > T_e$ were actually encountered during these measurements, then they would lead to errors in the calculations of n_e as presented, but with opposing effects.

Measurements of C II emission, as well as D_α emission, were made with an interference filter array [11] and a visible spectrometer, both mounted radially at the outer midplane. The interference filter array has a poloidal set of views toward the inner limiter, and data from this diagnostic are reported as a sum over the poloidal channels.

III. EDGE MEASUREMENTS

The effect of a typical 1.4 MA He conditioning sequence is illustrated by the decrease in the line-average plasma density $\bar{n}_e$, the D_α emission, the C II emission, and the edge electron density n_e , and the increase in the edge electron temperature T_e as shown in Figure 1. The Langmuir data

were taken with the CESEP probe 2.9 cm away from the plasma boundary [last closed flux surface (LCFS)], and the spectroscopy data came from the visible spectrometer system. The plasma density (a) at the starting point of this sequence, $\bar{n}_e = 1.95 \times 10^{13} \text{ cm}^{-3}$, was ~50% lower than is sometimes observed in a 1.4 MA conditioning discharge, which indicates that the limiter was not fully saturated with hydrogenic species. This is substantiated by a measurement of the electron density decay constant, τ_p , before this sequence. It had a value of 200 ms, short compared to typical values of several seconds for a saturated limiter [2]. τ_p decreased to 120 ms after the conditioning. There was only a small decrease in the C II emission (c) during the conditioning. We have observed that in a full conditioning sequence as shown in Figure 2, the C II emission decreases by about a factor of 2 and the D $_{\alpha}$ emission drops by an order of magnitude. We surmise that the small change in C II in Fig. 1(c) is due to the lower starting point for the plasma density in that run. The Langmuir probe data in Fig. 1(d) and 1(e) show that T_e increases by ~50% while n_e decreases at a slightly slower rate than $\bar{n}_e$.

Figure 3 contains radial profiles from the fast probe of ion saturation current density (or equivalently particle flux density), I_s , and electron density to the plasma boundary during selected discharges in a more recent 1.4MA He conditioning sequence. The highest and lowest values of $\bar{n}_e$ shown represent the start and termination of the sequence, respectively, which encompassed a total of only 13 discharges. The distance scale is assigned on the basis of nominal magnetics measurements, where the zero position corresponds to the LCFS. The true plasma boundary is best ascertained by probe measurements of the floating potential across the boundary, as described in Ref. 14. Lacking such measurements for this case, the uncertainty in the location of the LCFS is at least ± 1 cm. Extrapolating the data to this nominal LCFS yields $n_e(a) = 2.0 \times 10^{12}$ and $1.2 \times 10^{12} \text{ cm}^{-3}$ at the start and end of conditioning, respectively. The corresponding values for electron temperature are $T_e(a) = 28$ and 60 eV, respectively (not shown). The ion saturation current density profile remained unchanged during this sequence, in agreement with measurements by Erents et al. [15] on the Joint European Torus (JET). The n_e profile, meanwhile, showed considerable change, becoming flatter as the conditioning progressed, with a more pronounced effect closer to the plasma boundary. The plateau in the profiles at ~4 cm is thought to be due to some vacuum vessel component.

Scrape-off lengths were extracted from these Langmuir probe data assuming exponential

behavior, and are plotted as a function of $\bar{n}_e$ in Figure 4. The change in the density scrape-off length, λ_n , from ~ 5 to ≥ 7 cm is modest compared to the large and opposite swing in the temperature scrape-off length, λ_T , from ~ 21 down to $7 - 8$ cm. As noted in Fig. 3, the particle scrape-off length, λ_p , did not change.

The scaling of i_s , n_e , and T_e with $\bar{n}_e$ at the closest probe position for the discharges described in Figs. 3 and 4 is shown in Figure 5. Note that n_e and T_e are substantially lower than in Fig. 1, especially considering that those measurements were made 2.9 cm outside the LCFS. A number of factors may have contributed to this, including (1) poloidal asymmetries between the outer midplane and the bottom of the torus, including magnetic surface compression, (2) uncertainties in the distance to the LCFS, and (3) differing machine conditions, especially those caused by slight changes in the inner limiter configuration [16] between the two conditioning runs. The D_α and C II signals acquired by the interference filter array looked similar to those in Fig. 2, although the D_α intensity fell more rapidly in this case.

IV. DISCUSSION

The data presented in Fig. 5, plotted as a function of plasma density, are similar to data obtained during a deuterium density scan experiment [17]. The density scan began with low plasma densities, and gas was purposely added in successive discharges to raise the density from the recycling limit up to the density limit. At similar densities very similar values of $n_e(a)$ and $T_e(a)$ were obtained with the fast probe for both the He conditioning and the D_2 density scan discharges. In addition, the spectral emissions of D_α and C II are similar for the He and D_2 discharges.

In such a density scan, starting with a depleted limiter and raising the density by gas injection, the limiter pumps deuterium and makes it necessary to maintain a gas feed to establish a constant plasma density. In contrast, for the data presented in this paper, no gas injection was used; the density remained at a constant value through unity recycling of deuterium and carbon incident on the limiter. Despite this difference, the results are similar in the two scans. This is explained by the fact that although gas injection was used in the density scan, the magnitude of the gas puff was small compared to the amount of deuterium recycling at the limiter and thus had

little effect on the power and particle balance, resulting in similar values of edge parameters.

The trends shown in Figs. 1 and 2 are qualitatively similar to those predicted by Pitcher with a simple model of power and particle balance [18]. The model takes into account (1) the balance between the deuterium in the graphite limiter surface (based on a model by Möller and Scherzer [19]) with the deuterium in the plasma, (2) the erosion and redeposition of carbon impurities produced at the limiter by deuterium and carbon physical sputtering, and (3) the balance of input power with radiated power and power deposited on the limiter by the thermal boundary plasma. What is not included in the model is the process by which D_2 gas permanently leaves the limiter or becomes unavailable for further desorption. The physics behind this process are only poorly understood. However, if the gas leaving the system is taken as an input to the model then the observed trends can be understood and predicted using these simple power and particle balance considerations.

At the highest density the limiter is fully saturated, with the ratio of hydrogenic species (mostly deuterium) to carbon atoms being approximately 0.4 [20]. As the surface is depleted of gas, the amount of deuterium available for desorption drops sharply, resulting in a decrease in the D_α signal as shown in Fig. 2. As a result of the decreased fueling, both the edge density and the central density decrease through the conditioning sequence.

Since the power input is constant (~ 1 MW), the decrease in the particle flux requires, through the power balance, that the particle energies increase, which is observed in the edge electron temperature increase shown in Fig. 1. The increase in T_e results in an increase in the effective sputtering yield at the limiter. Thus, although the C II signal (roughly interpreted as a measure of the carbon influx) decreases with the D_α signal, its decrease is more gradual due to the compensating effect of increased sputtering yield. At the end of the conditioning sequence, the amount of gas leaving the torus between discharges becomes very small, thus halting further evolution of the discharge parameters.

V. CONCLUSIONS

We have described the evolution of some edge parameters during helium conditioning on TFTR, focusing on Langmuir probe measurements up to the plasma boundary and spectroscopic measurements of C II emission at the inner limiter. In general the edge electron density decreases

by less than a factor of 2 while the edge electron temperature doubles. Measurements near the outer midplane showed $n_e(a)$ decreasing from 2.0×10^{12} to $1.2 \times 10^{12} \text{ cm}^{-3}$ and $T_e(a)$ increasing from 28 to 60 eV. The magnitude of these changes depended on the extent of the conditioning performed. The radial profiles of these quantities change also: the density profile broadens (λ_n increases from ~ 5 to ≥ 7 cm), and the temperature profile narrows (λ_T decreases from ~ 21 to $7 - 8$ cm). The particle flux density near the boundary is unaffected. The C II emission decreases by a factor of 2, which is a smaller change than the decrease in the D_α emission due to the mitigating effect of the increasing carbon sputtering yield. These results were quite similar to those from a deuterium density scan experiment, and were in qualitative agreement with an existing model of power and particle balance.

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FIGURE CAPTIONS

- Fig. 1 Measurements of (a) plasma density, (b) D_{α} emission, (c) C II emission, (d) edge electron density, and (e) edge electron temperature during a 1.4 MA He conditioning sequence. The error bars for n_e and T_e represent the 95% confidence intervals for the fitted data.
- Fig. 2 The change in the C II and D_{α} intensities during a full conditioning sequence as measured by the interference filter array.
- Fig. 3 Radial profiles of ion saturation current density and edge electron density for selected discharges during a conditioning scan.
- Fig. 4 Plasma density variation on the scrape-off lengths for I_s , n_e , and T_e during the conditioning scan of Fig. 3.
- Fig. 5 Plasma density variation of (a) the ion saturation current density, (b) the edge electron density, and (c) the edge electron temperature during the conditioning scan of Fig. 3.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

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