**THE EFFECT OF PLASMA DENSITY ON THE BEHAVIOR OF THE PLASMA
BOUNDARY IN HELIUM DISCHARGES IN THE TOKAMAK FUSION TEST REACTOR**

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ABSTRACT

Langmuir probe measurements have been made across the plasma boundary in helium discharges of varying central electron densities in the Tokamak Fusion Test Reactor (TFTR). Radial profiles of ion saturation current density, I_s , electron density, n_e , and electron temperature, T_e , were achieved by small displacements of the plasma relative to a stationary probe. Scrape-off lengths outside the plasma boundary decreased somewhat with increasing plasma density. Inside the plasma, I_s , n_e , and T_e rose more steeply for the higher densities than the scrape-off lengths would predict. The floating potential, V_f , decreased sharply inside the boundary as expected, with some density dependence. I_s and n_e increased with plasma density, while T_e decreased a few eV. Measurements of C II emission at the inner wall combined with probe data support a relatively constant edge T_e with increasing plasma density and a constant ratio between the fluxes of helium and carbon ions.

(Presented at the 36th American Vacuum Society National Symposium, Boston, 23 - 27 October 1989, and accepted for publication in the Journal of Vacuum Science and Technology A.)

I. INTRODUCTION

It is important to measure the edge plasma parameters at or inside the tokamak plasma boundary [last closed flux surface (LCFS)] in order to understand such issues as fuel recycling, graphite limiter conditioning, and impurity generation and transport, and to connect the edge measurements to those of bulk plasma parameters. Several studies of this type have been made by edge probe diagnostics on large tokamaks [1-3].

In this paper we present the first Langmuir probe measurements inside the LCFS on the Tokamak Fusion Test Reactor (TFTR). A controlled sequence of Ohmic helium discharges forming a plasma density scan was investigated. A small vertical displacement of the plasma column during each discharge effectively scanned a stationary Langmuir probe across the LCFS. Radial profiles of ion saturation current density, electron density, electron temperature, and floating potential are reported. Their dependence on the plasma density is described. Simultaneous edge spectroscopy measurements are described and combined with the probe results.

II. EXPERIMENTAL

A. Diagnostics

The Langmuir probe measurements were made with the Combined Electrical and Sample Exposure Probe (CESEP) diagnostic, which has been described in detail elsewhere [4]. The probe enters the vacuum vessel from below the machine, at a major radius somewhat larger than the plasma center. The probe head was a 3.8 cm diameter cylinder of graphite with three 2.8 mm diameter graphite rods 6.4 mm in length protruding from the leading edge. Two were biased as a double probe with a sinusoidal voltage at 60 Hz. The third measured the floating potential, V_f . Data were collected at 5 kHz and analyzed [5] to yield electron density, n_e , and electron temperature, T_e , for every cycle of the applied voltage. For the lowest density plasmas, the gain circuit which was used unfortunately had high noise levels. Thus, only the ion saturation current density, I_s , could be extracted from these data during the plasma movement.

Measurements of C II emission were made with a multichannel visible spectrometer [6] mounted radially at the outer midplane, which has a poloidal array of views toward the axisymmetric graphite bumper limiter on the inner wall. The line-integral electron density was

monitored and controlled by a ten-channel far-infrared laser interferometer [7] with signal feedback. The diagnostic path length for these plasmas was 160 cm.

B. Plasma conditions

A series of eight consecutive helium discharges were made in this experiment, each with a constant line-integral electron density, incremented from $n_{e0}l = 1.4 \times 10^{15} \text{ cm}^{-2}$ (pre-fill gas only for plasma formation) to $4.5 \times 10^{15} \text{ cm}^{-2}$ over the course of the scan. The plasmas were run on the inner bumper limiter with major radius $R = 2.45 \text{ m}$ and minor radius $a = 0.80 \text{ m}$, with a toroidal field of $B_T = 2.87 \text{ T}$ and a plasma current $I_p = 1.0 \text{ MA}$.

At $t = 3.0 \text{ sec}$ after the start of each discharge the plasma was slowly moved downward 5 cm ($\Delta t = 0.4 \text{ sec}$) at constant major radius toward the probe to create radial profiles of electron density and temperature through the LCFS into the confined plasma. At $t = 3.4 \text{ sec}$ the plasma was moved quickly ($\Delta t = 0.1 \text{ sec}$) back to its equilibrium position to avoid overheating the probe. The probe position was fixed for these plasmas and chosen to give as much plasma penetration as possible during the plasma movement phase while preserving the integrity of the Langmuir signals and minimizing the perturbation of the plasma.

The distance of the Langmuir elements from the LCFS throughout the plasma movement was calculated using a filament code and the plasma magnetics data. The probe position with respect to the vacuum vessel is known to within $\pm 3 \text{ mm}$. According to the analysis, the LCFS at the bottom of the torus only moved $\sim 3.6 \text{ cm}$, because the plasma was distorted somewhat as it was pressed down against the curved bumper limiter. The computed initial position of the centers of the Langmuir elements was $+0.9 \text{ cm}$ (+ being defined as outside the plasma) with an absolute uncertainty of $+0.5/-0.8 \text{ cm}$ depending on which group of magnetic sensors were used. The relative movement of the plasma with respect to the probe is known to better than $\sim 1 \text{ mm}$. The probe floating potential measurements should also be an indicator of the LCFS. One would expect V_f to change abruptly from values close to zero in the scrape-off layer to large negative values as the tip penetrates the boundary and moves from a region where flux surfaces are shorted by the conducting limiter to a region which can support significant electric fields. Indeed, this was observed as shown below, and based on these measurements the initial probe position was $+2.0 \text{ cm} \pm 0.2 \text{ cm}$. This value was used to set the distance scale in the following analyses.

III. RESULTS AND DISCUSSION

A. Langmuir probes

Radial profiles of ion saturation current density (or equivalently ion flux density), electron density, and electron temperature generated by the movement of the plasma toward the probe are shown in Fig. 1 for the range of plasma densities encountered. An ion mass $m_i = 4$ and $T_e = T_i$ (where T_i is the ion temperature) were assumed. All three parameters rose significantly in the ~ 3.6 cm which were explored. The noise level in the Langmuir probe current was significantly reduced at higher densities, as can be seen in Fig. 1(a). A gentle hump in I_s and n_e was observed at the approximate position of the plasma boundary for the higher plasma densities. Exponentials were fitted to the I_s , n_e , and T_e curves for the data outside the LCFS ($d > 0$), and scrape-off lengths were calculated. These are plotted in Fig. 2 versus the line-integral density. Note the gradual steepening of the scale lengths with plasma density. These Langmuir data at $n_e = 1.4 \times 10^{15} \text{ cm}^{-2}$ are in general agreement with earlier probe profiles [3] up to the LCFS at the outer midplane in 1.0 MA deuterium prefill gas-only plasmas ($n_e = 1.3 \times 10^{15} \text{ cm}^{-2}$).

Inside the plasma, I_s , n_e , and T_e rose more steeply for the higher densities than the scrape-off lengths would predict, according to Fig. 1. The edge density rise has been compared to Abel-inverted [8] density profiles near the plasma periphery from the multichannel interferometer. There is good agreement between the two measurements, although at the LCFS the errors in the interferometer density values are approximately $\pm 10\%$ with a spatial resolution of $\sim 3 - 5$ cm.

Figure 3 shows the radial dependence of the floating potential (measured with respect to the vacuum vessel) for these plasmas. The sharp decrease in these curves always occurred at the same position and has been used to determine the location of the LCFS ($d = 0$). Some variation of the profiles with plasma density was observed. Outside the plasma boundary, V_f was greater than zero for low n_e , and gradually fell to negative values for high densities. Inside the plasma, V_f decreased more sharply with decreasing plasma density.

The plasma density dependence of the Langmuir data is highlighted in Fig. 4. I_s , n_e , and T_e are plotted against n_e for three radial positions of interest: before the plasma movement at $d =$

+2.0 cm (with data averaged over several cycles of the applied voltage), at the LCFS ($d = 0$), and approximately at the furthest penetration into the plasma, $d = -1.5$ cm. There is a density dependence which changes somewhat with radial position. The edge density data in Fig. 4(b) for $d = +2.0$ cm was fitted to a power law dependence, $n_e^{\text{edge}} \propto (n_e)^{0.7}$. The data can be fitted equally well to an offset linear dependence. Previous measurements on TFTR in deuterium plasmas showed an exponential dependence [9] for Ohmic discharges on a single outboard limiter and a linear dependence [10] during neutral-beam-heated discharges on the bumper limiter, while Ohmic deuterium data [1] from the Joint European Torus (JET) suggest $n_e(a) \propto n_e^k$, where k is usually 1 to 2.

B. Spectroscopy

Measurements of the C II intensity from the visible spectrometer as a function of poloidal angle from the plasma center are displayed in Fig. 5(a), with the data at 0° coming from the plasma contact point at the center of the bumper limiter and at 75° coming from a region above the top edge of the limiter. The C II radiation originates primarily from the boundary plasma in front of the limiter, where electron temperatures are only a few tens of eV. As one would expect, the peaks in these curves occur at the poloidal region on the limiter for which the incident particle flux and power flux are normally the highest [11], several degrees above the midplane. Note that the shape narrows somewhat at high plasma density. This is in qualitative agreement with the lower particle flux scrape-off lengths observed at higher densities.

The spatially integrated C II intensities are plotted against the spatially integrated ion saturation current densities for the density scan in Fig. 5(b). The C II integral was formed by summing the intensities from the five channels, while the I_s integral simply sums the measured I_s values for $d > 0$. A linear dependence is observed. Such behavior would be expected if the following remained constant during the density scan: (1) the physical sputtering yields for helium and carbon ions (the oxygen content is negligible in these discharges), (2) the photon efficiency for the radiating C II ions, and (3) the distribution of charge states in the boundary plasma. Both the sputtering yields [12] and the photon efficiency [13] depend only on the electron temperature in the boundary plasma, which from the probe measurements varies only modestly during the density scan, Fig. 4(c). As for the charge state distribution, both experiment and theory [14] predict a charge state distribution which is relatively insensitive to boundary plasma conditions. Thus, the linear relationship shown in Fig. 5(b) is consistent with a constant

sputtering yield for ions incident on the graphite bumper limiter and a constant ratio between the fluxes of helium and carbon ions.

IV. CONCLUSIONS

Langmuir probe measurements have been made across the LCFS in helium discharges in TFTR. Scrape-off lengths outside the plasma boundary decreased somewhat with increasing plasma density to $\lambda_n = \lambda_T = 5$ cm and $\lambda_p = 3.2$ cm at $n_e = 4.5 \times 10^{15}$ cm⁻³. Inside the plasma, I_s , n_e , and T_e rose more steeply for the higher densities than the scrape-off lengths would predict. The floating potential V_f decreased sharply inside the boundary as expected, with some density dependence. Outside the boundary, n_e increased as $(n_e)^{0.7}$. Meanwhile, T_e dropped a few eV and I_s steadily increased. Spatially integrated C II intensities were found to be proportional to the spatially integrated I_s data through the density scan, consistent with a relatively constant edge T_e and a constant ratio between the fluxes of helium and carbon ions.

ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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FIGURE CAPTIONS

- Fig. 1 Radial profiles of (a) ion saturation current density, (b) electron density, and (c) electron temperature for varying line-integral electron densities, $n_{e0}l$. Negative values of d , the distance from the LCFS, are defined as inside the plasma. The error bars for n_e and T_e represent the average 95% confidence intervals for the fitted data.
- Fig. 2 Plasma density variation of the scrape-off lengths λ_p , λ_n , and λ_T , which were calculated from the data outside the LCFS in Fig. 1.
- Fig. 3 The radial dependence of the floating potential (measured with respect to the vacuum vessel) for varying plasma densities, $n_{e0}l$.
- Fig. 4 Plasma density variation of (a) the ion saturation current density, (b) the electron density, and (c) the electron temperature for three radial positions of interest. The error bars for n_e and T_e represent the 95% confidence intervals for each fit.
- Fig. 5 (a) Measurements of the C II intensity near the inner wall along five poloidally spaced sightlines of a visible spectrometer array. The poloidal angle is measured with respect to the plasma center, with 0° being the bumper limiter midplane. (b) The spatially integrated C II intensity versus the spatially integrated ion saturation current density for the plasma density scan.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5(a)

Figure 5(b)