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FLUXES IN THE PLT EDGE PLASMA

BY

S. A. COHEN, AND H. F. DYLLA

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LOWER LIMITS FOR PARALLEL IMPURITY FLUXES
IN THE FLT EDGE PLASMA

S. A. Cohen and H. F. Dylla

Plasma Physics Laboratory, Princeton University,
Princeton, New Jersey 08540 U.S.A.

ABSTRACT

Lower limits for time-resolved $\bar{E}$ -parallel impurity fluxes to solid collectors immersed in the FLT edge plasma have been determined as a function of minor radius. Limiting factors are geometric shadowing of the probe surface, and losses attributed to finite ion gyro-radii have been determined. For $r = 48$ cm, heat pulses of ~ 2 ms duration and 2.5×10^3 W/cm² intensity were found to occur at the termination of many discharges.

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I. Introduction

The ion distribution near the limiter is dependent on and indicative of ionization, transport, and impurity generation rates. Both radial and $\bar{B}$ -parallel impurity transport have special importance in assessing the efficacy of scrape-off layers in impurity control schemes. With these motivations we have performed experiments in PLT designed to measure impurity fluxes near $r = a$. The technique consists of inserting into the plasma edge solid probes to act as collectors for impacting particles. After exposure to all or part of a discharge, the probe surfaces are analyzed for changes in elemental composition. By using an appropriate probe geometry, a measure of ion Larmor radii, and hence ion energy, can be made. Aspects of this approach, including some limitations, are discussed in Section II. The results are presented in Section III.

II. Experimental Procedure and Analysis Model

A detailed description of the apparatus may be found in Ref. [1]. The probe is a 1.3 cm wide, 330 cm long, .076 cm thick stainless steel tape welded into a continuous loop. It rides between two sprocket wheels at the ends of a ~ 160 cm long support rail. One end of the rail is in an analysis chamber, the other can be inserted into PLT at varying distances behind the limiter (see Fig. 1 of Ref. 1). The section inside PLT is surrounded by a cylindrical shield with a single slit (Fig. 1).

About 0.5 sec before each discharge, a drive sprocket wheel sets the tape into motion, thus causing time resolved exposure to the plasma of the tape surface behind the slit. The time resolution, τ , is given by h/s , where h is the width of the slit and s the speed of the tape. The tape continues to spin for 1 sec after the discharge terminates. At start-up the drive mechanism reaches full speed in ≤ 10 ms. Its absolute positioning accuracy is ± 0.013 cm over the entire 330 cm length.

As shown in Fig. 1, the probe intercepts the toroidal magnetic field at an angle of $(\pi/2 - \theta)$ with respect to the normal. For all of these experiments $\theta = 20^\circ$. By this skewed orientation one is able to separate charged from neutral particle impact. Perfectly magnetized ions with Larmor radii, $\ell_i \ll h$, would closely follow the magnetic field lines and land on the +x side of the tape, in the area marked "slit projection along B". Neutral particles, or highly energetic ions, would not be affected by B and would have a deposition profile standard for an effusive slit source. For $\ell_i \geq h$, the ions are only partially magnetized, and their deposition profile across x is between these extremes.

For most of the experiments described here $\sim 5000 \text{ \AA}$ indium films were vacuum evaporated over portions of the stainless steel tape. The main purpose for these films was to allow detection of Fe that might land on the tape. A serendipitous use, due to the low melting temperature of indium, is the determination of lower and upper limits on the power flux to the tape.

Elements on the tape are identified using standard $dN(E)/dE$ AES [2]. Absolute concentrations of each element on the surface were determined using the following assumptions:

- (1) The AE escape depths, $\sim 7\text{\AA}$, were taken from Ref. [3],
- (2) Substrate densities (N) were taken to be the thin film value ($\sim .8$ bulk), and (3) the AE sensitivities in the PHI Handbook [4] were used. W and Ag calibrations were also made.

In a separate apparatus the $dN(E)/dE$ peak heights and $N(E)$ computer fitted areas were compared for the oxygen-indium system for .001 monolayers to $\sim .4$ monolayers adsorbed oxygen. The data showed $[dN(E)/dE]/N(E) = \text{constant}$ over the entire range, for both In and O. Within this framework, the calculated surface concentrations are expected to have absolute accuracy of $\times 2$, and relative accuracy of $\pm 10\%$.

Measuring the absolute surface concentrations, n_s , is more straightforward than relating them back to concentrations, n_p , in the plasma [5]. In the first place, it is the flux of ions, Γ_i , to the probe that causes the changes in n_s . To determine n_p , both Γ_i and the ion velocity, v_i , must be found. We assume, by extending to hot, $Z \geq 1$ ions, the results found in the FM-1 divertor experiment [6], that Γ_i is given by

$$\Gamma_i = \frac{i n_p C_s}{2} = \frac{n_i}{2} [(T_i + Z_i T_e)/m_i]^{1/2}. \quad (1)$$

Where T_e and T_i are the electron and ion temperatures, Z_i , m_i , and $i n_p$ are the charge, mass, and density of the i^{th} ion

species, and C_s is the ion acoustic speed. However, all impacting ions do not necessarily stick. Also there may be removal of implanted ions from the surface by H^+ sputtering, massive ion sputtering, evaporation or diffusion into the bulk. Furthermore, the shallow angle, 20° , of the probe surface to B, does not allow ions with arbitrary pitch angles, V_z/V_n , to pass through the slit, i.e., only ions within "deposition cones" in the velocity distribution can reach the tape. With all these considerations we conclude that the flux determined from changes in concentration,

$$\Gamma_i = \Delta(n_s)/\tau \sin \theta, \quad (2)$$

represents a lower limit.

A typical experimental run consists of exposing different areas of the tape to ~ 10 different discharges within 1 or 2 hours. During each plasma discharge the tape may or may not be spun. A single AES y-scan (see Fig. 1) for C and O down the middle of the tape, $x = 0$, over all exposed areas is usually performed within 2 hours. Detailed y-scans at 1/2 mm spacing across the 1.3 cm tape are carried out for C, O, Cl, Fe, and W during the next day. Though the background C signal usually rose after several days, the signal from the implanted ions did not change by more than 30% during the first day.

III. Results

For a particular probe geometry at a particular toroidal location, the quantities of interest, Γ_i 's, are functions of five variables, $\Gamma_i = \Gamma_i(c, r, \tau, t, x)$; i.e., the inferred flux for each ion species will depend on: the conditions of a particular plasma discharge, c ; the minor radius location of the probe in the plasma, r ; the duration of the exposure, τ ; the time during discharge when exposure occurs, t ; and the position on the tape where analysis is made, x .

The r dependence of Γ_i was assessed by positioning the tape at $r = 46$ to 50 cm and varying the number of discharges to which a section of tape was exposed. In this case the time-resolved option was not used. As shown in Fig. 2(a) about 50 times less O was deposited in one discharge at $r = 50$ than at $r = 46$. After many discharges the O levels saturated near the same values, regardless of the value of r . In Fig. 2(b) the data for single discharges from Fig. 2(a) are plotted along with earlier data where each area of tape was exposed to three discharges. The behavior reported by McCracken et al. [7] and Staib and Staudenmaier [8], that the concentration first rises then falls with decreasing r , was not observed. However the saturation phenomena has been previously reported [9].

The x dependence of the deposited ions is shown in Figs. 3, 4, 5, and 6. The data in Figs. 3 and 4 were compiled with the tape located at $r = 50$ cm and exposed to 130 discharges. Again, the time-resolution option was not used. In Fig. 3 are shown profiles of O at different values of x . Note that the

FWHH of the profiles is only $\sim 10\%$ larger than the slit width of .15 cm. The same was true of the FWHH for the Fe and W profiles measured that day. The peaks of these three sets of profiles, O, Fe, and W, are shown in Fig. 4. From these deposition profiles it is inferred that partially magnetized charged particles were responsible for the deposition. The Larmor radii, ℓ_i , of 10 eV W^+ , Fe^+ , and O^+ are also shown in the Fig. 4. Consistent with the interpretation that the fall-off towards negative x is proportional to ℓ_i , the W profile is broader than the Fe which is broader than the O. Because of the complicated geometry, the $1/e$ fall-off should not be considered to be equal to ℓ_i , though it may be proportional to ℓ_i .

The minor radius, r , dependence of the x dependence is shown in Fig. 5. For these data the tape was exposed to three discharges at each r . Fitting the data to a function of the form $n_o \propto \exp(-X/X_o)$ the following values of X_o are obtained: $X_o = 3.1^{+1.4}_{-1.4}$ mm for $r = 46$ cm; $X_o = 2.6^{+1.3}_{-1.3}$ mm for $r = 47$ cm; $X_o = 2.3^{+1.3}_{-1.3}$ mm for $r = 48$ cm; and $X_o = 2.3^{+1.3}_{-1.3}$ mm for $r = 49$ cm. If X_o were simply proportional to ℓ_i , this small but systematic decrease in X_o with increasing r would indicate a 65% decrease in T_i . Perfectly magnetized ions, $\ell_i \leq 10^{-2}$ cm, could only land within the projection of the slit along $\bar{B}$, $1.5 < x < 6.5$ mm. Point A in Fig. 5 is the "leftmost" point accessible to ions with energies less than 1 keV. To land in B would require about 200 eV total energy; to land at C would require a minimum total energy of 50 eV, with $E_i \sim 10$ eV.

In Fig. 6 are shown the time behavior of the O and C signals along the $x = 0$ line of the tape for discharge #14617 - a D plasma with ~ 700 kW of D beam heating and a W limiter. The slit width and length were .1 cm and .32 cm respectively. The tape was at 46.7 cm. Two unusual features are seen. The first occurs at ~ 0.3 s, i.e., 300 ms before the discharge. This feature is due to "winding up" the OH primary coil causing a small pre-plasma, which, evidently knocks oxygen (bearing molecules) off the wall. As shown in Fig. 7 (solid curve), the x-scan of this feature reveals that the oxygen arrives at the tape as neutrals. (The toroidal field is on at this time.) The area under this pre-pulse feature represents 20% of the oxygen on the tape for this particular discharge. On other occasions it has been 80%. This pre-pulse may serve as an indicator of the state of cleanliness of the machine.

The second feature we term a "melt". It occurs at the termination of high power discharges. During this run there were minor melts for each of the eight discharges studied. The statistics on other days were not as consistent: 8 of 10; 2 of 14; 4 of 6; 1 of 12, etc. Though not all melts are pronounced, justification for the label can be seen in Fig. 8 where SEMs of one are shown. The melt is at $x = 2$ to 5 mm. Its shape, to the accuracy of measurement, is the projection of the slit along B, and thus is due to e^- or H^+ bombardment. The power required to melt the In film depends on the duration of the heat flux. Since the melt is less than 10% wider than the slit (even for $\tau = 20$ ms) we conclude that the energy is deposited in $t' \leq 2$ ms. Using

the thermal conductivities of In and stainless steel we find that this is still sufficient time for the heat to be transferred through the tape. Therefore the thermal inertia is the heat capacity of the .0076 cm steel tape and not the 5000 Å In film. Thus the power, P , required to melt the indium has to be greater than

$$P \geq T_M C_P m / t' \approx 2.3 \times 10^3 \text{ W/cm}^2,$$

where

T_M = melting temperature of In $\sim 150^\circ\text{C}$

C_P = specific heat of steel $\sim 0.5 \text{ J/gm}^\circ\text{K}$, and

m = mass/area of the steel tape.

Heat fluxes this high could cause loss of implanted ions from the surfaces by evaporation or diffusion. Using the broad (.005 cm) analyzing electron beam, of the SAS-AES, the following concentrations were measured for one melt: C-39%; O-19%; In-16%; K-14%; Fe-7%; Cl-3.8%; S-1.4%, and Ni-0.3%. No W was detected.

Also plotted in Fig. 7 are x-scans for $t = 50 \text{ ms}$, 450 ms and 700 ms . The largest O signal at $x = 0$ occurs at the end of the pulse. Its shape is similar to that for O in Fig. 4. It is suggested that the cause for the fall-off in O signal at $x \geq +1 \text{ mm}$ in this figure and Fig. 4 is due to the same bombardment that causes the melt. The signals at large $-x$ are probably due to neutral oxygen [10] as the energy required for charged particles to reach $x \leq -3 \text{ mm}$ is greater than 1 keV. Also, shown in Fig. 6 is a more detailed display of the oxygen signal, the ion temperature, and the raw charge exchange (CX) signal at 3 keV. During beam heating the O deposited

on the tape grows 50%, in proportion and synchronism with T_i . However, the CX outflux at 3 keV, as do those at 1, 6, and 12 keV, grow by x5 to x10. Thus the CX particles in the energy range 1-12 keV are not responsible for the increase in oxygen.

The changes in C and O concentrations during this run at $t \sim 450$ ms were $\sim 2\%$. Using equation (2), this gives fluxes of $\sim 4 \times 10^{15} \text{ cm}^{-2} \cdot \text{s}$. Inserting this into Eq. (1) along with the values T_e , $T_i \sim 10$ eV and $Z_i = 1$, we find a lower limit for C and O of $n_p \sim 6 \times 10^9 / \text{cm}^3$ at $r = 46.7$ cm. Tentimes higher fluxes have been measured. Though Fe was not detected during this discharge, in earlier runs an increased flux of $4 \times 10^{14} / \text{cm}^2 \cdot \text{s}$ was measured during the beam heating period.

IV. Summary

Measurements of $\bar{B}$ -parallel plasma impurity fluxes, particularly O, have been made in PLT for $46 < r < 51$ cm. Typical lower limits on O, C, and Fe fluxes to the probe during the current flattop are: $\Gamma_O \approx 2 \times 10^{15} / \text{cm}^2 \cdot \text{s}$; $\Gamma_C \approx 2 \times 10^{15} / \text{cm}^2 \cdot \text{s}$ and $\Gamma_{Fe} \approx 1 \times 10^{14} / \text{cm}^2 \cdot \text{s}$ at $r = 48$ cm. The deposited particles are shown to have deposition profiles of partially magnetized ions with energies ~ 50 eV. The importance of saturation effects in determining fluxes has been demonstrated.

Two new features have been discovered: a pre-pulse deposition of oxygen; and an end-pulse heat flux of order 10^3 W/cm^2 and duration ~ 2 ms. These underscore the need for time resolved measurements.

Acknowledgments

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FIGURE CAPTIONS

Fig. 1. (a) Cutaway drawing of the probe. A stainless steel tape, which acts as the impurity ion collector, is transported on a sprocket wheel behind a slit, thus allowing time-resolved exposure to the plasma. In most of the experiments described here, the tape was coated with vacuum evaporated In. (b) Schematic of the probe. Note that the toroidal magnetic field is at an angle of θ from the tape surface. Perfectly magnetized particles could only land on that area of the tape marked "slit projection along B." One oxygen ion, with a large Larmor radius, is shown landing several mm to the left of that area. The leftmost possible impact location for ions (with energies less than 1 keV) is also shown.

Fig. 2. (a) Oxygen concentration on a Ag-coated section of the tape vs. number of discharges and radial position. A signal of 1 volt is approximately 20% of a monolayer. With the probe at $r = 50$ cm, exposure to 50 discharges will raise the oxygen signal to ~ 1 volt. The tape was not spun during any of these discharges. (b) Oxygen concentration on the tape vs. radial position. For the upper curve, at each radial position a different area of the tape was exposed to three discharges; for the lower curve, only single discharges.

Fig. 3. Oxygen profile across tape after exposure at $r = 50$ cm to 130 D pulses.

Fig. 4. x profile of O, Fe, and W for the same discharges as shown in Fig. 3. Also indicated in the figure are the Larmor radii of 10 eV O^+ , Fe^+ , and W^+ . The decrease in O for $x \geq 1$ mm, may be due to preferential H^+ bombardment of that area.

Fig. 5. Plot of normalized oxygen concentration across the Ag-coated tape (x-direction) for the probe located at different minor radii, r . The outside limiter was at $r = 45$ cm. The slit was 1.5 mm wide. A, B, and C are discussed in the text.

Fig. 6. Time resolved fluxes of C and O to the tape during a beam heated discharge. The plasma current, I_p , and the time when the beam was on, are both indicated in the lower left. The time period 300 to 600 ms is expanded on the right showing more clearly that the increase in O is in synchronism with the beam heating.

Fig. 7. Oxygen x-scans for the same discharge as shown in Fig. 6. The four different curves in (7) correspond to the four symbols in the upper left of (6). The solid curve, the pre-pulse feature, shows behavior expected for neutral O impact. The fall-off of the $\circ$, Δ , and $\bullet$ Oxygen signals for $x > 1$ mm may be due to H^+ impacts. The large Δ and $\circ$ signals at $x \leq -2$ mm are probably due to neutral oxygen.

Fig. 8. Optical and SE micrographs of a "melt". Melts occur at the ends of discharges if the probe is inside $r = 48$ cm. The line of droplets that parallels the circumference is probably due to surface tension effects at the boundary. Not all melts are so pronounced. The parallel lines across the bottom of the optical micrograph are scratches in the In film.

Fig. 1. 783346

Fig. 2. 783341

Fig. 3. 783343

Fig. 4. 773690

Fig. 5. 783344

Fig. 6. 783067

14617

Fig. 7. 783345