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Langmuir Probe Measurements in the TEXTOR Tokamak During ALT-I Pump Limiter Experiments

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ABSTRACT

Langmuir probes have been used to characterize the edge plasma of the TEXTOR tokamak and measure the parameters of the plasma incident on the ALT-I pump limiter during ohmic and ICRH heating. Probes mounted directly on the ALT limiter, and a scanning probe located 90° toroidally from the limiter, provide data for the evaluation of pump limiter performance and its effect on the edge plasma. The edge plasma is characterized by density and flux e-folding lengths of about 1.8cm when ALT is the main limiter. These scrape-off lengths do not vary significantly as ALT is moved between the normal 42-46cm minor radii, but increase to over 2.2cm when ALT is inserted to 40cm. The flux to probes at a fixed position in the limiter shadow varies by less than 25% for core density changes of a factor of five. This suggests that the global particle confinement time, τ_p , scales as the core density. Estimates from the probes indicate that τ_p is on the order of the energy confinement time, τ_E . The edge electron temperature, T_e , typically decreases by a factor of two when the core density is raised from 1 to $4 \times 10^{13} \text{ cm}^{-3}$. The T_e profile is essentially flat in the limiter shadow, with values of 10-25 eV depending on the core plasma density and ICRH power. ICRH heating increases the edge electron temperature and flux in proportion to the coupled power. With ALT as the primary limiter and no direct shadowing, the ion side receives 2 to 3 times the flux of the electron side during both ohmic and ICRH heating. The edge plasma is not directly modified by pump limiter operation, but changes with the core plasma density as particle removal lowers the recycling of neutrals in the boundary.

I. INTRODUCTION

The Advanced Limiter Test (ALT-I)¹⁻³ is a pump limiter experiment on the TEXTOR tokamak⁴. The purpose of this experiment is to study the particle removal capabilities of several actively-pumped limiter modules in the long pulse-length plasma of TEXTOR. To understand the pump limiter operation and efficiency in removing particles incident on the entrance slots of several different limiter geometries, a series of probe studies have been undertaken. The Langmuir probes are utilized to measure the scrape-off layer (SOL) plasma parameters such as density, electron temperature, parallel ion flux to the limiter entrance slot, and radial scrape-off e-folding lengths of these respective parameters. Measurements of these values are made both locally at the limiter by probes mounted on and inside the ALT module, and by a scanning probe positioned 90° toroidally from ALT.

Characterizations of the scrape-off layer plasma by probes have been made in most major tokamaks such as PLT⁵, PDX⁶, ISX-B⁷, DITE^{8,9}, ASDEX¹⁰, Alcator-C¹¹, and TFTR^{12,13}. Probe data has also been used in the interpretation of results from past pump limiter experiments: the Box pump limiter on Macrotor¹⁴, the Scoop on PDX¹⁵, and the Mushroom limiters on ISX-B¹⁶, for example. The ALT experiments have several features not available in these other studies. In particular, TEXTOR is capable of very high recycling from hot walls, and has a pulse length of over 3 seconds which is long compared to the gas flow time constants in the tokamak vessel. Probe data provides information on the TEXTOR SOL plasma and the total ion flux entering the limiter opening. Performance by different pump limiter geometries, and the removal efficiency during active pumping, can then be determined. Additional investigations of the SOL plasma modifications during ICRH auxiliary heating¹⁷ of up to 2 MW have been made and will be discussed.

The TEXTOR tokamak⁴ has been described elsewhere. Typical conditions during ALT experiments are: $R_0=1.75\text{m}$, $a=40\text{-}48\text{cm}$, $I_p=350\text{kA}$, $B_T=2.0\text{ T}$, $n_e=1\text{-}5\times10^{13}\text{cm}^{-3}$, $T_e(0)<1.2\text{keV}$, and $T_i<1\text{keV}$. The liner temperature is normally maintained between 150-300°C, and the walls are carbonized¹⁸ prior to plasma operation. ALT-I is inserted into the TEXTOR edge as

an additional limiter, and has the ability to be moved between shots from 40 to 50cm minor radius. The TEXTOR limiters are also movable, and are normally retracted to a 48cm radius during the ALT program.

II. EXPERIMENTAL ARRANGEMENT

ALT has three different limiter modules, each of which can be mounted on the common manipulator and pumping system. The "closed" pump limiter geometry, with a low conductance for neutral gas to escape to the plasma and named ALT-VG, is shown schematically in Fig.1. The more "open" geometry, named ALT-FG2 and shown schematically in Fig.2, features two-sided collection and a higher conductance for backflowing gas. The ALT-FG1 is similar in design to the ALT-FG2, having a different neutralizer plate geometry but identical probes. The views of ALT in Figs.1 and 2 show the probe locations for the two modules. ALT-VG has five fixed probes, located between the entrance into the limiter and the plasma neutralization plate. The probe mounted exterior to the throat region (called the EXALT probe), is used to measure the plasma parameters at the entrance to the limiter. The three throat probes are staggered radially in the same poloidal plane to provide rough information on the scrape-off lengths locally at ALT. The combination bolometer-Langmuir probe at the neutralizer plate has a thermocouple attached to measure the heat flux striking the neutralizer region. The ALT-FG2 module has two probes centered in the entrance slot and facing in the ion and electron directions. The ALT-FG2 probes are of the same design as the EXALT probe.

The probe design was determined largely by the high heat flux and long pulse length requirements of being part of the primary limiter in TEXTOR. ALT is designed to handle up to 1MW of power for 3 seconds. Preliminary analysis indicated that passively cooled molybdenum probes located at the entrance slot must have a diameter of at least 4mm in order remain below the temperature for thermionic electron emission during the TEXTOR pulse. The single, flat faced probes shown in Fig.3a, with a Mo shield to eliminate collection from the sides and back, were installed to measure the parallel ion flux, density, and electron temperature of the plasma flowing

into the entrance of ALT. The fact that the probes are mounted directly on a very large limiter means that they are shadowed at the rear and receive flux from the plasma facing side. It will be shown in Section V that the probes in the entrance are sufficiently close to the plasma neutralization plate in the limiter shadow to correctly measure the incident flux into the entrance slot. The probe collection area is well determined by the shield opening, and any backflowing plasma that might be generated by ionization in the throat region is collected on the shield. The shield and the entire ALT limiter float relative to the rest of TEXTOR, and act as the reference electrode¹⁹ in the probe circuit.

The scanning Langmuir probe, modified from a deposition probe²⁰ and located 90° toroidally from the ALT position on the horizontal midplane, is shown in Fig. 3b. This probe is not positioned on the field line that intersects ALT directly, and like ALT has a very long connection length (several times around the torus when ALT is the primary limiter) to other limiters. The probe head is made of graphite, with the plasma collected by a biased Ta electrode positioned behind the aperture. The Ta electrode is thermally isolated from the structural support, and also acts as a bolometer to measure the parallel heat flux in the SOL. Measurements of the heat flux and the power scrape-off length will be reported elsewhere.²¹ The scanning probe floats relative to the limiters and liner in TEXTOR, and acts as a double probe of greatly unequal areas.

The probes are driven by identical sets of electronics coupled to a common data acquisition system. The probe bias is supplied by bipolar power supplies, which are driven by a linear ramp from a common programmable function generator. It is therefore a simple matter to check the linearity of the voltage sweeps with the computer and detect noise induced distortions. Voltage sweeps of $\pm 60\text{V}$ for 2-5msec are typically used. Precision shunt resistors are used to detect the probe current, and high impedance voltage dividers monitor the probe bias. The probe signals are optically isolated from the Camac Crate data loggers at TEXTOR diagnostic ground. Each system was tested for 20kHz operation and up to 1.5kV isolation, with special care taken to avoid ground loops. The bipolar power supplies current limit probe arcs, eliminating possible melting of the probe tips by arcing during the long pulse lengths. The problem of the circuit

breakers tripping on the Kepco bipolar power supplies was eliminated by disabling a remote-control shut-off option that was sensitive to rf noise and common-mode voltage jumps which occur during disruptions.

An example of the line averaged core plasma density from a standard discharge, and the associated ion saturation current signal from the EXALT probe, is shown in Fig.4. The probe data loggers are normally operated in the burst acquisition mode during the probe voltage sweep period to decrease the data memory requirements, resulting in the short gaps in the trace. The typical level of oscillations in the ion saturation current ($\delta I/I$) is 20-30%. Closing the throat to ALT allows examination of the noise pickup by the throat probes, which is found to be negligible even during ICRH heating. Electron temperature data is obtained by initiating the voltage sweeps during the data acquisition periods and evaluating the current-voltage curves. Up to 300 traces from the six probes are stored and analyzed for each shot.

III. PROBE SIGNAL ANALYSIS

Proper analysis of the local plasma parameters in tokamak SOL plasmas from Langmuir probe *I-V* characteristics has received considerable attention in recent years. The standard theory described by Chen²² has been widely used to evaluate the plasma density and electron temperature from the ion saturation current and voltage sweeps of single and double probes. This technique still works well in certain cases, in spite of some uncertainties due to the effects of strong magnetic fields and edge ion temperatures exceeding the electron temperature. Recent analysis by Stangeby²³⁻²⁵ has refined the modeling of probe characteristics for tokamak edge plasmas. Additional work by Stangeby^{19, 26,27} details the effect of large probes in the SOL plasma and provides techniques to evaluate the local plasma parameters from the probe traces. The probe interpretation described here for the large, flat probes in the shadow of ALT-I has been recently detailed by Stangeby¹⁹.

The current to the single probe in the portion of the current versus voltage characteristic with small electron collection is given by

$$I(V) = \frac{1}{2} n_e e c_s A - \frac{1}{4} (8 T_e / \pi m_e)^{1/2} n_e e A \exp[-(V-V_p)/kT_e] , \quad (1)$$

where $c_s = [k(T_e + T_i)/M_i]^{1/2}$, n_e is the plasma density, A is the probe collecting area, V_p is the plasma potential, and T_e and T_i are the electron and ion temperatures respectively. The ion and electron temperatures have been assumed to be equal in our calculations. Stangeby's model²³ accounts for the strong reduction in the electron current due to the magnetic fields by introducing an electron diffusion parameter "r" in the $I(V)$ equation. This model need not be included in our case unless fits to the large electron current region of the probe characteristic are needed²³. Equation 1 is used in our analysis to determine density and electron temperature by a least squares fitting routine over the portion of the I-V characteristic between ion saturation current and the floating potential where the electron flux follows a simple exponential in T_e and the ion saturation current is constant. The quality of the fitting is normally checked by an interactive program, and the routine provides density data from the probes that agrees very well with data from a Li-beam probe²⁸.

IV. SCRAPE-OFF LAYER CHARACTERIZATION

The scanning probe has been used to characterize the SOL parameters and e-folding lengths. The standard procedure is to position ALT at a fixed minor radius, retract the other TEXTOR limiters, and take several shots until reproducible discharges are achieved. The probe is then scanned during successive shots at 1/2 cm intervals from the main limiter location at 48 cm to within 1 cm of the ALT tangency point. The data presented in this section is with ohmic heating only. The profiles of the average ion saturation current, density, and electron temperature, evaluated at 0.8sec, are shown in Fig.5 for ALT at 40cm and a constant line averaged density of $3 \times 10^{13} \text{cm}^{-3}$. The flux and density have the identical e-folding lengths of about 2.2cm, but the T_e profile is essentially flat. Equal flux and density e-folding lengths, and flat T_e profiles, are

characteristic of all the shots with ALT as the main limiter. A model predicting flat electron profiles in the SOL, as observed in TEXTOR, has recently been published.²⁹

A comparison of the scrape-off lengths for standard ohmic discharges with either ALT or the TEXTOR main limiters inserted is given in Table 1. Operation with the TEXTOR main limiters results in shorter scrape-off lengths compared with ALT because of the larger total poloidal angle subtended by the main limiters. The variation in density scrape-off length scales approximately with the square root of the average connection length to the limiters. Similar results have been obtained from Li-beam³⁰ profiling of the SOL density in TEXTOR.

The variation in the SOL parameters with central line averaged density is shown in Fig. 6 for ALT at 40 cm and the probe positioned at 43 cm. The flux to the probe at a fixed position is insensitive to changes in the core density. The electron temperature characteristically decreases with increasing core density. The values of the electron temperature have been observed to depend on the machine condition, and have varied over the range of 8-20eV with no auxiliary heating. High density, low Z_{eff} discharges with carbonization typically have the lowest edge electron temperatures.

The SOL density and flux e-folding lengths do not vary significantly with core density or ALT position between 42 and 46cm. Fig. 7 shows λ_n derived from the scanning probe data and the Li-beam versus ALT position. Since the SOL density is position dependent and insensitive to the core density, as seen in Figs. 5 and 6, it follows that the scrape-off length for density also does not vary significantly during density scans. The value of λ_n is typically found to be 1.8 ± 0.2 cm for ALT positioned from 42 to 46 cm. Rough estimates of λ_n and λ_T by the three throat probes in ALT-VG produce the same e-folding lengths as measured with the scanning probe. Similar scrape-off length measurements are expected¹⁹ from these probes because the connection lengths to both the scanning probe and ALT are very long, and no direct shadowing by the limiter is observed. Interestingly, impurity scrape-off lengths of about 1.9cm, measured with collection probes, have been reported.³¹ The density scrape-off length measured with ALT positioned at 48 cm is less than 1.3 cm, which is expected from the presence of other limiters located at that

radius. When ALT is inserted to 40 cm, λ_n increases to about 2.2 cm. The tokamak is observed to disrupt much more frequently with ALT at this position. The longer scrape-off lengths and unstable operation may indicate a modification in the confinement associated with the reduction in safety factor, $q(a)$, with deep insertion of the limiter.

V. PLASMA PARAMETERS AT ALT

The probes on the ALT pump limiter modules measure the parameters of the plasma incident on the entrance slot. Information on the ion flux into the limiter is crucial to understanding the particle removal efficiency and its scaling with edge plasma parameters such as density and electron temperature. Estimates of the total ion current into the pump limiter opening, the global particle confinement time and the power to ALT, for example, will be made in Section VII from the following measurements at ALT.

The average ion saturation current measured by the ion and electron side probes at one second into the pulse on the ALT-FG2 as it is inserted into TEXTOR is shown in Fig. 8. The line averaged core density was $3.3 \times 10^{13} \text{ cm}^{-3}$, and the TEXTOR main limiters were retracted to 48 cm. The ion side flux is a factor of 2 to 3 times the electron side flux depending on the position of ALT. The electron temperature on the ion and electron sides is roughly equal and increases as ALT is inserted, as shown in Fig. 9. With ALT-FG2 located at 44 cm, the variation in the collected fluxes with line averaged density is shown in Fig. 10. As with the scanning probe, the flux does not change significantly with core density. However, the electron temperature, plotted in Fig. 11, decreases by about a factor of two as the density is increased from 1.5 to $4 \times 10^{13} \text{ cm}^{-3}$.

The probes on ALT-VG, which has only ion side collection but many more probes, give similar results to those on the ALT-FG2. The flux and electron temperature dependence on line averaged density for ALT-VG inserted to 42 cm is shown in Fig. 12. The flux is fairly constant as the core density changes, and varies typically by about 25% over the core density range of 1 to $5 \times 10^{13} \text{ cm}^{-3}$. The electron temperature again decreases by a factor of two over this density range. The average local plasma density at the probe is about $2.8 \times 10^{12} \text{ cm}^{-3}$, calculated from Eq. 1 and

the data in Fig.12 at an average core density of $3 \times 10^{13} \text{cm}^{-3}$. Since the density e-folding length is the same as the flux e-folding length over the slot opening, and electron temperature is shown in the figures, it is simple to calculate the local plasma density along the entrance of the slot for any core density. It is clear from the data shown here that at a given minor radius with ALT as the main limiter, the edge flux and density vary by only about a factor of a square root of 2 during TEXTOR density scans.

The effect of introducing pumping by ALT-I is to change the core density by reducing the recycling.^{1,2} The SOL parameters follow the core density changes as described above, but are not significantly modified directly by the pumping. This is illustrated in Fig.13, where the ion saturation current to the EXALT probe is plotted versus the line averaged density for several different pumping speeds. Despite an increase in the pumping speed from 1000 l/sec to 7,000 l/sec, the flux follows the same relationship with the core density. The flux measured by the EXALT probe is also shown to be the same at a given core density with the entrance flap open or closed. This means that the probe is sufficiently close¹⁹ to the limiter (1cm with the flap closed) or neutralizer plate (25cm) to correctly measure the incident plasma flux. Since the pre-sheath length is estimated to be a few meters for the SOL plasma in TEXTOR, entrance probe measurements made 25 cm from the neutralizer plate are relatively deep in the pre-sheath potential and far from the flow stagnation region. Modifications in the flow velocity near the throat region by fluid effects are not observed or expected.

The SOL electron temperature at a given core density is primarily determined by machine conditions, such as amount of carbonization and impurity level. In general, the local value of T_e at ALT increases by 2-5eV with pumping at a given core density, but any systematic dependence of T_e with pumping speed has not been established. This is because 2eV is typically on the order of the reproducibility of the temperature measurements, and variations with machine conditions have been difficult to isolate. However, these measurements indicate that the local plasma density in the SOL is not decreased significantly during pumping by ALT. Strong modifications of the SOL plasma by pumping are not expected, in any case, because ALT removes only a small

amount of the core efflux. The SOL plasma parameters are determined by global edge processes and not by small local changes due to ALT.

To check the poloidal symmetry of the flux into the slot, the EXALT probe and the middle probe of the three throat probes were positioned at the same minor radius, but near the top and bottom of the entrance of ALT-VG. Examinations of these probe fluxes have been made for core density scans at different ALT-I radial positions. *There is no systematic variation in the poloidal symmetry of the flux into the slot over the extent of limiter opening.*

VI. ICRH HEATING MODIFICATION OF THE BOUNDARY PLASMA

ALT-I is located 45° toroidally from two half turn ICRH antennae with an innermost radius of 48.8 cm. Initial studies of the effect of ICRH heating on the SOL plasma are illustrated in Fig. 14, which shows the average flux to ion and electron side probes for a plasma radius of 44cm, determined by ALT-FG2, and $n_e = 3.4 \times 10^{13} \text{cm}^{-3}$. The ICRH heating pulse results in an increased flux of particles to both sides of ALT. The magnitude of the increase depends on the ICRH power level. The electron temperature in the SOL also increases during the low power heating pulse of Fig. 14, from an initial value of 12eV to about 15-18eV. Recent high power shots with 2MW of ICRH have resulted in electron temperature increases of over a factor of two to 26eV. Systematic investigations are underway at this time to characterize the SOL modification with ICRH power level.

VII. DISCUSSION

a. Total Current Collected by ALT

The total ion current into the pump limiter opening can be calculated from the probe measurements of the flux, its radial scrape-off length, and its poloidal distribution. The total ion current into ALT, I , is then given by

$$I = \int \Gamma_{\parallel} dA = \int d\theta \int \Gamma(r) r dr, \quad (2)$$

where the integrations are over the entrance openings, $\Gamma_{||}$ is the parallel flux in the SOL, r is the minor radius, A is the area of the entrance slot, θ is the poloidal extent of the opening. The radial flux dependence is

$$\Gamma(r) = \Gamma_a \exp [-(r-a)/\lambda_r] , \quad (3)$$

Γ_a is the parallel flux at the limiter tangency point, a is the minor radius to the ALT tangency point, and λ_r is the flux scrape-off length. For ALT, the slot subtends about 30° of the poloidal arc. The parallel flux at the tangency point in terms of the probe flux Γ_p is simply

$$\Gamma_a = \Gamma_p \exp (x / \lambda_r) , \quad (4)$$

where x is the distance from the ALT tangency point to the probe radius.

With the flux approximately poloidally symmetric, Eq.2 is easily integrated over the entrances of the different ALT geometries to give

$$I = \frac{\Gamma_a}{2} \left[(r' + a) \lambda_r + \lambda_r^2 \right] \exp(-r'/\lambda_r) \bigg|_{r_1}^{r_2} , \quad (5)$$

where r_1 and r_2 are the radii of the entrance slot edges. The total ion current into the entrance as a function of the EXALT probe flux is calculated from Eq.5 in Table II for the different ALT modules with one sided collection only. If both sides of the ALT-FG2 are open for collection, then the total flux must have the weighted current from the electron side added. Note that two sided collection by ALT-FG2 at 44 cm is within 20% of the 88A collected by the one sided ALT-VG at 42 cm. The comparable collection at different radii results from the shorter distance from the tangency point to the slot opening and two sided collection for ALT-FG2. This advantage of the ALT-FG2 geometry is offset by the high leading edge heat loading which limits the total power that the limiter can handle.

b. Global Particle Confinement Time

Probe measurements of the ion flux to the limiter, and the e-folding lengths, can be used to estimate the value of a global particle confinement time, τ_p , for the particles in the core plasma. The total core efflux can be expressed as

$$\Gamma_c = N_e / \tau_p \approx \bar{n}_e V / \tau_p, \quad (6)$$

where N_e is the total number of particles in the TEXTOR plasma, $\bar{n}_e$ is the line averaged core density, and $V = 2\pi^2 R a^2$ is the plasma volume. During ALT experiments in TEXTOR, N_e found from integration over the density profile is typically within 10% of $\bar{n}_e V$.

In the evaluation of τ_p , we will use two models of the SOL plasma in an effort to bound the value of the core efflux in Eq. 6 from the probe information. As a first case, simply assume that the flux scrape-off length is constant up to the limiter tangency point. The total flux collected by the limiter is then

$$\Gamma_L = \int d\theta \int \Gamma(r) r dr = \int d\theta \int \Gamma_a \exp[-(r-a)/\lambda_r] r dr, \quad (7)$$

where the θ integration is over the limiter poloidal extent. This equation describes the collection on the ion or electron side, and the asymmetries are accounted for by integrating the flux to each side and adding for the total when evaluating Γ_a . Since the ion side receives about 2.5 times the electron side flux in all cases with ALT, this evaluation can be accomplished by simply multiplying Γ_p (ion side) by 1.4. Integrating Eq.7 over the SOL from the tangency point to the TEXTOR liner results in

$$\Gamma_L = 0.22 \pi \lambda_r (a + \lambda_r) \Gamma_a. \quad (8)$$

The total core efflux is given by

$$\Gamma_c = \Gamma_L + \Gamma_w, \quad (9)$$

where Γ_W is the flux that missed the ALT limiter and hit the main limiters, the ICRH antenna guard ring, and the liner. A calibrated H_α detector positioned to observe the main limiter at $a=48$ cm, and H_α detector arrays observing the liner and antenna, indicate during ALT operation at 44cm that Γ_W is about 1/3 of Γ_L . For ALT positioned between $a=42$ and 44cm, the other limiters are 2.5-3 e-folding lengths behind the tangency point and ALT, therefore, collects a large fraction of the core efflux.

Generally, $\lambda_T / a \ll 1$, and Eqs. 6, 8 and 9 can be combined to express τ_p as

$$\tau_p = 6.9 \pi \frac{R a \bar{n}_e}{\lambda_T \Gamma_a} . \quad (10)$$

While simply assuming a constant λ_T over the entire SOL limits the accuracy of Eq.9, the scaling with machine and SOL parameters of interest is clearly illustrated. As shown in Sec.4 and 5, the flux to the probes does not vary significantly during a core density scan for a fixed ALT position. Therefore, τ_p scales linearly with the line averaged plasma density in TEXTOR.

It is possible to improve the simple model used above to calculate the total core efflux. The probes measure a constant λ_T to within about 1-2 cm of the ALT tangency point. Recent analysis indicates that strong variations in the electron temperature exist at the limiter surface near the tangency point²⁸. Additionally, Thomson scattering measurements show electron temperatures of 30-50eV near the tangency point for ALT at 44cm. A reasonable model²⁸ of this electron temperature variation is

$$T_e(r) = T_{e1} \exp[-(r-a)/\lambda_T] + T_{e2} , \quad (11)$$

a pedestal model with T_{e2} equal to the probe measurements in the SOL, $T_{e1} + T_{e2}$ equal to the tangency point the tangency point electron temperature estimate, and $\lambda_T = 1$ cm. This approximate value of λ_T is suggested by the heat flux measurements made on the face of ALT with IR cameras.

The probe and Li beam measurements give

$$n(r) = n_a \exp [-(r-a)/\lambda_n] , \quad (12)$$

which is assumed to be valid up to the tangency point. Since the flux scales as $nT_e^{1/2}$, the radial variation in flux is

$$\Gamma(r) = \Gamma_a (T_{e1}/T_e(a))^{1/2} \exp[-(r-a)/\lambda_n] \{ \exp[-(r-a)/\lambda_T] + T_{e2}/T_{e1} \}^{1/2}, \quad (13)$$

valid for $r \geq a$. The limiter flux, from Eqs. 4 and 7, is then

$$\Gamma_L = 0.68 \int_p \exp(x/\lambda_T) (T_{e1}/T_e(a))^{1/2} \exp[-(r-a)/\lambda_n] \{ \exp[-(r-a)/\lambda_T] + T_{e2}/T_{e1} \}^{1/2} r dr. \quad (14)$$

This must be numerically integrated from the tangency point to infinity. The results are shown in Table III for some reasonable cases for the electron temperatures. The heat fluxes included in Table III will be calculated in the next section. The result of the simplified analysis of Eq.10 is recovered in the first example by proper selection of T_{e1} and T_{e2} . It is interesting to note that a large variation in the electron temperature at the tangency point leads to only a 30% change in the evaluation of the core efflux, but almost a factor of four change in the heat flux.

It is now possible to calculate the particle confinement time by substituting the results from Eq.14 into Eqs. 6 and 9. Using the density scan data in Fig.10, and accounting for both the ion and electron sides, τ_p is plotted in Fig.15 versus the line averaged density. The range in the values of τ_p results from different the electron temperatures that we have used to estimate the total particle flux to the limiter in Table III. The highest values for τ_p are calculated assuming $T_e = 15\text{eV}$ and a flat electron temperature profile that extends to the tangency point. The lowest values for τ_p are for the extreme case of $T_e(a) = 100\text{ eV}$ and $\lambda_T = 0.5\text{ cm}$. Values for $T_e(a)$ from Thomson scattering and the limiter heat flux calculations (next section) are in the range of 30-60eV, and τ_p is estimated to lie within the hashed area of Fig.15. The global particle confinement time is linearly proportional to the density over the density range from 1 to $4 \times 10^{13} \text{cm}^{-3}$. For comparison, τ_E scaling typical of TEXTOR density scans³² is also plotted. The values of τ_p are on the order of and slightly larger than the energy confinement time.

Scaling of τ_p from H_α intensity measurements over the volume of other tokamak plasmas have been reported. During ohmic heating in Alcator-A³³ and JET³⁴, τ_p proportional to the core density was observed for $\bar{n}_e$ below a critical density. As the density was increased beyond this value, τ_p was found to decrease in both experiments. This behavior of τ_p at higher density was interpreted to be caused by the edge plasma becoming opaque to neutrals. Recycling then takes place predominantly in the edge, decoupling τ_p from the core plasma. In TEXTOR, the ionization mean-free-path for 1-2eV H neutrals from the limiter surface³⁵ is estimated to be on the order of 10cm for the highest core densities of Fig.10. This is not sufficiently short to confine the recycling to only the edge plasma, indicating that the critical density has not yet been achieved. Therefore, the behavior of τ_p observed from the probe measurements follows the same density scaling reported from H_α measurements in other machines in the proper density range.

It is of interest to apply this analysis from the probe data for τ_p during ICRH heating. From Eq.9, τ_p is seen to scale inversely with both the probe flux and SOL flux e-folding length. The data in Fig.14 during ICRH shows that the probe flux is proportional to the power coupled to the plasma. The edge e-folding lengths are also observed^{17,32} to broaden during ICRH heating. It follows that τ_p decreases as the ICRH power level increases. The reductions in τ_p are estimated from initial studies to be similar to the changes in τ_E reported⁴ during ICRH heating.

c. Limiter Heat Flux

The parallel heat flux density to the ALT limiter is given by

$$q(r) = \gamma_s T_e(r) \Gamma_p(r), \quad r \geq a \quad (15)$$

where γ_s is the total sheath transmission factor for ions and electrons. For the assumption of equal ion and electron temperatures, γ_s is calculated²⁷ to be 6.5. Utilizing the pedestal model with Eqs. 11 and 13, the total heat flux to the limiter is

$$Q = 4.5 \int \Gamma_p \exp(x/\lambda_T) T_{e1}^{3/2} T_e(a)^{-1/2} \exp[-(r-a)/\lambda_n] \{ \exp[-(r-a)/\lambda_T] + T_{e2}/T_{e1} \}^{3/2} r \, dr. \quad (16)$$

The results of a numerical integration of Eq.16 are included in Table III for $a=44\text{cm}$. Estimates of the power to ALT at this radius from thermocouple measurements of the bulk temperature rise indicate that ALT typically receives 10-30 percent of ohmic power. This is in reasonable agreement with the values calculated in Table III for $T_e(a)$ on the order of 50eV.

Detailed analysis³⁶ of the heat flux to ALT, as measured by an IR camera,³ has been made for the limiter positioned at 40cm. ALT is typically found to collect 150kW of power during this deep insertion into the plasma. The EXALT probe flux during these runs was 1.4A/cm^2 . Using the ion to electron side asymmetry of 3 to 1 and density e-foldings of 2.2cm, the power to ALT calculated from Eq. 16 is shown in Fig.16. Two possible temperature e-folding lengths are shown. The electron temperature required at the tangency point to predict the measured 150kW power deposition is about 50-60eV. This is in good agreement with the values estimated from Thomson scattering. If the flat T_e profile with 15eV up to the tangency point is used, the power deposition is a factor of three too low. The pedestal model with a reasonable value for $T_e(a)$ predicts the correct power flux to ALT.

d. Perpendicular Diffusion Coefficient

From probe measurements, a simple estimate of the perpendicular diffusion coefficient, $D_\perp$, in the SOL plasma can be made. The average core efflux over the plasma surface area S is equal to the perpendicular flux at the edge,

$$\frac{\Gamma_c}{S} = -\nabla \Gamma_i = D_\perp \frac{dn}{dr} \quad (17)$$

Approximating the gradient scale length as $n_e(a) / \lambda_n$, using Eqs. 8 and 9 for the core efflux, and taking λ_T equal to λ_n , the perpendicular diffusion coefficient is

$$D_\perp = \frac{\lambda_n^2 \Gamma_a}{14\pi R n_e(a)} \quad (18)$$

From the expression for the ion current term in Eq.1, the flux Γ_a is $n_e(a) c_s / 2$, and Eq. 18 becomes

$$D_{\perp} = \lambda_n^2 c_s / 28R, \quad (19)$$

where c_s is evaluated at the limiter tangency point. If we assume that the electron temperature at the limiter tangency point is 30eV, and the edge density scrape-off length is 1.8 cm, then the perpendicular diffusion coefficient from Eq.12 is 5.1×10^3 cm²/sec. The Bohm diffusion coefficient evaluated for this value of T_e , and TEXTOR magnetic field of 2.0T, is 9.4×10^3 cm²/sec. Within the accuracy of this simple calculation the diffusion of the edge plasma is consistent with Bohm diffusion values.

d. Pump Limiter Physics

Measurements of the plasma parameters in the ALT throat provide information on the physics which occurs in the pump limiter. As shown above, typical plasma densities of $1-5 \times 10^{12}$ cm⁻³ and electron temperatures of 8-25eV are measured by the probes on ALT. The electron temperature inside the throat region is essentially unchanged from the edge plasma in the boundary of TEXTOR. Fig.17 shows T_e from the probe at the neutralizer plate plotted against T_e found from the EXALT probe during the density scans of Fig.13. No consistent difference in the electron temperature is found. Since the EXALT and scanning probe values of T_e are generally the same, Fig.17 indicates that the recycling which occurs at ALT and the neutralizer plate does not strongly modify the local plasma. This result has led to recent modeling of ALT³⁷ which assumes constant plasma parameters in the throat region, and which correctly predicts the pressure rise in the pump limiter.

VIII. Summary

Langmuir probes have been used to determine the total flux into the pump limiter and the local density and electron temperature in the SOL and limiter throat. In TEXTOR, equal density and flux scrape-off lengths of about 1.8 cm have been measured while ALT is the primary limiter positioned between 42-46 cm. These e-folding lengths increase to over 2.2 cm when ALT is inserted to 40 cm. The perpendicular diffusion coefficient in the boundary of TEXTOR is found to be consistent with Bohm diffusion, and is about $5 \times 10^3 \text{ cm}^2/\text{sec}$. Flat electron temperature profiles in the SOL are observed for all ALT experiments with ohmic heating, with T_e ranging from 8 to 20 eV. The electron temperature characteristically decreases as the core plasma density is raised during density scans.

The flux to the probes in the shadow of the limiter is insensitive to the core density, indicating that τ_p is proportional to $\bar{n}_e$ over the density range of these experiments. This behavior of τ_p has been observed from H_α measurements in other machines below a critical density at which the recycling becomes localized in the edge. It appears that this critical density was not achieved during the experiments reported here. The values of τ_p estimated from the ALT probe measurements agree remarkably well (within about 20%) with recently published values by Samm³⁰ derived from separate H_α and spectroscopic measurements in TEXTOR. The pedestal model, and the IR camera measurements of the power loading to ALT, results in predictions of tangency point electron temperatures of about 50 eV, in good agreement with the measurements by Thomson scattering.

The fact that τ_E scales with $\bar{n}_e$ in the ohmic heating phase implies that τ_p is proportional to τ_E . Systematic investigations of this confinement time behavior during ICRH auxiliary heating are now underway. However, τ_p is found, in the initial experiments reported here, to decrease with increasing ICRH power. This is consistent with the observed decrease of τ_E with ICRH power, although a scaling law of τ_p with ICRH heating is not yet available.

Finally, pump limiter operation does not directly affect the SOL plasma during ohmic heating. Operation with pumping and particle removal decreases the line averaged core plasma

density by changing the recycling at the boundary. The flux to the limiter and the edge T_e follow the changes in the core density.

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REFERENCES

1. A.E.Pontau, et al., J. Nucl. Mat., 128&129 , 434 (1984).
2. K.H.Dippel, et al., Plasma Physics and Controlled Nucl. Fusion Research (Proc. 10th Intl. IAEA Conf., London 1984), Vol. 1, IAEA Vienna (1985).
3. G.J.Thomas, et al., J. Vac. Sci. Tech, Proc. American Vac. Soc., Fusion Tech. Div. Meeting, Houston, Texas (1985), to be published.
4. J.Schluter, et al., and V.P.Bhatnagar, et al., Nucl. Fusion, 25, 1065 (1985).
5. R. Budny, J. Vac. Sci. Tech., 20, 1238 (1982).
6. R. Budny and D. Manos, J. Nucl. Mat., 121, 41 (1984).
7. A.J. Wootton, K.E.Yokoyama, and P.H. Edmonds, ORNL Report TM-8938, (1985).
8. G.M.McCracken, et al., J.Nucl.Mat.,128&129 , 150 (1984).
9. G.Proudfoot, P.J.Harbour, J.Allen, A.Lewis, J.Nucl.Mat.,128&129 , 180 (1984).
10. M. El Shaer, "Probe Measurements in the ASDEX Boundary Layer and the Effect of Neutral Beam Injection and Lower Hybrid Heating," Max-Planck Institut fur Plasmaphysikk Report, IPP III/96, Garching bei Munchen, April 1984.
11. B.LaBombard, et al., Bull.Am.Phys.Soc.,30,1413 (1985).
12. D.Manos, R.V.Budny, S.A.Cohen, J.Vac.Sci.Tech. A, 1 , 845 (1983).
13. R.Budny, et al., Bull. Am. Phys. Soc., 30 , 1523 (1985).
14. S.Talmadge, et al., Nucl. Fusion, 22 , 1369 (1982).
15. R.Budny, et al., "Initial Results from the Scoop Limiter Experiment in PDX", Plasma Physics Laboratory Report, PPPL-2061, Princeton University, Dec.1983.
16. P.K.Mioduszewski, et.al., J.Nucl.Mat., 121, 285 (1984).
17. A.M.Messiaen, et.al.. Plasma Physics and Controlled Fusion, 28, 71 (1986).
18. J. Winter, et al., J.Nucl.Mat.,128&129 , 841 (1984).
19. P.C. Stangeby, J. Phys. D: Appl. Phys.,18 , 1547 (1985).
20. R.A.Zuhr, Proc. 8th Conf. on Appl. of Accelerators in Research and Industry, November 12-14, 1984, Denton, Texas.

21. W.R.Wampler, to be published.
22. F.F.Chen, "Electric Probes," in *Plasma Diagnostic Techniques*, edited by R.H.Huddelstone and S.L.Leonard (Academic Press, New York) p.113-200.
23. P.C.Stangeby, J.Phys. D, 15 , 1007 (1982).
24. P.C.Stangeby, Phys. Fluids, 27 , 682 (1984).
25. P.C.Stangeby, J. Nucl. Mat., 128 & 129 , 969 (1984).
26. P.C.Stangeby, J. Nucl. Mat., 121 , 36 (1984).
27. P.C.Stangeby, Phys. Fluids, 28 , 644 (1985).
28. E.Hintz and P.Bogen, J.Nucl.Mat.,128&129 , 229 (1984).
29. A.K.Prinja and R.W.Conn, J.Nucl.Mat.,128&129 , 135 (1984).
30. U.Samm, et al., Proc. IEEE Conf.Plasma Sci., Austin, Texas, Nov. 1985, to be published in IEEE Journal of Plasma Science, 1986.
31. R.A.Zuhr and W.R.Wampler, J. Vac. Sci. Tech., Proc. 31st Natl. Symp. American Vac. Soc., Reno, Nevada, Dec. 4-7, 1984.
32. G. Waidmann, et al., Plasma Physics and Controlled Nucl. Fusion Research (Proc. 10th Intl. IAEA Conf., London 1984), Vol. 1, IAEA Vienna (1985).
33. E.S.Marrar, J. Nucl. Mat., 76&77 , 59 (1978).
34. J.G.Cordey, et al., Plasma Physics and Controlled Nucl. Fusion Research (Proc. 10th Intl. IAEA Conf., London 1984), Vol. 1, IAEA Vienna (1985).
35. S.A.Cohen, J. Nucl. Mat., 76&77, 68 (1978).
36. R. McGrath, to be published.
37. G.A.Campbell, et al., submitted to Phys.Rev.Lett., April 1986.

TABLE I. Comparison of the scrape-off lengths for standard limiter positions in TEXTOR.

ALT Position (cm)	Main Limiters (cm)	λ_n (cm)	λ_{Te} (cm)
44	48	1.9	>10
50	45	1.3	4.5

TABLE II. Total ion current into one side of the ALT module openings as a function of the measured probe fluxes for several standard positions.

MODULE	a (cm)	x (cm)	λ_r (cm)	Geometric Area (cm ²)	I (Amperes)
ALT-VG	40	3.5	2.25	69	67.7 Γ_p
ALT-VG	42	3.5	1.8	69	73.8 Γ_p
ALT-VG	44	3.5	1.8	69	77.1 Γ_p
ALT-FG2	43	2.0	1.8	48	45.2 Γ_p
ALT-FG2	44	2.0	1.8	48	46.2 Γ_p

TABLE III. Particle and heat fluxes calculated for ALT-FG2 operation for reasonable values of the electron temperatures in the pedestal mode!

$$a = 44\text{cm} \quad \lambda_n = 1.8\text{ cm} \quad P_{OH} \approx 350\text{kW} \quad T_e(a) = T_{e1} + T_{e2} \quad \Gamma_p \approx 1.3\text{A/cm}^2$$

T_{e1} (eV)	T_{e2} (eV)	λ_T (cm)	Γ_a (A/cm ²)	Total Efflux (particles/sec)	Total Heat Flux (kilowatts)	%Ohmic (%)
15	0	∞	4	1.33×10^{21}	21.4	6.1
25	15	1	5.8	1.5×10^{21}	41.1	11.7
35	15	1	6.3	1.55×10^{21}	49.5	14.1
85	15	0.5	9.7	1.76×10^{21}	78.1	23.3

FIGURES

1. ALT-VG schematic view indicating the general geometry and the probe locations.
2. ALT-FG2 schematic view showing only the head and the location of the two probes, each on the horizontal midplane and facing in the ion and electron drift directions.
- 3a. Design of the fixed probes attached to the ALT modules. Large probe design was determined by the power loading expected in TEXTOR.
- 3b. Geometry of the scanning probe head and the probe electrode. The probe body was allowed to float relative to the rest of TEXTOR.
4. Standard shot showing the line average density in TEXTOR and the ion saturation current collect by the EXALT probe on ALT.
5. Profiles of the flux, density and T_e versus radius from the scanning probe. Data was taken with a constant line averaged core density of $3 \times 10^{13} \text{ cm}^{-3}$, ALT positioned at 40cm, and the main limiters retracted to 48cm. The values of λ_T and λ_n are characteristically equal in the SOL.
6. Scanning probe flux, density, and electron temperature versus line averaged core density for ALT at 40cm and the probe at 43cm.
7. Density e-folding length in the SOL versus position of the ALT limiter. The value of λ_n does not change with ALT position between 42 and 46 cm, and increases only when ALT is inserted to 40 cm. Data from the scanning probe agrees well with the Li-beam values.
8. Ion and electron side probe flux versus ALT-FG2 position. Data was taken for a constant line averaged density of $2 \times 10^{13} \text{ cm}^{-3}$.
9. Electron temperature from the ion and electron side probes as ALT-FG2 is inserted into the plasma with a line averaged density of $3 \times 10^{13} \text{ cm}^{-3}$.
10. Density scan dependence of the probe fluxes on the ion and electron sides of ALT-FG2 at a position of 44 cm.
11. Electron temperature measured by the ion and electron side probes during a density scan with ALT-FG2 inserted to 44 cm.

12. Flux and electron temperature measured by the EXALT probe for ALT-VG at 42cm during a density scan.
13. EXALT probe flux to ALT-VG for a scan of the line averaged core density. Variations in the pumping speed and flap position do not change the measured flux at a given core density.
14. Average probe current on the ion and electron facing sides during ICRH heating. The measured flux increase is proportional to the ICRH power level.
15. The global particle confinement time τ_p and energy confinement time τ_E in TEXTOR versus the line averaged density, evaluated from the probe measurements in the SOL. Range in τ_p results from uncertainty in the electron temperature profile near the limiter surface when evaluating the total core efflux.
16. Power deposition on ALT at 40cm calculated from the probe data and the pedestal model. IR camera measurements indicated that about 150kW is actually deposited, indicating that $T_e(a)$ is about 50-60eV.
17. The electron temperature measured at the neutralizer plate probe versus the electron temperature from the EXALT probe. The value of T_e is essentially constant along the field line in the ALT throat inspite of recycling occuring at the neutralizer plate.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

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Figure 11

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Figure 13

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Figure 16

Figure 17