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Low Energy Neutral Outflux from the PLT Tokamak

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ABSTRACT

A time-of-flight system has been developed to measure the energy spectrum of neutral deuterium atoms emitted from the PLT tokamak plasma in the energy range 20 - 1000 eV. D^0 neutrals are mechanically chopped by a rotating 25 cm OD stainless steel disc with 24 .025 cm wide slots photo-etched at an 11.4 cm radius. The gated neutrals free stream 181 cm where they impinge on a Cu-Be disc, thereby ejecting secondary electrons which are collected and amplified by an electron multiplier. Since the energy dependence of the Cu-Be secondary emission coefficient as well as the multiplier gain are known from prior calibration, quantitative D^0 fluxes can be determined.

The time evolution of the D^0 outflux emission spectra, $d\Gamma/dE d\Omega$, has been measured for low density, ohmically heated PLT discharges. Our data, which covers the energy range 28 - 1000 eV, represents the first measurements of tokamak neutral outflux below 100 eV. For D^0 energies above 100 eV, we find $d\Gamma/dE d\Omega$ vs particle energy monotonically decreases, typically in an exponential fashion. Early in a discharge, $d\Gamma/dE d\Omega$ is weighted towards low energy. Plasma edge temperatures, deduced from the falloff rate of $\ln[d\Gamma/dE d\Omega]$ vs E for $E < 300$ eV, are 52, 89, and 119 eV at 40, 100, and 200 msec, respectively. Concurrent with this rise in mean energy the total particle flux $\Gamma = \int dE \int d\Omega (d\Gamma/dE d\Omega)$ falls by a factor of 25. Throughout these ohmically heated discharges the charge exchange power loss away from the limiter is a small fraction, less than 2%, of the ohmic heating power; the charge-exchange particle loss away from the limiter is relatively unimportant in particle balance; the bulk of the particle emission is typically at energies below 200 eV.

I. Introduction

Measurement of the outflux of neutral atoms is an important tool in understanding the particle and energy confinement properties of hot, magnetically confined tokamak plasmas. Typically these deuterium atoms have adequate energy to sputter heavy atoms from the vacuum vessel wall, and so also act as a mechanism for injection of impurities back into the plasma. In addition, the energy spectrum of neutral outflux is an important tool in understanding plasma recycling, which determines the effectiveness of gas programming as a control of plasma density.

Gas stripping cells followed by magnetic and electrostatic analysis of the positively charged ions have long been used to energy and momentum analyze plasma neutral atomic outflux at energies above 1000 eV.¹ In this energy range of a few keV and above, most D^0 atoms, produced by charge exchange of cold neutrals with energetic ions, are born near the hot core of the tokamak plasma;² thus gas stripping cell experiments serve primarily as a diagnostic of the central ion temperature.³

Most charge-exchange neutrals, however, are emitted at energies of a few hundred eV and below, due to the peaking of the cold neutral density near the relatively cool plasma edge. For various reasons, these particles are difficult to observe with standard stripping cell diagnostics. Low energy neutrals can, however, be detected by secondary electron emission when

they impact a Cu-Be surface. In the time-of-flight experiment described here, this detection scheme is utilized together with mechanical chopping of the tokamak outflux to measure the energy distribution function of deuterium atoms D^0 emitted from an ohmically heated PLT plasma in the energy range from 20 eV to 1000 eV.

II. Apparatus

Figure 1 is a schematic of the time-of-flight experiment as installed on the PLT tokamak. Charge exchange neutrals leaving the plasma travel through a 40 cm diameter pump duct to a two slit stator located 2.9 m from the plasma edge. In addition to acting as a beam collimator, the stator also acts as a vacuum break between the diagnostic vacuum system (base pressure $\approx 2 \times 10^{-8}$ torr) and the PLT vacuum system (peak fill pressure $\approx 3 \times 10^{-4}$ torr). Located 1 mm behind the stator is a 25.4 cm diameter chopper disc, which has 24 equally spaced slots of .025 cm width photoetched at an 11.43 cm radius. In the work described here, the chopper disc is spun at 10500 RPM, resulting in an effective aperture time (full width for half integrated transmission) of 1.2 μ sec for the gated D^0 neutrals. The motor which drives the chopper disc, described elsewhere,^{4,5} utilizes magnetic levitation of the shaft in order to avoid the outgassing and wear problems associated with the use of mechanical bearings in vacuum. An optical laser, located

external to the chopper vacuum vessel, triggers a PIN diode detector to determine slit opening time. The entire chopper system operates steady state for periods of a week during tokamak operation.

As shown in Fig. 1, the chopped neutrals free stream 181 cm and impinge on a 9 cm diameter Cu-Be disc, where they eject secondary electrons which are subsequently collected and amplified by an off-axis electron multiplier. Because the secondary electron emission coefficient of the Cu-Be disc is a sensitive function of D^0 energy, i.e. .083 at 100 eV and .46 at 500 eV, a separate experiment must be carried out with known energy beams to calibrate the detector (see Appendix). The electron multiplier gain, however, can be measured in-situ with the aid of an off-axis filament used as an electron current source.

The above detection scheme, as described, will fail when applied to measuring tokamak outflux. The reason is that intense UV light is emitted from the plasma together with the charge exchange neutrals. When the chopper slits open, this UV light strikes the Cu-Be detector, causing large numbers of secondary electrons to be emitted by the photo-electric effect. This photon current is sufficiently large to drive the multiplier into saturation, and since the multiplier recovery time is tens of μsec , the D^0 neutrals arriving from 5 to 35 μsec after slit opening cannot be detected.

In order to quench this "photon peak", typically $\sim 10^3$ times more intense than the neutral flux signal, the photoelectrons from the Cu-Be must be prevented from reaching the electron multiplier. This is accomplished by using a high slewing rate pulse generator (≈ 500 volts/ μ sec) to drive the Cu-Be disc to 100 volts more positive than the front face of the electron multiplier, thus preventing the photoelectrons from reaching the multiplier. Within 2 μ sec of the chopper slit closing, the Cu-Be disc is driven back to -400 Volts so that the signal from the chopped neutrals can reach the multiplier. This technique attenuates the photon peak sufficiently that it is no longer a problem. A small residual photon peak is still present, due to non-specular reflection of the UV light from the Cu-Be surface into the multiplier itself; it is useful as a $t=0$ fiducial in the analysis of the arrival time signal.

Using the above scheme, chopped D^0 neutrals are detected as a time varying negative current at the anode of the electron multiplier. A 2 MHz bandwidth preamp converts the anode current to voltage and drives an 8 bit digitizer which is equipped with 128 K of local memory; the digitizing rate is either 4, 2, or 1 MHz as determined by a programmable clock module. Typically 1024 D^0 arrival time distributions (ATD) are stored per shot; these are sent to a PDP 10 computer for archiving and subsequent data analysis. Note that the chopping

frequency for 10000 RPM motor speed is 4 kHz; hence only one of every four ATD's can be stored for a 1 s discharge.

The data reduction computer program calculates and plots several useful quantities from the digitized ATD signal, including flux and power energy spectra, integrated particle and power outflux, sputtered flux, and average D^0 energy. These are now described.

III. Data Analysis

Fig. 2 shows some typical raw data for a deuterium discharge in the PLT tokamak. The digitized preamp output voltage is plotted as a function of time, referenced to the chopper slit opening, for 3 times during the discharge. Digital averaging times for the plots at $t=40, 100, \text{ and } 200 \text{ msec}$ are 10, 25, and 50 msec, respectively. The line average electron density for the three times, measured by a microwave interferometer, is .5, .9, and $1.7 \times 10^{13} \text{ cm}^{-3}$.

Note the residual photon peak shown in the 40 msec trace. The photon signal is ten times greater than the D^0 arrival time distribution (ATD) signal, even though it has been attenuated by ~ 100 , as discussed in Sec. II.

The trend for the 3 ATD's of Fig. 2 is clear: as the plasma heats up, the neutral outflux decreases in amplitude and moves to higher energy (shorter flight time). Quantitative analysis, however, requires that the secondary electron emission

coefficient $\eta(E)$ as well as geometrical factors be specified and unfolded from the raw data. The desired quantity is the differential flux emission function $\frac{d\Gamma}{dEd\Omega}$, defined as the D^0 flux emission per eV per steradian, evaluated at the plasma surface. This is calculated according to:⁶

$$\left(\frac{d\Gamma}{dEd\Omega}\right)_{\theta=0} = 8.87 \times 10^{14} \frac{V(t)}{E^{3/2} \eta(E)} \frac{D^0}{\text{cm}^2\text{-sec-eV-ster}} \quad (1)$$

where

$V(t) \equiv$ Digitized voltage vs time (volts)

$E \equiv D^0$ energy (eV)

$= 3.41 \times 10^4 / t^2$ (for path length of 180.7 cm)

$t \equiv$ particle flight time referenced to slit opening (μsec)

$\eta(E) \equiv$ Cu-Be secondary emission coefficient as a function of energy

$\theta \equiv$ observation angle relative to normal from plasma surface.

The numerical coefficient of (1) includes all geometrical and electronics gain factors, as well as a factor dependent on motor speed, taken as 10450 RPM for the data of Fig. 2. Error bars for $d\Gamma/dEd\Omega$, due to uncertainties in V , E , and η , are derived in the Appendix.

The atomic deuterium outflux emission spectra $d\Gamma/dEd\Omega$ is plotted in Fig. 3 for the same three discharge times and same shot as are shown in Fig. 2. The energy range covered is

28 eV to 1040 eV, corresponding to D^0 flight times of 35 and 5.7 μ sec, respectively. Aside from the turnover at the low energies below 50 eV, $dI/dEd\Omega$ is monotone decreasing with energy. This result is consistent with the experimental geometry: neutrals originating anywhere on a chord through the midplane of the PLT plasma all have line of sight to the detector. Thus the cold edge is viewed simultaneously with the hot core, and a superposition of Maxwellian distributions at different temperatures is seen. The superposition is not linear, however, since neutrals originating deep in the plasma suffer much greater attenuation than neutrals born near the edge.

If we assume that the peaking of the neutral density near the plasma edge is so strong that virtually all the low energy neutrals originate there, then edge temperatures can be determined from the data of Fig. 3. Measuring the $1/e$ fall off rates in the energy range from 50 to 300 eV, the deduced "edge" temperatures at 40, 100, and 200 msec are 52, 89, and 119 eV, respectively, roughly agreeing with the location of the peak in the spectrum.

A second quantity of interest is the differential power emission function $dP/dEd\Omega$, defined as the D^0 energy flux emission per eV per steradian, evaluated at the plasma surface. This is given by:

$$\left(\frac{dP}{dEd\Omega} \right)_{\theta=0} = eE \left(\frac{dI}{dEd\Omega} \right)_{\theta=0} \frac{\text{Watts}}{\text{cm}^2 \cdot \text{eV} \cdot \text{ster}} \quad (2)$$

where

$$e \equiv 1.6 \times 10^{-19} \text{C} = \text{electron charge.}$$

Fig. 4 shows $dP/dEd\Omega$, calculated from (2), for the same three discharge times as Fig. 3. Note that the curves are all monotone decreasing with energy, for $E \geq 100$ eV, indicating that the power loss is weighted towards the low energy particles. For some discharge conditions, however, in particular during neutral beam injection, the power emission spectra become nearly flat, indicating substantial power flux at energies above 1 keV.

The arrival time distribution (ATD) data of Figs. 2-4, while useful, are hardly adequate to characterize an entire discharge. As discussed in Sec. II, the digitizer is able to store 1024 ATD's; hence, in principle, an entire 1 s discharge can be studied with 1 msec time resolution, or alternately, any 1/4 sec time slice can be studied with 250 μ sec resolution.

The quoted time resolution refers to entire energy spectra. However, what is often of interest is not the spectra themselves, but rather "reduced" quantities, representing, for example, particle or power flux within specified energy windows. We now define several reduced functions and plot their time evolution for a typical low density ohmically heated deuterium discharge in PLT.

$$\text{Reduced Flux } \Gamma \equiv \int d\Omega \int_{E_1}^{E_2} dE \frac{d\Gamma}{dEd\Omega} \frac{D^0}{\text{cm}^2\text{-sec}} \quad (3)$$

$$\text{Reduced Power } P \equiv \int d\Omega \int_{E_1}^{E_2} dE \frac{dP}{dEd\Omega} \frac{W}{\text{cm}^2} \quad (4)$$

$$\text{Averaged } D^0 \text{ Energy } \bar{E} \equiv P/eI \text{ eV} \quad (5)$$

$$\text{Sputtered Flux } S \equiv \int_{E_1}^{E_2} dE \frac{d\Gamma}{dEd\Omega} Y(E) \frac{\text{atoms}}{\text{cm}^2\text{-sec}} \quad (6)$$

where $Y(E)$ is defined to be the sputtering yield for D^0 incident on stainless steel.⁷

Evaluation of the integral over solid angle in (3)-(6) requires that some assumption be made for the angular distribution of the neutral outflux. Usually the dependence is taken as $\cos\theta$, where θ is the angle from the plasma surface normal. While this assumption is rigorously true for sources emitting isotropically in plane geometry, it is certainly not valid for tokamaks, due both to geometry and the dependence of neutral attenuation on emission angle. Nevertheless, we will make the $\cos\theta$ assumption in (3)-(6), since we estimate the correction to be small for these low density discharges.

Plots of the time evolution of Γ , P , $\bar{E}$, and S are shown in Figs. 5-8, respectively, for the case of a .75 s long ohmically heated deuterium discharge. Line average electron density is $1.2 \times 10^{13} \text{ cm}^{-3}$, and central ion temperature, as measured by bulk thermonuclear neutron emission, is 800 eV. The data is plotted with 10 msec time resolution, corresponding to an averaging of 13 ATD's measured 750 μsec apart. The limits on the energy integrals of (4)-(6) are taken to be $E_1=28$ and $E_2=1000$ eV, as in Figs. 2-4.

Fig. 5 is a plot of the reduced flux Γ for two different energy windows. For the upper plot, $28 \leq E \leq 1000$ eV, covering nearly the entire useful energy range of the instrument. For the lower plot, $200 \leq E \leq 1000$ eV; hence only relatively high energy particles are included. The relative size of these two traces shows two effects. First, excepting a small 50 msec interval near the end of the discharge, the bulk of the charge exchange neutrals are emitted at energies below 200 eV. Second, the burst of outflux at the end of the discharge contains a proportionately higher fraction of particles in the high energy channel as compared with the burst at the plasma beginning. From the upper trace alone we see an initial "burnout" time for the neutrals of 200 msec, although the flux tends to decrease on a slower time scale throughout the entire discharge. The ratio of neutral outflux at 40 msec to that at 400 msec is 25; for the "flat top" portion of the discharge, D^0 outflux is nearly constant at $10^{14}/\text{cm}^2\text{-sec}$.

Fig. 6 is a plot of the time evolution of the reduced power P , defined by (4), for the same shot as Fig. 5. Note that P burns out on the same time scale as Γ , 200 msec. However, the ratio of P at 40 msec to that at 400 msec is 10, compared with 25 for Γ . Thus, emission is at lower energies early in the discharge. This conclusion is borne out by Fig. 7, which is a plot of the average D^0 energy $\bar{E}$ as defined by (5). $\bar{E}$ is seen to increase monotonically from discharge initiation until its steady state value of 200 eV at about 130 msec. An

increase in average energy to ≈ 350 eV for an interval of ≈ 40 msec is observed just prior to discharge termination.

Fig. 8 is a plot of the time dependence of the iron sputtered from the vacuum vessel wall by charge exchange D^0 , calculated from (6). The yield factor $Y(E)$ has been taken as twice the published value⁷ for D^+ on 304 stainless steel; the factor 2 is a simple way of simulating increased sputtering yield with angle of incidence. We see that the sputtered flux peaks at 50 msec and burns out to .1 of its initial value until at 400 msec the sputtered flux is 2.2×10^{12} atoms/cm²-sec. The burst of sputtered atoms at the end of this low density discharge is nearly half the value at the beginning. For higher density discharges, the opposite condition occurs, and sputtering is greater at the end of the discharge, due to the larger quantity of collapsing plasma.

IV. Discussion

Since the limiter is separated toroidally by 100° from our diagnostic, the data presented in Sec. III is probably typical of neutral outflux in most of the torus away from the limiter. From Figs. 5 and 6, we measure the particle and power outflux at $t = 400$ msec to be $\Gamma = 10^{14}$ /cm²-sec and $P = 4 \times 10^{-3}$ W/cm². Multiplying by the total PLT plasma area of 2×10^5 cm² gives an estimate for the particle ($\dot{N}$) and power ($\dot{E}$) loss by neutrals away from the limiter, during the "flat top" portion of the discharge:

$$\dot{N} = 2 \times 10^{19} \text{ D}^0/\text{sec}$$

$$\dot{E} = 8 \times 10^2 \text{ W}$$

These numbers should be compared with the total ohmic heating power input $P_{OH} = 600 \text{ kW}$ and the estimated plasma particle recycling rate $\dot{R}$:

$$\dot{R} \approx \frac{\langle n_e \rangle V}{\tau_p} \approx \frac{(1.2 \times 10^{13}) (4 \times 10^6)}{50 \text{ msec}} = 9.6 \times 10^{20} / \text{sec.}$$

Here $\langle n_e \rangle$, V , and τ_p are the average electron density, plasma volume, and particle confinement time, respectively.

Comparing $\dot{E}$ to P_{OH} , we conclude that power loss by charge exchange neutrals away from the limiter is negligible in a low density ohmically heated deuterium discharge. Comparing $\dot{N}$ with $\dot{R}$ shows that particle recycling by charge exchange neutrals away from the limiter is a small fraction, ~2%, of the total plasma recycling rate. The latter conclusion implies that virtually all the particle recycling in the flat top portion of a low density deuterium discharge occurs at the limiter, or at energies below 20 eV.

Our conclusions depend on the absolute calibration of the diagnostic. The main sources of error are discussed in the Appendix where we find that for $50 < E < 1000 \text{ eV}$, accuracy is within a factor of 2. As a completely independent check, the PLT charge exchange analyzer was run in parallel with the time-of-flight experiment and data taken for 500 eV H^0 , for a single D beam into H plasma shot. The two diagnostics are at essentially

the same toroidal location. The measured absolute fluxes at $t = 400$ msec agreed to within a factor of 4, well within the overlapping error bars of the two instruments at the measured energy.

V. Appendix - Absolute Calibration

We estimate the absolute accuracy of $d\Gamma/dE d\Omega$, as given by (1), for several D^0 energies. Three sources of error are considered:

- (1) Electron multiplier gain G_M
- (2) Secondary electron emission co-efficient $\eta(E)$
- (3) Time-of-flight instrumental broadening factor $c(E)$

Geometrical and other physical quantities contribute a negligibly small error to $d\Gamma/dE d\Omega$.

Electron multiplier gain was determined by injecting 500 eV electrons via an off-axis filament and simultaneously measuring the current to the anode and the first dynode. The measured gain $G_M = 9.4 \times 10^4 \pm 20\%$ was found to be consistent with the single particle generated pulse size of $\sim 10^5$ electrons. Gain was measured 11 days after the discharges reported in Figs. 2-8. In the intervening period the vacuum vessel base pressure was held at 3×10^{-9} torr; hence any multiplier gain loss was negligible.

The secondary emission coefficient $\eta(E)$ was measured with a mono-energetic deuterium ion beam from a hot cathode, low

energy spread ion source.⁸ Other workers⁹ have shown that for hydrogen bombarding Cu over the energy range from 30 eV to 2 keV, the ratio of secondary emission with incident neutrals to secondary emission with the incident ions is constant at $1.15 \pm .08$; we have assumed the same relation holds for D^0 on Cu-Be, and calibrated with ions. Our results have error bars which are relatively large at low energies. The measurement is difficult because both the incident beam current and the secondary electron emission current are small, the former due to space charge effects, the later because $\eta \ll 1$.

The instrumental broadening factor $\epsilon(E)$ is a measure of the distorting effect of finite chopping time on the arrival time distribution. Since $\epsilon(E)$ is proportional to the ratio of gate time to flight time, it scales as $E^{1/2}$.

Table I below shows the relative importance of errors in η , G_M and E , and their collective effect on $dI/dE \propto (G_M \cdot \eta \cdot E^{3/2})^{-1}$:

D^0 Energy E	1000	500	200	100	50	30
η	.96	.46	.18	.083	.034	.015
$\delta\eta/\eta$	.20	.20	.30	.50	1.0	2.0
$\epsilon \propto \delta E/E$	.65	.46	.29	.21	.15	.11
$\delta G_M/G_M$	.20	.20	.20	.20	.20	.20
Total $\delta I/I$	1.02	.75	.57	.62	1.04	2.02

Table I - Sources of Error in dI/dE

The bottom line shows that the absolute calibration in the energy range 50-1000 eV is roughly a factor of 2. At low energies the dominant error source is poor knowledge of the secondary emission coefficient; at high energies the instrumental energy resolution limits the absolute accuracy of $dI/dEd\Omega$.

VI. Acknowledgment

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FIGURE CAPTIONS

- Fig. 1. Time-of-flight schematic. Chopped neutrals are detected by secondary electron emission from a Be-Cu disc.
- Fig. 2. Raw data is shown at discharge times of 40, 100, and 200 msec for shot #24534. Photo-electric emission from scattered light entering the multiplier gives a "photon peak" when the chopper slits are open.
- Fig. 3. The differential flux emission function $d\Gamma/dE d\Omega$ is plotted at 40, 100, and 200 msec for the data of Fig. 2.
- Fig. 4. The differential power emission function $dP/dE d\Omega$ is plotted at 40, 100, and 200 msec for the data of Fig. 2.
- Fig. 5. Time evolution of the reduced flux Γ is plotted with 10 msec resolution for two energy windows. $T_{i,axis}$, $\langle n_e \rangle$, I_p for shot #24581 shown are 800 eV, $1.2 \times 10^{13} \text{ cm}^{-3}$, and 450 kA., respectively.
- Fig. 6. Reduced power emission P is plotted for the energy window 28-1000 eV for the same shot as Fig. 5.
- Fig. 7. Average D^0 energy $\bar{E} \equiv P/e\Gamma$ is shown for the same shot as Fig. 5.
- Fig. 8. Time dependence of the flux of iron atoms sputtered from the stainless steel vacuum vessel wall by D^0 neutrals in the energy window 28-1000 eV is shown for the same shot as Fig. 5.

Fig. 1. (PPPL-803603)

Fig. 2. (PPPL-803606)

Fig. 3. (PPPL-803605)

Fig. 4. (PPPL-803604)

Fig. 5. (PPPL-803607)

Fig. 6. (PPPL-803609)

Fig. 7. (PPPL-803608)

Fig. 8. (PPPL-803610)