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LOW-ENERGY NEUTRAL-ATOM SPECTROMETER

BY

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ABSTRACT

DISCLAIMER

The design, calibration, and performance of a low energy neutral atom spectrometer are described. Time-of-flight analysis is used to measure the energy spectrum of charge-exchange deuterium atoms emitted from the PLT tokamak plasma in the energy range from 20 to 1000 eV. The neutral outflux is gated on a 1 μ sec time scale by a slotted rotating chopper disc, supported against gravity in vacuum by magnetic levitation, and is detected by secondary electron emission from a Cu-Be plate. The energy dependent detection efficiency has been measured in particle beam experiments and on the tokamak so that the diagnostic is absolutely calibrated, allowing quantitative particle fluxes to be determined with 200 μ sec time resolution. In addition to its present application as a plasma diagnostic, the instrument is capable of making a wide variety of measurements relevant to atomic and surface physics.

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I. Introduction

Measurement of the magnitude and energy spectrum of neutral hydrogenic atom emission is an important tool in understanding the particle and energy confinement properties of tokamak^{1,2} plasmas for controlled thermonuclear fusion applications. While directly affecting the particle and energy balance of the ion component of the plasma, charge-exchange neutrals typically have adequate energy to sputter heavy impurity atoms from the vacuum vessel wall, which can in turn modify the energy balance of the electron component through increased line, recombination, and bremsstrahlung radiation.³ The shape of the neutral atom emission spectrum is useful as a diagnostic of both the central⁴ and edge ion temperature, and, provided the electron density and temperature profiles are known, it can also yield neutral atom density profiles. In addition, neutral atom emission is an important signature of plasma recycling⁵ and gas puffing, processes which are responsible for maintenance and control of the plasma density.

Most charge-exchange neutrals are emitted at energies of a few hundred eV and below, due to the peaking of the neutral density near the relatively cool plasma edge. For various reasons, these particles are difficult to observe with standard stripping cell diagnostics.⁶ Low energy neutrals can, however, be detected by secondary electron emission when they impact a Cu-be surface. This paper describes the utilization of this

detection scheme together with mechanical chopping of the neutral outflux to measure the energy spectrum of neutral atoms emitted from the PLT tokamak⁷ in the energy range from 20 to 1000 eV. The results of these time-of-flight experiments^{8,9} represent the first measurements of tokamak neutral atom outflux at energies below 100 eV, and also represent a considerable improvement in the time resolution and accuracy of charge-exchange measurements at energies much less than that of the core plasma ions.

In addition to its utility in plasma diagnosis, the low energy neutral spectrometer (LENS), when coupled to a tokamak, can in principle make measurements relevant to surface and atomic physics. Such experiments will be possible because the tokamak neutral hydrogenic outflux is sufficiently intense, broadband in energy, and reproducible. Utilizing the tokamak as a well characterized source, phenomena, such as secondary electron emission and gas phase scattering, can be measured in the energy range from 20 to 1000 eV, previously accessible by conventional sources only with considerable difficulty.

Other experiments have been designed to measure the energy distribution of low energy neutral atoms emitted from plasma devices. A cesium gas electron attachment apparatus¹⁰ has operated on the Elmo Bumpy Torus to detect particles in the energy range from 50 to 1000 eV. However, its time resolution, 1 s, is not adequate for tokamak applications. Stripping cell

measurements on the ASDEX tokamak¹¹ have been extended downward to particle energies of 100 eV. Further improvement is unlikely due to a strongly decreasing stripping cell efficiency at low energies. An uncalibrated time-of-flight system has been used on a theta pinch.¹²

The main improvements in the instrument described in this paper are, its absolute calibration and associated long term gain stability due to ultra-high vacuum design, advanced data acquisition system allowing sub-msec time resolution, high sensitivity, and use of a large solid angle detector, of order 10^{-3} steradian, to give adequate signal-to-noise ratio to 20 eV particle energy.

II. Chopper System

Figure 1 is a schematic of the time-of-flight experiment as installed on the PLT tokamak. Energetic deuterium atoms D^0 , originating predominantly from the resonant charge-exchange reaction

within the plasma, travel through a 40 cm diameter pump duct to a two-slot stator located 2.9 m from the plasma edge. The stator has two slots in order to double the signal relative to a one slot stator. In addition to acting as a collimator, the stator acts as a vacuum break between the diagnostic vacuum

system (base pressure $\approx 10^{-8}$ torr) and the PLT vacuum system (peak fill pressure $\approx 3 \times 10^{-4}$ torr). Located 1 mm behind the stator is the 25.4 cm diameter chopper disc, which has 24 equally spaced slots of 1.143 cm length and 0.0254 cm width photoetched at an 11.43 cm radius. Typically the chopper disc is spun at 10500 rev/min, resulting in a full-open-to-full-closed gate time of 2 μ sec for the chopped D^0 neutrals. The motor which drives the chopper disc, described elsewhere,¹³ utilizes magnetic levitation of the shaft in order to avoid the outgassing and wear problems associated with the use of mechanical bearings in vacuum. The experiments carried out with this instrument^{9,14} represent the first known application of magnetic levitation to vacuum beam chopping.¹⁵

Time fiducials for particle gating are generated by an optical laser which triggers a PIN diode detector approximately 1 μ sec prior to maximum gate transmission, shown schematically in Fig. 1. The chopper system vacuum vessel, pumped by a 450 liter/s turbomolecular pump, is made of 0.95 cm thick 400 series ferritic stainless steel in order to shield the magnetic suspension from the tokamak magnetic field. The entire chopper system runs continuously for one week periods during tokamak operation.

The chopped neutrals free stream 181 cm where they strike a 9 cm OD Cu-Be disc, emitting secondary electrons which are collected and amplified by an off-axis electron multiplier. This detector assembly, fabricated entirely from metals and ceramics, is pumped by a separate turbomolecular pump to a

base pressure of 3×10^{-9} torr, and magnetically shielded by an iron box surrounding the vacuum vessel.

III. Neutral Atom Detector System

A. Configuration

In the order that the secondary electrons emitted from the Cu-Be disc reach the multiplier efficiently and with adequate kinetic energy, the detector components are positioned and electrically floated according to Fig. 2. The need for negative high voltages is a direct consequence of the ground referencing of the electron multiplier anode signal, a convenient constraint for interfacing to the high gain preamplifier and subsequently to the digital data acquisition system. Thus, the entrance grid of the electron multiplier is held at negative high voltage (-3300 V for approximately 10^5 gain), and the Cu-Be plate is held at -3700 V so that secondary electrons born there impact the multiplier with 400 eV kinetic energy.

The geometrical placement of the detector assembly components is dictated by the need for local electric field shaping near the surface of the Cu-Be disc. In order to channel the low energy (few eV) secondary electrons into the off-axis multiplier with high efficiency, the Cu-Be plate is tilted at 15° from vertical and isolated from ground inside a 43 cm long, 9.55 cm inside-diameter shielding cylinder. Tilting of the detector results in a timing uncertainty of 0.5%, negligibly small

relative to the timing uncertainty introduced by the finite gate time of the chopper. Secondary electrons are channeled through a 3.18 cm diameter extraction hole at the top of the cylinder and impact the electron multiplier with 400 eV kinetic energy. The collection efficiency f_c for this process is measured to be $f_c = 0.745$ in the experiment described in Sec. III-B; to within 5% it is constant and independent of position over the sensitive area of the Cu-Be disc. Calibration experiments show that f_c is sensitive to vertical magnetic fields, decreasing at a rate of 3.5%/gauss. For operation in the ~ 20 G tokamak fringe field, the entire detector vacuum vessel is enclosed in a 0.635 cm thick iron box. This shielding is found to reduce the overall detector magnetic field sensitivity to an acceptably small level, less than 20%, during the duration of the plasma discharge.

The acceptance solid angle of the detector, 9.4×10^{-4} steradian, is determined by a 5.08 cm diameter aperture which functions as a beam collimator 34.3 cm in front of the Cu-Be plate and 146.5 cm behind the chopper system stator. Projection of this aperture through the two chopper slots yields a roughly rectangular spot 12 cm long and 15.5 cm high on the plasma surface; this is the spatial resolution of the diagnostic.

Although designed as an efficient neutral-to-electron converter, the detector assembly actually functions as a universal particle detector. Electrons, ion, photons, and neutrals with

energies ≥ 10 eV all have measurable probabilities of ejecting secondary electrons. When this time-of-flight experiment is used in a tokamak environment, the unwanted charged particles are automatically deflected by the stray magnetic fields related to plasma production. But the unwanted photons cannot be rejected, so that the intense UV light is mechanically chopped together with the D^0 outflux. The chopping allows the photons to be rejected in the time domain. Once separated from the neutrals, the signal from the UV plasma light is useful as a diagnostic of the chopper system itself, serving both as a time fiducial and as a direct measurement of the aperture (areal transmission versus time) function.

In practice this application is made difficult because the signal from the plasma light is approximately 10^3 times more intense than the signal due to the chopped neutrals, so that the electron multiplier may be driven into saturation. Since the multiplier recovery time is tens of μsec , the D^0 neutrals arriving from 5 to 40 μsec after slot opening cannot be detected. In order to quench this photon peak, the photoelectrons from the Cu-Be are prevented from reaching the electron multiplier by using a high slewing rate pulse generator (≈ 500 volts/ μsec), the look-ahead pulse generator, to drive the Cu-Be disc to 100 volts more positive than the front face of the electron multiplier. Within 2 μsec of the chopper slot closing, the Cu-Be disc is driven back to -400 volts so that the signal from

the chopped neutrals can reach the multiplier. A residual photon peak is still present, probably due to non-specular reflection of UV light from the Cu-Be surface into the multiplier itself. A typical arrival time distribution (ATD) signal showing the residual photon peak and the delayed arrival of the neutral atoms is shown in Fig. 3. Note that this particular ATD signal is statistics limited for particle energies less than ~ 27 eV, corresponding to flight times exceeding 25 μ sec; this part of the trace reflects the arrival of single atoms at the Cu-Be plate.

B. Calibration

The overall sensitivity of the neutral atom detector scales as the product of the secondary electron emission coefficient $\eta(E)$, the electron collection fraction f_c , and the electron multiplier gain G_M . Each quantity is measured in a separate experiment. Preparation of the Cu-Be plate itself was by glow discharge cleaning in an oxygen atmosphere, assuring a gas-covered surface and stable secondary emission properties.

Calibration of secondary emission for incident neutrals was first accomplished using an ion beam and the results of other workers which relate the measured secondary emission coefficient for ions η_{D+} to the desired secondary emission coefficient for neutrals η_{D0} . For hydrogen incident on a gas covered copper surface with energies from 30 to 1600 eV, it

has been found¹⁶ that the ratio of secondary emission for atomic neutrals to that for ions is constant at $\eta_{H^0}/\eta_{H^+} = 1.15 \pm 0.08$. It is thus assumed that

$$\eta_{D^0} = 1.15\eta_{D^+}, \quad (2)$$

since it has been shown that deuterium and hydrogen have the same secondary emission coefficient at the same velocity over this energy range.¹⁷

The calibration of the Cu-Be plate of the detector assembly in Fig. 2 is carried out with a 0.1 μ A mass-selected molecular deuterium D_2^+ beam.¹⁸ The beam is defocused to roughly a plane source at the detector entrance aperture and allowed to fall on the Cu-Be plate, ejecting secondary electrons. An ammeter connected between the Cu-Be plate and ground measures the positive current thus generated. The shielding cylinder and electron multiplier are electrically connected to a common ground referenced power supply at voltage V_{CYL} . For negative V_{CYL} (typically ≈ -5 V) the cylinder acts as a secondary electron suppressor and the ammeter reads the incident beam current $I_- = I_{D_2}$. For positive V_{CYL} (typically, + 5 V) the cylinder acts as a secondary electron extractor and the ammeter reading I_+ includes an additional contribution due to the secondaries so that $I_+ = I_{D_2} + I_{SEC}$. The ion secondary emission coefficient $\eta_{D_2^+} \equiv I_{SEC}/I_{D_2}$ follows as

$$\eta_{D_2^+} = \frac{I_+ - I_-}{I_-} \quad (3)$$

and under the assumption

$$\eta_{D_2}^{+}(2E) = \eta_D^{+}(E) + \eta_D^{+}(E), \quad (4)$$

the desired secondary emission coefficient for atomic deuterium $\eta \approx \eta_{D^0}$ follows from Eqs. (2-4):

$$\eta_{D^0} = 0.535 \frac{I_+ - I_-}{I_-}. \quad (5)$$

The additivity of secondary electron emission from the separate atoms of composite projectiles, assumed in Eq. (4), has been verified experimentally for both molecules^{19,20} and metal clusters.²¹

The secondary emission coefficient η calculated from Eq. (5) and the measured beam currents I_+ , I_- is shown in Fig. 4 for the energy range from 400 to 2500 eV, and in Fig. 5 for D^0 energies from 50 to 400 eV. Except for very low energies, below 100 eV, the data are well represented by the linear fit shown,

$$\eta(E) = 9.69 \times 10^{-4} (E - E_T), \quad (6)$$

where the extrapolated threshold energy for onset of secondary emission E_T is taken as 14 eV. A linear dependence of $\eta(E)$ below 100 eV has been observed by Fleischmann and Tuckfield²² for atomic hydrogen bombarding a Cu-Be surface down to 30 eV incident energy, consistent with Eq. (6); extrapolation of their data to lower energies yields a threshold energy of ≈ 14 eV

for onset of secondary emission. Within experimental error the onset energy observed in this work by extrapolation of the data for $E \geq 100$ eV is the same as Fleischmann and Tuckfield's. The threshold energy will be discussed further in Section V-B.

The data points below 100 eV in Fig. 5 underestimate the line fit n value, presumably due to defocusing of the incident ion beam occurring in front of the detector aperture by a radial electric field E_r in the aperture's vicinity. The change in ion trajectories due to E_r has been calculated⁸ and the corrected secondary electron yields plotted in Fig. 5 as open circles. These corrected values are in good agreement with the line fit to the data measured at energies above 100 eV where the defocusing effect is negligible.

Because of imperfect electric field shaping and distribution of secondary electron kinetic energies, the fraction of secondary electrons actually collected by the multiplier relative to the total number produced, f_c , is always less than unity. In order to maximize f_c as a function of the potentials of the Cu-Be plate, shielding cylinder, and electron multiplier, a separate experiment is carried out with a neutral deuterium beam.

An approximately planar neutral beam is produced by passing a diverging 1000 eV D_2^+ ion beam through an argon neutralization gas cell and subsequently magnetically rejecting the remaining ions. The secondary emission current I_{SEC} is measured by an ammeter connected between the Cu-Be plate and

ground. The multiplier shielding grid and dynode 1 are electrically shorted together and biased at voltage V_{SG} with a ground referenced dc power supply. A floating ammeter, inserted between V_{SG} and the multiplier dynode 1, reads the current of secondary electrons collected by the multiplier I_{COL} . Secondary emission from dynode 1 is suppressed by holding dynode 2 at -50 V. The shielding cylinder voltage V_{CYL} is controlled by a ground referenced dc power supply.

For a given extraction voltage $V_{SG} - V_{CuBe}$ between the multiplier shielding grid and the Cu-Be plate (typically 400 V), the collection fraction f_c is measured in two steps. The shielding cylinder is connected to a +24 volt battery, extracting all secondaries from the Cu-Be; the ammeter thus reads the positive current to the Cu-Be plate I_{SEC} , typically of order 2×10^{-8} A. Next, the shielding cylinder is connected to voltage V_{CYL} so that the floating ammeter on dynode 1 reads the negative electron current $-I_{COL}$ collected by the multiplier. The collection fraction f_c is thus the ratio of these two currents:

$$f_c = \frac{I_{COL}}{I_{SEC}}. \quad (7)$$

Figure 6 is a plot of measured f_c versus $V_{CYL} - V_{CuBe}$ for two values of extraction voltage, $V_{SG} - V_{CuBe} = 400$ and 100 V. The narrow peak in f_c is at $V_{CYL} - V_{CuBe} = -1.5$ and -1.0 V for $V_{SG} - V_{CuBe} = 400$ and 100 V, respectively. Optimal

extraction efficiency is obtained by biasing the shielding cylinder at a small repulsive potential, comparable in magnitude to the few eV kinetic energy of the secondary electrons. It is found that the detector component potentials required for maximum electron extraction efficiency are independent of the incident atom's kinetic energy; this result is reasonable since the magnitude of the extraction voltage dominates the typical energy of the secondary electrons. The actual operating point used in the time-of-flight experiment is the peak of the 400 V curve; the maximum collection efficiency $f_c = 0.745$ is obtained at $V_{CYL} - V_{CuBe} = -1.5$ V. During typical operation at $V_{CuBe} = -3700$ V, the voltage between the shielding cylinder and Cu-Be plate is held rigidly at -1.5 V with a battery; in this way the detector collection efficiency f_c is made insensitive to the small voltage drifts inherent in high voltage supplies.

Electron multiplier gain G_M is determined by injecting 500 eV electrons via an off-axis filament and simultaneously measuring the current to the anode and the first dynode. A two step process is used. Absolute gain is first measured at a relatively low voltage (dynode 1 voltage $V_{D1} = -1700$ V) so that the anode current and first dynode current are of same order; the ratio of the two is the gain. Next, relative gain at high voltage, $V_{D1} = -3200$ V, compared with low voltage, $V_{D1} = -1700$ V, is measured by monitoring the anode current as the

electron multiplier voltages are increased with constant input current from the filament. Measured gain $G_M = 9.4 \times 10^4$ is stable to an accuracy of 20% for output currents up to 100 μ a.

IV. Data Acquisition System

The time-of-flight instrument generates a D^0 arrival time distribution signal for each slot opening, typically spaced at 250 μ sec intervals for the nominal 10,000 rev/min rotor speed. The neutral outflux energy spectrum is thus measured at 4000 time positions during a 1-sec long PLT discharge. Full utilization of the inherent instrumental time resolution of 250 μ sec requires the use of a digital data acquisition system, which is now described.

Chopped D^0 neutrals are detected as a time varying negative current at the electron multiplier anode, which in turn drives a 4 MHz bandpass preamplifier as shown in Fig. 7. The preamp output $V(t)$ is then fed to a commercial (LeCroy Research Systems Model 2264) 8-bit transient digitizer; the time development of this $V(t)$ signal can be inverted to an absolute flux emission spectrum following the prescription of Sec. V. Preservation of the timing information is achieved with a computer programmable clock. The clock's function is to output a pulse burst (128 pulses) to the digitizer each time the chopper slots open, causing a sequence of numbers to be stored in the digitizer memory. This number sequence is a digital map of $V(t)$

representing the D^0 arrival time distribution (ATD) for that particular slot opening. The digitizer is run in the external clock mode so that a single 8-bit number is stored for each of the 128 TTL level pulses received from the clock per slot opening.

Following Fig. 7, the sequence of events for data acquisition is as follows. Prior to each plasma shot, a controlling PDP 10 computer issues commands clearing the digitizer and programming the clock. The chopper system runs steady-state; time fiducials are generated continuously by a PIN diode light sensor, triggered by He-Ne laser light which has passed through both the stator and the moving chopper slot. The PIN diode signals slot opening by outputting TTL pulses to the clock at the chopping frequency. As shown in the bottom of Fig. 7, the clock output remains low until a pulse is received from the PLT timer indicating discharge initiation. This pulse arms the clock. For each subsequent opening of the chopper slots, as determined by the PIN diode sensor, the clock outputs a pulse burst causing the ATD signal to be stored. This process is repeated for each slot opening until the entire digitizer memory is full. The 128-k digitizer memory allows storage of 1024 ATD's at 128 8-bit words per ATD. After each discharge the PDP 10 computer reads out the digitizer memory and creates a file on disc to archive the data. The entire data acquisition process is automated and runs without operator intervention.

Because the digitizer memory can store only 1024 ATD's out of a total of ≈ 4000 generated during a typical 1 sec PLT discharge, most data is necessarily lost. Time resolution can, however, always be interchanged for a longer discharge sampling time within the finite memory constraint. For example, any 1/4 sec time slice can be measured with 250 μ sec time resolution by digitizing each successive ATD, or alternatively, the entire 1 sec plasma discharge can be sampled with 1 msec time resolution by digitizing every fourth ATD. These options are selected by reprogramming the clock via the PDP 10 computer.

The ATD signal generated by a tokamak plasma varies rapidly during slot opening and closure, as described in Sec. IIIA. This "photon peak" signal varies on the time scale of 1 μ sec, while the typical signal due to the chopped D^0 neutrals varies on the time scale of several μ sec. In order to efficiently capture these signals digitally while minimizing the memory usage, it is useful to digitize at a higher frequency near the beginning of the ATD than for the rest of the ATD. This "importance sampling" technique is used in the acquisition of all data presented in this paper. As shown schematically in Fig. 7, the usual scheme is for the clock to output 75 pulses at 1/4 μ sec spacing followed by 50 pulses at 1/2 μ sec spacing (followed by 3 pulses at 1 μ sec spacing which are not used) for each digitized ATD signal. The $V(t)$ signal is thus stored from $t = -1$ to $t = 42$ μ sec, the latter particle flight time corresponding to a D^0 energy of 19 eV.

Archived data are presented in a meaningful form by a data reduction computer program which unfolds the secondary emission coefficient and gain factors. The code 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 discussed in the following section.

V. Results

In this section measurements of the neutral atom emission from a tokamak discharge are presented. The equations for data analysis are given; typical data showing the density and energy resolution of the instrument are presented; and the minimum detectable signal is discussed.

A. Data Analysis

From standard time-of-flight theory (see Appendix), the neutral atom emission function $d\Gamma/dEd\Omega$ (number/cm²-s-eV-ster) follows from the arrival time distribution data $V(t)$ (preamp output voltage V vs particle flight time t) through the equations

$$\frac{d\Gamma}{dEd\Omega} = \left(\frac{\ell_{CD}}{A_C} \frac{\ell_{CA}^2}{A_{AP}} \right) \left(\frac{\sqrt{m_p c^2/8}}{e c} \right) \left(\frac{1}{G_M G_P f_C} \right) \quad (8)$$

$$\times \left(\frac{M^{1/2} V(t)}{t_G E^{3/2} n(E)} \right)$$

$$= 1.243 \times 10^9 \frac{M^{1/2} V(t)}{t_G E^{3/2} \eta(E)} \frac{\text{Neutrals}}{\text{cm-s-eV-ster}},$$

and

$$E = \frac{M m_p c^2}{2t^2}$$

$$= 3.41 \times 10^{-8} M/2t^2 \text{ eV}, \quad (9)$$

where the quantities appearing here are defined in the Appendix. The first of the four terms on the right-hand-side of Eq. (8) is a collection of geometrical factors; the second term is a constant calculated from the proton mass m_p , electron charge e , and the speed-of-light c ; the third term is a set of gain factors for the detector and its associated electronics. Energy dependent factors are collected in the fourth term; here M is the particle mass in units of m_p ; $V(t)$ is the time dependent preamp output voltage; t is the particle flight time referenced to the chopper slot opening, which determines the particle energy E through Eq. (9); t_G is the time for the chopper gate to go from full open to full closed; and $\eta(E)$ is the measured secondary-emission calibration function, Eq. (6).

B. Tokamak Neutral Atom Emission

Data taken with the LENS diagnostic has been published for low-density ohmically heated discharges.⁹ In this section data is presented for a typical medium density deuterium discharge in the PLT tokamak. No attempt is made here to interpret the data, as this will be done in future work describing the variation in the neutral emission with operating conditions. We first present a check of the $\eta(E)$ calibration using the tokamak.

i) Tokamak Calibration of $\eta(E)$

An independent check of $\eta(E)$ for $E \leq 100$ eV can be made with the LENS diagnostic installed on the tokamak. This is possible because the neutral hydrogen atom outflux during discharge start-up can be simply related to the rate of plasma formation, i.e., the fill gas acts both as a source for fresh plasma and a driving mechanism for the charge-exchange neutral outflux. An essential feature to this argument is that during discharge start-up the charge-exchange excitation and ionization processes are measured to be toroidally symmetric by the LENS system and H_α detectors,²³ respectively.

To relate the charge-exchange outflux to the rate of plasma formation we develop the following plasma startup model. Several simplifying assumptions are made. It is assumed that the time rate-of-change of the electron density, dn_e/dt , is determined solely by electron bombardment ionization of atomic deuterium D^0 according to:

$$\frac{dn_e}{dt} = n_e n_n \langle \sigma_{\text{ioniz}} v_e \rangle_{T_e} \quad (10)$$

Here n_e and n_n are the electron and neutral densities, and $\langle \sigma_{\text{ioniz}} v_e \rangle_{T_e}$ is the Maxwellian averaged ionization rate coefficient for electrons at temperature T_e . Recombination and molecular processes have been shown⁸ to be negligible. In addition, particle loss by diffusion is neglected.

The model neglects all processes which attenuate the charge-exchange outflux. Electron collisional ionization losses are thus neglected but charge-exchange of escaping fast neutrals and D^O - D^O elastic scattering processes are included, since they do not destroy neutrals. The validity of the assumption rests on the smallness of the optical thickness parameter ϵ_{op} , defined as

$$\epsilon_{\text{op}} \equiv \bar{n}_e a \langle \sigma_{\text{ioniz}} v_e \rangle_{T_e} / v_D \quad (11)$$

where $\bar{n}_e$ is the line-averaged electron density, a is the plasma minor radius, and v_D the D^O velocity. During plasma startup $\bar{n}_e \lesssim 5 \cdot 10^{12} \text{ cm}^{-3}$, $T_e \lesssim \text{few} \cdot 10^2 \text{ eV}$, and typical charge-exchange D^O energies are 50 eV, so that $\epsilon_{\text{op}} \lesssim 0.9$; the plasma is thus approaching the upper limit of the optically thin density regime for neutrals during startup. The accuracy of the startup model in predicting the neutral outflux is therefore limited to roughly a factor of 2. A mitigating factor here is that as the discharge develops and the electron density

increases, the neutrals tend to become more energetic and originate preferentially nearer the plasma edge. Both these factors are favorable and tend to keep the plasma in the optically thin regime for neutral emission.

With the neglect of attenuation processes, the areal emission and average volume creation rate of charge-exchange neutrals must balance:

$$\Gamma \cdot A = R_{cx} \cdot V. \quad (12)$$

Here A and V are the plasma surface area and volume, respectively, Γ is the neutral outflux at the plasma surface ($D^0/\text{cm}^2 \text{ sec}$) and R_{cx} is the volume averaged charge-exchange creation rate ($D^0/\text{cm}^3 \text{ sec}$), given by:

$$R_{cx} = [n_i n_n \langle \sigma_{cx} v_i \rangle_{T_i}]_{va} \quad (13)$$

where n_i is the ion density, $\langle \sigma_{cx} v_i \rangle_{T_i}$ is the Maxwellian averaged charge-exchange rate coefficient for ions at temperature T_i , and the brackets indicate volume averaging. With the neglect of impurities, the quasi-neutrality condition implies $n_i = n_e$, so that

$$n_i n_n = n_e n_n = \langle \sigma_{ioniz} v_e \rangle_{T_e}^{-1} \frac{dn_e}{dt}, \quad (14)$$

according to Eq. (10). Substituting (14) into (13) yields

$$R_{cx} = \left[\frac{\langle \sigma_{cx} v_i \rangle_{T_i}}{\langle \sigma_{ioniz} v_e \rangle_{T_e}} \frac{dn_e}{dt} \right]_{va}. \quad (15)$$

The ionization rate coefficient $\langle \sigma_{\text{ioniz}} v_e \rangle_{T_e}$ is set equal to $\langle \sigma_{\text{ioniz}} v_e \rangle_0 \equiv 2.8 \cdot 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$; for the electron temperature interval from 30 eV to 1 keV (typical of plasma start-up), the rate coefficient has this value to within 25%. The charge-exchange rate coefficient is evaluated at the average ion temperature $\bar{T}_i$, where $\bar{T}_i$ is the ion temperature deduced from the $1/e$ falloff with energy of the measured low energy neutral emission spectrum. The estimated error introduced here is small, owing to the slow variation of the charge-exchange rate coefficient over the temperature range of interest, i.e., a factor of 2 between $T_i = 20$ and 200 eV. Eq. (15) thus simplifies to

$$R_{\text{cx}} = \frac{\langle \sigma_{\text{cx}} v_i \rangle_{\bar{T}_i}}{\langle \sigma_{\text{ioniz}} v_e \rangle_0} \left[\frac{dn_e}{dt} \right]_{\text{va}}. \quad (16)$$

The observable quantity is the line average electron density $\bar{n}_e$. For the density profile, estimated to be parabolic, $n_e(r) = n_{e0} (1 - r^2/a^2)$, volume and line averaged densities are related by $[n_e]_{\text{va}} = 3/4 \bar{n}_e$, approximately compensating for the heavy weighting given to the central plasma in a line averaged measurement. Substituting Eq. (16) into (12) yields the desired relation between the neutral outflux Γ , as measured by the low energy neutral diagnostic, and the plasma formation rate $d\bar{n}_e/dt$, as measured by the microwave interferometer:

$$\Gamma = \frac{3}{4} \frac{V}{A} \frac{\langle \sigma_{\text{cx}} v_i \rangle_{\bar{T}_i}}{\langle \sigma_{\text{ioniz}} v_e \rangle_0} \frac{d\bar{n}_e}{dt}. \quad (17)$$

This equation gives the neutral outflux prediction of the plasma startup model. It is valid during the startup phase while the plasma creation rate and neutral outflux are determined by toroidally and poloidally symmetric volume processes.

Figure 8 shows the microwave interferometer data for line averaged electron density $\bar{n}_e$ for a representative RF heated deuterium discharge. The plasma formation rate, $d\bar{n}_e/dt$, is measured directly from the interferometer data. The ion temperature $\bar{T}_i$ is taken as the $1/e$ decay constant of the low energy part of charge-exchange neutral energy spectrum, as measured by the low energy neutral diagnostic. Two representative neutral energy spectra, as well as the raw data used to calculate them, are shown in Fig. 9 at discharge times $t = 30$ and $t = 50$ msec; the data have been averaged over a 5.5 msec (± 2.7 msec) interval. Discharge initiation, as measured by the microwave interferometer, occurs at $t = 25 \pm 2$ msec; to within 2 msec, the first emission of charge-exchange neutrals and the first UV light emission occur concurrently. The UV light is detected as a photon peak in the neutral arrival time distribution signal.

The ion temperatures for the two spectra, inferred from the $1/e$ decay constants, are $\bar{T}_i \approx 18$ and 52 eV at $t = 30$ and 50 msec, respectively. The straight line fit to the data from which the ion temperature is deduced shows that emission fall-off with energy is essentially purely exponential over a two order of magnitude dynamic range. The plasma neutral emission is thus typical of a single temperature source during startup.

This situation persists until $t \approx 55$ msec (approximately 30 msec from discharge initiation) when the spectrum begins curving away from the exponential at high energies in a manner characteristic of a multi-temperature source. A spatial temperature profile is developed over the region of charge-exchange neutral emission.

Substituting the data from Fig. 8 for $d\bar{n}_e/dt$ and data as in Fig. 9 for $\bar{T}_i$ into the model, Eq. (17), yields the predicted values for the outflux Γ as a function of time. The results are plotted as solid dots in Fig. 10 along with the measured D^0 outflux in the energy range from 20 to 1008 eV for the same discharge.

The model prediction for Γ has an associated error of $\pm 25\%$ as shown in Fig. 10, due to uncertainty in the measurement of $d\bar{n}_e/dt$ from the data of Fig. 8. There is also an estimated 10% uncertainty in the $\bar{T}_i$ measurement, originating from the exponential fit to the measured neutral atom emission spectrum. The error in $\bar{T}_i$, however, makes a negligible contribution to the uncertainty in Γ , due to the weak variation of the charge-exchange rate coefficient with ion temperature. The charge-exchange rate coefficient used in the model has been adjusted for deuterium.⁸

The agreement between the measured outflux and that predicted by the plasma startup model is typically within the expected factor of 2 error bar, except for the earliest data point at 30 msec. The discrepancy at very early times, less than 5 msec into the discharge, probably occurs because most

of the neutral emission is at energies below the detection threshold of ~ 14 eV due to the very low ion temperature. For example, the ion temperature at 28 msec (with 1 msec averaging), corresponding to ~ 3 msec from discharge initiation, is measured as $\bar{T}_i = 9.5$ eV from the emission spectrum falloff rate in the 20 to 60 eV energy interval. The actual plasma outflux in the first 5 to 10 msec is therefore higher than the measured value of $\Gamma \sim 3.3 \times 10^{15} \text{ cm}^{-2} \text{ sec}^{-1}$; the value predicted from the startup model, $\Gamma \sim 4.5 \times 10^{15} \text{ cm}^{-2} \text{ sec}^{-1}$, is a better estimate for the initial neutral burst due to the importance of energies below 20 eV.

Since the tokamak emission spectrum during start up can show a Maxwellian shaped tail giving $T \sim 10$ eV, it is natural to ask if the LENS system detects atomic deuterium with energy $E \leq 14$ eV, the estimated threshold, or more properly, particles with arrival times $\geq 50 \mu\text{sec}$. We have examined this in special discharges formed to have a high neutral flux at low energies. The detector enabling gate, whose pulse length was usually programmed to only quench the photon peak, was set so that its pulse width could extend out to arrival times of 10 to 60 μsec . In this way any instrumental recovery time due to a higher neutral signal at an earlier time could be suppressed. With this preparation, we have been able to observe a measurable signal at $t = 50^{+5}_{-2} \mu\text{sec}$, corresponding to atomic D energies of 14^{+2}_{-3} eV. This, of course, is

predicated on the assumption that unexcited neutral D^0 is the only species impacting the CuBe plate.

ii) Neutral Emission During an Entire Discharge

The representative discharge described here is characterized by a line-averaged electron density of $3 \times 10^{13} \text{ cm}^{-3}$, ohmic-heating current of 500 kA with a loop voltage of 1 volt, a central ion-temperature of 1.1 keV, and a toroidal magnetic field of 29 kG. With the chopper disc rotational speed of 10200 rev/min, the gate time t_G is 2.1 μsec and the time between slot openings is 245 μsec . In order to follow the time evolution of the neutral atom emission during the entire 738 msec discharge, the data acquisition system is software-programmed to store every third ATD signal; these 1024 stored ATD signals record the neutral emission from 0 to 753 msec at intervals of 0.735 msec. Post-shot averaging yields the data of Fig. 11. Four ATD signals are shown in the left plot, with averaging times as described in the figure caption. Corresponding emission spectra $dI/dE d\Omega$, calculated from Eq.(8), are shown in the center plot. The right plot is the corresponding power emission spectra $dP/dE d\Omega$, calculated from

$$\frac{dP}{dE d\Omega} = E \frac{dI}{dE d\Omega} . \quad (18)$$

This data indicates that both the particle and power emission is dominantly at low energies in this discharge.

For some applications, it is not the emission spectra themselves that is of interest, but rather reduced quantities,

representing, for example, particle or power flux within specified energy windows. The particle flux Γ , power flux P , average D^O energy $\bar{E}$, and sputtered flux S are defined as

$$\Gamma = \int d\Omega \int_{E_1}^{E_2} dE \frac{d\Gamma}{dE d\Omega} \frac{D^O}{\text{cm}^2\text{-s}} , \quad (19)$$

$$P = \int d\Omega \int_{E_1}^{E_2} dE \frac{dP}{dE d\Omega} \frac{W}{\text{cm}^2} , \quad (20)$$

$$\bar{E} = P/\Gamma \text{ eV} , \quad (21)$$

$$S = \int d\Omega \int_{E_1}^{E_2} dE \gamma(E) \frac{d\Gamma}{dE d\Omega} \frac{Fe^O}{\text{cm}^2\text{-s}} , \quad (22)$$

where $\gamma(E)$ is the energy-dependent sputtering yield for D^O incident on stainless steel. This latter quantity is useful for estimating the impurity influx to the plasma due to charge-exchange neutrals impacting the vacuum vessel wall.

The time dependence of these reduced quantities is plotted in Fig. 12 for the same discharge as the Fig. 11 data. Solid angle integrals in Eqs. (19-22) have been carried out assuming the plasma emission varies as $\cos \theta$, with θ the angle from the normal to the plasma surface. The LENS diagnostic views the plasma at $\theta = 12.5^\circ$ in the PLT midplane, and is

separated toroidally by 100° from the plasma limiter. The data shows a strong peaking in the D^0 particle and power flux, and the sputtered Fe flux at the beginning and end of the discharge. The main effect of the gas puff, which increases the line-averaged electron density from 1 to $3 \times 10^{13} \text{ cm}^{-3}$, is to depress the average emission energy. This gas puff originated at a toroidal position 100° away from the LENS diagnostic port.

C. Minimum Detectable Signal

Statistical effects due to the discreteness of the D^0 atoms are the dominant mechanism in determining the signal to noise ratio of the measured tokamak emission spectrum. Additional contributions come from noise pulses generated in the electron multiplier, finite digitizing rate, finite digitizer bit size, and digitization jitter.

Figure 13 is an oscilloscope trace of the preamp output signal for a delta-function current source generated by electron multiplier noise pulses. This represents the overall detector response for the secondary electron burst generated by impact of a single atom on the Cu-Be plate. The 340 nsec pulse full width at half maximum sets a signal level threshold of at least three secondary electrons per usec for the detector to be operating in the analog mode with a signal to noise ratio of order unity. The detector must be in the analog mode to allow inversion of a single ATD to a meaningful energy spectrum.

If sufficient signal is not available, averaging over adjacent ATD's can be carried out digitally to build up the signal to an analog level.

Four factors affect the accuracy of the digitized ATD waveform when flux levels are below the threshold necessary for analog operation. First, the maximum digitizing rate of four points per μsec is too slow to accurately capture the narrow single atom pulse of Fig. 13. Second, the voltage pulse size generated by a single secondary electron is comparable to the digitizer bit resolution of 20 mV. At low flux levels, digital storage of the signature of a single atom impacting the detector is thus carried out only crudely with a signal to noise ratio of order unity. Third, jitter in the digitization process itself introduces errors of one bit in the storage of the preamp output voltage. Fourth, the electron multiplier generates noise pulses at a rate of approximately five per msec which are superimposed on the ATD signal. Together these four statistical effects create a noise voltage which masks sufficiently small ATD signal levels, providing a lower bound on the flux level that can be measured. The linearity of the data acquisition process guarantees that these collective noise voltages decrease as $N^{-1/2}$ relative to the ATD signal, where N is the number of ATD's averaged over. Averaging thus allows detection of smaller particle fluxes than is possible with data from a single ATD signal. The price paid is decreased time resolution.

Improvement in the signal to noise ratio of the measured emission spectrum with averaging is shown in Fig. 14. The upper two plots show the digitized ATD signal and calculated emission spectrum for a single slot opening measured in the current rise stage of a PLT discharge. The bottom plots are data for the same discharge averaged over 24 successive ATD's spanning a 5.5 msec interval. Typically the emission source function remains constant on this time scale.

Figure 14 shows two benefits of the averaging process. First, the observed reduction in the noise level is consistent with the expected improvement factor of $\sqrt{24}$. Second, the calculated minimum detectable flux level, or threshold flux, is reduced by the same factor. The threshold flux $(d\Gamma/dEd\Omega)_{th}$ is defined as

$$\left(\frac{d\Gamma}{dEd\Omega}\right)_{th} = \left(\frac{d\Gamma}{dEd\Omega}\right)_{V(t) = V_{noise}} \quad (23)$$

where the right hand side is evaluated from Eq.(8) with V_{noise} the estimated noise voltage of the ATD signal. $(d\Gamma/dEd\Omega)_{th}$ represents the smallest neutral flux that can be measured in the presence of a masking voltage of amplitude V_{noise} . For the upper and lower ATD signals of Fig. 14, V_{noise} is estimated as 100 mV and 20 mV, respectively, to produce the calculated threshold emission spectra shown as dashed lines. The constraint that the flux emission spectrum must exceed the threshold flux determines the low energy instrumental cutoff

for a given ATD signal, since the threshold flux rises sharply at low energies. For the single slot opening and averaged ATD cases of Fig. 14, the intersection of the measured emission spectrum with the threshold flux gives the low energy cutoff as approximately 50 and 30 eV, respectively. Equivalently stated, for flight times longer than those corresponding to these cutoff energies, the ATD signal is no longer in the analog regime.

The threshold flux spectrum is shown in Fig. 15 for the entire instrumental energy range from 20 to 1000 eV. The input quantities to Eqs. (8) and (9) are $t_{ap} = 2.02 \text{ } \mu\text{sec}$, for a typical rotor speed of 10500 rev/min, and $V_{noise} = 20 \text{ mV}$, corresponding roughly to the noise level of the raw data after averaging over 25 ATD's, as in Fig. 14. The plot shows that the time-of-flight system used with a secondary emission detector has an energy dependent sensitivity factor which varies by 5×10^4 in the 20 to 1000 eV energy range.

Figure 15 has a second interpretation. It represents, through the $E^{3/2} \times n(E)$ factor of Eq. (8), the compression effect introduced by the time-of-flight measurement process. The high energy part of the spectrum is amplified while the low energy part is attenuated. This weighting is quite favorable because it follows roughly the shape of tokamak emission itself. Emission spectra can thus be measured over three orders of magnitude when the ATD signal has a dynamic range of only 25, as in the bottom plots of Fig. 14.

Appendix - Calculation of the Emission Spectrum From the Time-of-Flight Signal

The plasma emission spectrum $d\Gamma/dE d\Omega$ follows from the arrival time distribution (ATD) signal $V(t)$ under the following assumptions:

- (i) Spatial variation in the emission spectrum over the region of the plasma surface sampled by the instrument is negligible;
- (ii) Variation in the emission spectrum is negligible on the time scale of a particle flight time, of order 50 μsec ;
- (iii) The chopper aperture function can be represented by a delta function in time.

The plane source approximation (i) should be a good one since the 8 cm instrumental resolution is small relative to the plasma major and minor radii of 130 and 40 cm, respectively. Assumption (ii), slow time variation of the source, can be verified from the data. The accuracy of the delta-function gate approximation (iii) has been studied elsewhere.⁸ The assumption is generally valid when the chopper gate time is much smaller than the particle flight time, a condition satisfied by the data presented here.

In the absence of attenuation processes the brightness of a plane source is independent of distance from the source.

Thus, the differential flux emission function $d\Gamma/dEd\Omega$, defined as the D^0 flux emission per eV per sterndian ($D^0/\text{cm}^2\text{-sec-eV-ster}$), is the same whether evaluated at the surface of the plasma or at the surface of the stator, provided only solid angles near the detector-chopper-plasma line-of-sight are considered. Gating of the atomic flux $d\Gamma/dEd\Omega$ at $t = 0$ causes an equivalent current $I(t)$ (atoms/sec) to impact the detector plate delayed by the flight time t . Particle conservation requires

$$I(t)dt = \frac{d\Gamma}{dEd\Omega} \times dE \times \delta\Omega \times I_c \times t_g, \quad (24)$$

where the detector acceptance solid angle $\delta\Omega = A_{ap}/\ell_{ca}^2$; A_{ap} is the area of the collimating aperture (20.3 cm^2); A_c is the area of the chopper slots (0.0581 cm^2); and the chopper gate time $t_g = 0.0212/s$ sec with the rotor speed s in rev/min. The atom kinetic energy E follows from the measured velocity v as

$$E = \frac{1}{2} m v^2 = \frac{M m_p \ell_{cd}^2}{2 t^2}, \quad (25)$$

where the atom mass $m = M m_p$, m_p is the proton mass, and ℓ_{cd} is the chopper to detector plate distance (180.7 cm). The preamp voltage output versus time $V(t)$ depends on the atom current impacting the Cu-Be plate $I(t)$ according to

$$V(t) = e f_c \eta(E) G_M G_p I(t), \quad (26)$$

where e is the electron charge; f_c is the electron collection fraction (0.745); $\eta(E)$ is the energy dependent secondary

electron emission coefficient; and G_M and G_P are the electron multiplier (9.44×10^4) and preamp (8.49×10^4) gains, respectively. The above three equations yield the desired formula for calculation of the flux emission spectrum $d\Gamma/dE d\Omega$ from the ATD signal $V(t)$, given by Eq. (11).

Conclusion

Utilizing neutral atom detection by secondary electron emission and time-of-flight energy dispersion, the LENS diagnostic described here has made the first measurements of tokamak atomic deuterium outflux at energies below 100 eV. Absolute calibration of the spectrometer has been done in laboratory beam experiments, and these results have been verified by measurements made during tokamak startup.

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FIGURE CAPTIONS

Fig. 1. Schematic of the time-of-flight instrument. Charge-exchange deuterium neutrals D^0 are mechanically chopped by a rotating slotted disc and detected by secondary electron emission from a Cu-Be plate. Fiducial timing pulses are generated when laser light passes simultaneously through the moving and stationary slots.

Fig. 2. Perspective view of the neutral atom detector assembly. Nominal operating voltages of the various components are indicated. Chopped neutrals are collimated by the aperture and impact the Cu-Be plate, ejecting secondary electrons which are channelled upward through a hole in the shielding cylinder and impact the electron multiplier. The filament located external to the shielding cylinder is used to generate a current in the multiplier for calibration purposes.

Fig. 3. Oscilloscope trace of the arrival time distribution signal for a single slot opening, taken at $t = 60$ msec in a 400 kA hydrogen discharge. The triangular aperture function is mapped out by the photon peak. The apparent noise in the neutral signal is a statistical effect due to atom discreteness. The small pulses just above baseline at flight times larger than 25 μ sec reflect single atoms arriving at the detector plate.

Fig. 4. Measured secondary electron emission coefficient versus energy for D^0 on Cu-Be. The solid line is used as an analytic representation for $\eta(E)$ in the inversion of the raw time-of-flight data to neutral atom emission spectra. The data at energies below 400 eV are plotted in Fig. 5.

Fig. 5. Measured secondary electron emission coefficient versus energy for D^0 on Cu-Be. The open circles below 100 eV energy represent data points which have been approximately corrected for defocusing of the ion beam occurring at the detector aperture. The solid line is used as an analytic representation for $\eta(E)$ in the inversion of the raw time-of-flight data to neutral atom emission spectra.

Fig. 6. Measurement of the collection efficiency of the electron multiplier for electrons born at the Cu-Be plate as a function of cylinder voltage $V_{CYL} - V_{CuBe}$, for two values of multiplier shielding grid potential $V_{SG} - V_{CuBe}$. The detector operating point is at $V_{CYL} - V_{CuBe} = -1.5$ volts, corresponding to the peak of the upper curve.

Fig. 7. Schematic of the data acquisition system for the LENS diagnostic. The negative current from the electron multiplier drives the preamplifier, whose output signal $V(t)$, representing the raw ATD data, is fed to an 8 bit digitizer. The $V(t)$ signal is digitized when a pulse burst (3) is received from the programmable clock. The clock outputs a pulse burst beginning at the instant of slot opening, as defined by the PIN diode laser detector (1), provided an arm pulse (2) has been received from the PLT timer. A total of 1024 ATD signals per shot are stored in the local digitizer memory.

Fig. 8. Time evolution of line-averaged electron density $\bar{n}_e$ during startup for a medium density deuterium discharge. The peak plasma current $I_0 = 500$ kA and the toroidal magnetic field $B_0 = 29$ kG.

Fig. 9. Measurement of the ion temperature during startup from the charge-exchange energy spectrum. The arrival time distribution (ATD) signals and calculated emission spectra are shown for times $t = 30$ and $t = 50$ msec (with 5.5 msec averaging) for the same discharge as Fig. 5.2.F1. The dashed lines were hand fit to the emission spectra to yield the temperatures shown.

Fig. 10. Comparison of the measured charge-exchange out-flux (solid line) and the value predicted by the startup model (dots) for the discharge of Fig. 8. The energy bandwidth for the flux measurement is 20 eV to 1008 eV.

Fig. 11. The measured neutral emission and power spectrum, and the ATD signal from which they are calculated, is shown during the startup (A), density rise (B), quasi-steady-state (C), and termination (D) phases of a medium density discharge. Averaging times are A: 30 to 130 msec; B: 130 to 350 msec; C: 350 to 680 msec; and D: 680 to 738 msec. The sharp cutoff in the calculated energy spectrum in the region of ~20 eV is an artifact due to the ATD signal approaching baseline for flight times ≥ 35 μ sec.

Fig. 12. Time evolution of the neutral emission, power emission, average D^0 energy, and sputtered flux, calculated from the measured energy spectra, is shown for the same medium density discharge as the data of Fig. 11. The energy integration bandwidth is 20 to 1049 eV for discharge times $t > 130$ msec. Averaging time is 11.6 msec.

Fig. 13. Response of the preamplifier to a delta function current source produced by noise pulses in the detector electron multiplier. The pulse full width at half maximum of 340 nsec, corresponding to the expected signal for arrival of a single atom at the detector, is negligibly small compared with particle flight times of interest.

Fig. 14. Improvement in the signal to noise ratio and reduction of the minimum detectable flux achieved with averaging over adjacent arrival time distributions, for data taken at $t = 50$ msec in a deuterium discharge. The upper plots show the ATD signal and calculated emission spectrum corresponding to a single slot opening. The bottom plots show the ATD signal and calculated emission spectrum after averaging over 24 adjacent slot openings, corresponding to 5.5 msec time resolution. The minimum detectable flux curves for the single shot and averaged cases are calculated for a 100 and 20 mV estimate, respectively, of the baseline noise level of the raw data.

Fig. 15. Threshold flux for the time-of-flight instrument for the usual operating voltages of the detector (see Fig. 2), chopper speed of 10500 rev/min, and a baseline noise level of 20 mV. This noise level is typical of that achieved with averaging over 25 ATDs. Incident flux must exceed the threshold flux to be detected in the presence of the various noise sources.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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Fig. 8

Fig. 9

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Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15