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**Investigation of Edge Neutral
Flux on the ISX-B Tokamak
Using a Low-Energy Charge
Exchange Analyzer**

Dan McDougal Thomas

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INVESTIGATION OF EDGE NEUTRAL FLUX ON THE ISX-B TOKAMAK USING A LOW-ENERGY CHARGE- EXCHANGE ANALYZER

Dan McDougal Thomas

Date Published - August 1983

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PREFACE

This is a report of work carried out with support from the Applied Plasma Physics Division, Office of Fusion Energy of the U.S. Department of Energy at the Oak Ridge National Laboratory (ORNL) within the Physics and Fusion Energy divisions. The report summarizes both development of a specialized neutral particle spectrometer for use in the study of high-temperature plasmas and the application of this spectrometer to particle flux measurements on the Impurity Study Experiment tokamak.

The work was performed as part of the plasma diagnostics development activities of the Atomic Physics for Fusion Program in the Physics Division at ORNL. The project also represents the dissertation work of Dan M. Thomas as a University of Texas graduate student and was carried out through an ORNL sub-contract with the University of Texas at Austin.

INVESTIGATION OF EDGE NEUTRAL FLUX ON THE ISX-B TOKAMAK USING A LOW-ENERGY CHARGE EXCHANGE ANALYZER

Dan McDougal Thomas

ABSTRACT

To study the emission of D^0 from the periphery of a tokamak plasma, a low-energy neutral particle spectrometer optimized for ($16 < E < 500$ eV) has been built and employed on the Impurity Study Experiment (ISX-B) tokamak. The diagnostic utilizes a cesium vapor cell to form negative ions from the incident D^0 neutrals and a four-channel electrostatic analyzer to energy analyze the negative ions. The spectrometer was absolutely calibrated using D^0 beams formed by electron capture by positive ions in a gas cell and by photo-detachment of negative ions by a yttrium-aluminum-garnet laser.

For the observation region chosen on ISX-B (120° toroidally away from the limiter, near the gas puff), the neutral particle flux has a two-component nature. These data are well fit by two separate exponential distributions of equivalent temperatures 6 to 8 eV for particle energies below about 80 eV and 70 to 80 eV for particle energies above 80 eV. For ohmically heated discharges, the measured particle flux in the energy range 25 to 700 eV is $\sim 2.5 \times 10^{15} \text{ cm}^{-2} \cdot \text{s}^{-1}$; the mean particle energy is ~ 70 eV, and the calculated flux at the wall is $\sim 30 \text{ mW/cm}^2$. The major effect of neutral beam heating is to increase the particle flux in the 25- to 700-eV range by a factor of 3.

1. INTRODUCTION

One of the major scientific undertakings in the world today is the search for a method to produce useful power from nuclear fusion.¹⁻³ This search has been characterized by unparalleled international scientific cooperation and investment of countless employee-hours and vast sums of money over the past few decades—with as yet no practical success.

Nuclear reactions of the type

have energy yields on the order of megajoules per gram of reactants, involve easily obtainable fuels, and are expected to pose fewer environmental risks than either present-day nuclear (fission) or conventional (e.g., coal) energy sources. To initiate such reactions on a useful scale, the energy of the fuel particles must be increased to a point sufficient to

overcome the coulombic repulsion between fusing nuclei; moreover, this condition must be maintained at sufficient densities and time scales to produce more power than required to sustain the reaction. These physical necessities have been recognized for years and are roughly quantified by the Lawson criteria:⁴ (mean density) $\times$ (confinement time) $> 10^{14} \text{ cm}^{-3} \cdot \text{s}$ at (mean energy) $> 10^4$ eV for the most energetically favorable system (D-T).

One of the most promising approaches involves the concept of magnetic confinement whereby a Maxwellian plasma is heated through various means within a configuration of magnetic fields. If arranged correctly, the fields may prevent the expansion of the plasma until the energy/particle confinement times are sufficiently long for an appreciable fraction of the particles in the high-energy tail of the velocity distribution to undergo fusing collisions. Various B -field configurations

have been tried throughout the years; one of the most rewarding has been the tokamak.⁵⁻⁷

The basic tokamak configuration is shown in Fig. 1. The geometry is toroidal, with the plasma being formed from hydrogenic gas within a doughnut-shaped vacuum vessel. Requirements for plasma confinement equilibrium and gross stability are provided by the interaction of three magnetic fields: a toroidal field B_t produced by external coils, a poloidal field B_p produced by a toroidal current driven in the plasma itself, and a vertical field B_v also created by external coils. The field ordering is $B_t > B_p > B_v$. In addition to its confining effects, the plasma current I_p may be used for ohmic heating of the plasma by finite plasma resistance. This mode of heating becomes less efficient at higher temperatures; thus, the development of alternative heating schemes such as injecting high-energy neutral beams or radio-frequency (RF) waves is of great interest.

The refinement of the tokamak concept to its current state, as exemplified by such machines as the Princeton Large Torus (PLT), the tokamak at Fontenay-aux-Roses (TFR-600), Doublet III, Alcator C, and the Impurity Study Experiment machine (ISX-B), has resulted in considerable progress toward the fusion goal; however, serious problems remain. One of the most serious problems with existing tokamak systems—and magnetic confinement schemes in general—is the loss of energy from the reaction region via the nonconfined plasma components (i.e., neutral particles and photons).

Photon and neutral fluxes are useful for diagnostic purposes because they carry valuable information about the plasma region, but they are extremely detrimental to energy confinement. This is attributable in part to the energy lost in the primary fluxes but chiefly comes from the effect the primary fluxes have on the material surfaces nearest the plasma. This plasma-wall interaction⁸⁻¹⁰ (including ion-limiter effects) contributes nonhydrogenic impurities to the plasma via such mechanisms as sputtering, blistering, and arcing and also provides an abundant yet uncontrolled source of fuel atoms by enhanced desorption from the walls. These effects lessen control over the discharge and lead to further degradation of energy confinement.^{8,11}

Because this interchange of energy and material at the plasma-wall interface has such a significant effect on present-day confinement experiments and is expected to be as important in the next generation of machines, it would seem crucial that a thorough understanding of this region be acquired. Although models of increasing sophistication have evolved in the past few years,¹²⁻²⁰ there is rather little experimental information to compare them with directly. In particular, measurements of the low-energy ($E < 500$ eV) neutral particles emerging from the plasma periphery are rare. Such neutrals, presumably originating in the edge region, are quite interesting. In addition, because the first measurements of neutral flux (Γ_0) were made at higher energies, it has been obvious that the vast majority of the neutrals being emitted were in the low-energy range; this is attributable to the peaking of the neutral density (and thus the charge exchange source) near the relatively cool edge.

The lack of data on Γ_0 for low energies is a consequence of several factors. In trying to observe low-energy atomic fluxes, one is hampered by the lack of suitable detection schemes. Conventional neutral particle charge exchange analyzers, which rely on stripping collisions to create positive ions from neutrals,²¹⁻²³ are inefficient at low energies. There has been some success using various material probes,²⁴⁻²⁷ which are exposed to edge plasmas and then removed for surface analysis of the trapped flux. Exposure times are generally too long to obtain time resolution of flux behavior; one simply

Fig. 1. Schematic of a typical tokamak configuration.

measures the flux integrated over one or more slots. Recent experiments with rotating probes²⁸⁻³⁰ attempt to circumvent this difficulty. The perturbing effects of probes on the edge plasma are unknown.

Spectroscopic examination of various line emissions from both hydrogenic^{31,32} and impurity³³⁻³⁵ atoms can give information on the densities and temperatures of these components in the edge region. Calibrations to standard sources are difficult, as are stray light problems. Spatial resolution is complicated by the line-integrated nature of the measurement. An additional spectroscopic approach using resonance fluorescence has been pursued in the past few years on several machines.³⁶⁻³⁸ In this method one uses laser radiation tuned to a resonant transition of the species of interest to induce fluorescence. This method has the advantage of being a local measurement and divorces the atomic excitation from the electron behavior (one need not worry about edge T_e , N_e). Limitations on this approach include difficulties in creating the proper pump radiation as well as background problems from the natural line emission. Absolute calibration is still a serious obstacle.

Brissom et al.³⁹ have used a variation on the familiar charge exchange analyzer to examine the low-energy hydrogen flux from the ELMO Bumpy Torus (EBT-1). Their apparatus replaces the gas stripping cell with a cesium vapor cell that converts low-energy neutrals to negative ions via electron attachment capture collisions. Measurements with low-energy atomic beams yielded an absolute calibration for neutral hydrogen for energies above about 100 eV. At that energy, overall efficiency was over two orders of magnitude greater than that for a similar device using a nitrogen stripping cell. The analyzer had only one channel suitable for measurements on an EBT steady-state discharge.

Time-of-flight analysis^{40,41} of neutral particles has recently been pursued by Voss^{42,43} on the PLT tokamak and by Brocken⁴⁴ on the Tortur II turbulently heated torus. In both cases a high-speed vacuum rotor⁴⁵ is used to chop the neutrals that then stream freely over a specified distance to a Daly detector. The arrival time distribution of the neutrals at the detector may be unfolded to yield

the energy spectrum, if one assumes a unique mass for the neutrals. Response of the detector as a function of energy was calculated from secondary emission data in the literature⁴⁶ in the case of the Tortur device, whereas it was measured using atomic beams in the case of the PLT device as part of an absolute calibration.⁴³ Comparison of measured flux with calculated flux values showed much better agreement in the latter case. Voss's results are the most informative to date on the effects of such parameters as neutral beam injection, RF heating, and gas puffing on the behavior of low-energy emission from present-day tokamak devices.

The current study deals with the development and implementation of a multichannel charge exchange analyzer, similar to the one used by Brissom, optimized for low-energy measurements on the ISX-B tokamak. After construction, the system was calibrated using neutral deuterium beams to provide absolute values for the low-energy neutral flux observed. Data were taken on ISX-B for a variety of discharge conditions during fall 1981. No attempt was made to vary the viewing angle or to do mass analysis of the flux during this period. The main thrust was to quantify for one viewing angle the total emission behavior as a function of time and energy (under the assumption of a pure deuterium flux). After removal from the machine, a more rigorous calibration was performed to verify the conversion efficiencies and long-term stability of this type of diagnostic. This procedure yielded $\Gamma_0(E, t)$ for approximately 700 shots on ISX-B. Experimental difficulties restricted the energy range of accurate calibration to $\sim 40 \text{ eV} < E_0 < 750 \text{ eV}$; however, signals could be seen down to 16 eV.

Chapter 2 discusses the edge region and low-energy neutral flux in the context of what one can measure and outlines the procedure for an experimental determination of Γ_0 . Chapter 3 discusses the apparatus developed for making a local measurement of the flux and discusses the salient features of each component. Chapter 4 describes the procedures used to obtain an absolute calibration of the spectrometer. Chapter 5 gives information on the interfacing of the diagnostics to the ISX-B tokamak, giving a basic description of the machine as well as the types of plasma discharges commonly

encountered. In chapter 6, the experimental results are discussed with emphasis on the parametric behavior of the low-energy flux for various plasma

conditions. Finally, in chapter 7 the results are summarized and directions for future work in this area are pointed out.

2. THEORY OF THE MEASUREMENT

2.1 INTRODUCTION

In all present-day magnetic confinement devices, there is an edge or scrapeoff region that separates the main plasma discharge ($kT > 100$ eV) from the material wall ($kT \sim 1/40$ eV). The boundary may be caused by a material limiter or by a contactless magnetic divertor. This region is characterized by a high neutral hydrogenic density (atomic and molecular) that arises from several sources. Molecular hydrogen enters via gas puffing and desorption from the walls. These cold molecules can undergo a variety of reactions in the periphery (Table 1)—for example, successive electron impact ionization and dissociation, leading to Franck-Condon neutrals having energies of a few electron volts. These neu-

trals may in turn interact with edge plasma ions through charge exchange and so forth. The limiter itself is an important source of fast neutrals through neutralization of the incident ion flux.

All of these neutrals as well as higher energy neutrals resulting from charge exchange and recombination in the core plasma are unconfined by the magnetic fields and will tend to escape, creating a neutral flux Γ_0 at the wall. This flux is one of the primary components of the plasma-wall interaction. Figure 2 shows schematically the edge region of a tokamak as well as a diagram illustrating various fluxes involved in the interaction picture. Because Γ_0 is in general a complex function of neutral species, angle, energy, and position, a complete experimental determination is prohibitive. What is

Table 1. Some atomic and molecular reactions of interest in the edge region

Electron impact ionization	$e^- + H_2 \rightarrow H_2^+ + 2e^-$ $e^- + H \rightarrow H^+ + 2e^-$
Proton impact ionization	$H^+ + H_2 \rightarrow H_2^+ + H^+ + e^-$ $H^+ + H \rightarrow H^+ + H^+ + e^-$
Dissociation (Franck-Condon)	$e^- + H_2 \rightarrow H + H + e^- + \text{k.e.}$
Dissociative ionization	$e^- + H_2 \rightarrow H^+ + H + 2e^- + \text{k.e.}$ $\rightarrow H^+ + H^+ + 3e^- + \text{k.e.}$
Dissociative recombination	$e^- + H_2^+ \rightarrow H^* + H + \text{k.e.}$
Dissociative excitation	$e^- + H_2^+ \rightarrow H^+ + H^* + \text{k.e.}$
Charge exchange:	
Resonant	$H^+ + H \rightarrow H + H^+$
Nonresonant	$H^+ + H_2 \rightarrow H + H_2^+$
To excited level	$H^+ + H \rightarrow H^* + H^+$
Electron attachment	$e^- + H_2 \rightarrow H_2^-$
Electron capture	$H_2^+ + H_2 \rightarrow H_2 + H_2^+$ $H + H_2 \rightarrow H^- + H_2^+$
Rearrangement	$H_2^+ + H_2 \rightarrow H_3^+ + H$
Transfer ionization	$H^+ + H_2 \rightarrow H + H_2^{2+} + e^-$
Photodissociation	$h\nu + H_2 \rightarrow H + H + \text{k.e.}$
Photoionization	$h\nu + H_2 \rightarrow H_2^+ + e^-$
Photodetachment	$h\nu + H^- \rightarrow H + e^-$
Negative ion	$H^- + H_2^+ \rightarrow H + H_2$
formation/destruction	$H^- + H^+ \rightarrow H + H$ $e^- + H^- \rightarrow H + 2e^-$

Fig. 2. On the left is a cross section through a tokamak showing the edge or scrapeoff region between the plasma and vacuum vessel along with the various sources contributing to the hydrogen inventory. The schematic on the right illustrates the associated particle fluxes Γ_i .¹⁴

Γ^G	=	flux attributable to gas puffing
Γ^D	=	flux attributable to wall desorption/detrapping
Γ^R	=	flux attributable to reflected plasma outflux
Γ^H	=	flux attributable to plasma
Γ^L	=	flux attributable to limiter

In general, any ion hitting the limiter will be reemitted as a neutral (which is subsequently reionized). Thus, the limiter acts as a sink for ions and a source for neutrals.

feasible is to make a local measurement of the neutrals escaping through a small hole in the wall and then, based on simplifying assumptions, relate its behavior to that of the total flux. We now discuss the mechanics of this measurement.

2.2 RELATION BETWEEN FLUX AND MEASURED QUANTITIES

The apparatus developed for observing the neutral flux is quite similar to an optical system, and many of the quantities of interest have exact ana-

logues in the field of radiometry (Table 2).^{47,48} We begin by examining the geometry of the local measurement.

Consider the situation shown in Fig. 3 where we have a black box viewing a local region of the plasma through the defining apertures having areas A_1 , A_2 . The projected area at the surface of the plasma from any point in A_2 is given by $A_p = A_1(L_{p1} + L_{12})^2/L_{12}^2$, while the solid angle subtended by the detector is $d\Omega = A_2/(L_{p1} + L_{12})^2$. Note the étendue $A_p d\Omega = A_1 A_2 (L_{12})^{-2}$ is independent of the distance L_{p1} . We may identify the

Table 2. Optical analogs of flux parameters

Parameter	Optical analog
$\frac{dN}{dt} = \Phi_n \frac{\text{particles}}{s}$	Φ_I radiant power $\frac{\text{ergs}}{s}$
$\frac{d\Phi_n}{dE} \frac{\text{particles}}{s \cdot \text{eV}}$	$\frac{d\Phi_I}{d\lambda}$ spectral radiant power $\frac{\text{ergs}}{s \cdot \text{\AA}}$
$\Gamma = \frac{d\Phi_n}{dA} \frac{\text{particles}}{s \cdot \text{cm}^2}$	$M_I = \frac{d\Phi_I}{dA}$ irradiance $\frac{\text{ergs}}{\text{cm}^2 \cdot s}$
$\frac{d\Phi_n}{d\Omega} \frac{\text{particles}}{s \cdot \text{sr}}$	$I_I = \frac{d\Phi_I}{d\Omega}$ radiant intensity of a point source $\frac{\text{ergs}}{s \cdot \text{sr}}$
$\frac{d\Gamma}{d\Omega} = \frac{d^2\Phi}{dA d\Omega} \frac{\text{particles}}{s \cdot \text{cm}^2 \cdot \text{sr}}$	$L_I = \frac{d^2\Phi_I}{dA d\Omega}$ radiance of an extended source $\frac{\text{ergs}}{\text{cm}^2 \cdot s \cdot \text{sr}}$
$\frac{d\Gamma}{dE d\Omega} \frac{\text{particles}}{\text{eV} \cdot \text{cm}^2 \cdot s \cdot \text{sr}}$	$\frac{d^3\Phi_I}{dA d\Omega d\lambda}$ spectral radiance $\frac{\text{ergs}}{\text{\AA} \cdot \text{cm}^2 \cdot s \cdot \text{sr}}$

neutrals entering the detector with the differential neutral flux $d\Gamma/(dE d\Omega)$ through the aperture A_1 . This quantity is equivalent to the spectral radiance in radiometry and has units of particles/($\text{cm}^2 \cdot s \cdot \text{sr} \cdot \text{eV}$). The flux through A_1 may be related to the flux through the observed surface A_p under the following assumptions:⁴³

1. uniform luminance of source— A_p must be small compared to the dimensions over which plane source assumptions are valid;
2. small solid angle (i.e., $d\Omega \ll 4\pi$); and
3. negligible losses—the attenuation of the low-energy neutrals in traversing L_{p1} must be small.

This last condition is the most difficult to satisfy physically because the collimating aperture A_1 is generally located outside the vacuum vessel and is separated from the plasma periphery by a blanket of neutral gas. The pressure in this blanket region is of order 10^{-4} torr, and it may be of considerable length in contemporary tokamaks ($L_{p1} = 290$ cm) in PLT.⁴³ For the current study, $L_{p1} = 82$ cm. To the extent that conditions 1 to 3 are satisfied, we may consider the source to be at the plasma edge;

otherwise, what we are observing is an extended source encompassing the entire edge region.

Information about the energy distribution of the neutral flux is dependent on the resolving capabilities of the black box. As mentioned previously, we use electron capture in cesium vapor to convert a

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Fig. 3. Geometry for observing a surface flux from a plasma. The black box detector having entrance aperture of area A_2 views the projected area A_p through the collimating aperture of area A_1 . For small enough solid angles (dotted lines) the source may be approximated as a plane source; θ is the angle from the normal.

fraction of the neutrals to negative ions and then energy analyze the ions. In particular, each of the analyzer channels will have its own overall conversion efficiency $\eta_i(E)$ and passband $\Delta E_i(E)$. The time resolution is determined by the rate at which the ion detectors are sampled.

From the above, we may express the neutral flux at energy E_i in terms of the counts in the i^{th} detector by

$$\left. \frac{d\Gamma}{dE d\Omega} \right|_{E_i} = \frac{N_i}{(\Delta E_i)(\Delta A \Delta \Omega)(\Delta t)[\eta_i(E_i)]}, \quad (2.1)$$

where

$$\begin{aligned} N_i &= \text{number of counts in the } i^{\text{th}} \\ &\quad \text{channel, ions;} \\ \Delta E_i &= \text{passband of } i^{\text{th}} \text{ channel at energy} \\ &\quad E_i, \text{ eV;} \\ \Delta A \Delta \Omega &= \text{étendue of system, cm}^2 \cdot \text{sr;} \\ \Delta t &= \text{counting interval, s;} \\ \eta_i(E_i) &= \text{overall conversion efficiency,} \\ &\quad \text{ions/neutrals.} \end{aligned}$$

The experimental setup on ISX-B requires that two additional factors be taken into account:

1. Nonnormal viewing angle: Measurements of the flux at $\theta = 0$ requires an assumption about the angular distribution of the emitted flux. Consistent with assumption (1) regarding the uniform luminance, we assume the emission to be Lambertian:

$$\left. \frac{d\Gamma}{dE d\Omega} \right|_{\theta=0} = \left. \frac{d\Gamma}{dE d\Omega} \right|_{\theta=\theta_0} \cdot \left(\frac{1}{\cos \theta_0} \right). \quad (2.2)$$

For the current study, $\theta_0 = 35^\circ$, $(1/\cos \theta_0) = 1.22$.

2. Scattering inside the detector: Until now, we have assumed an ideal black box with perfect detection/analysis capabilities. This led to the tacit assumption that the number of negative ion counts could be unambiguously related to the total number of neutrals traversing A_2 . In reality,

because of the large angular scattering and attenuation of low-energy neutrals in the cesium vapor,⁴⁹ it is difficult if not impossible to account for all of the flux entering the heat pipe. This same scattering affects the manner in which the converted ions enter the energy analysis region, changing the energy resolution (see chapter 4). Thus, the convention followed in previous charge exchange measurements^{21,50} of placing the limiting aperture in front of the scattering region is unwise in this case. If, on the other hand, we place the limiting aperture behind the cesium cell, we can decouple the analyzer somewhat from the scattering; more importantly, we can now unequivocally identify the conversion efficiency during calibration (chapter 4) in terms of the flux through the analyzer entrance aperture. The only requirement is that we always illuminate the heat pipe in a similar manner, whether during observations on the tokamak or during calibration. The former case is always satisfied because there is only one aperture between the plasma and the heat pipe. During calibration, precautions must be taken to similarly fill the heat pipe entrance.

2.3 ADDITIONAL RELATIONS

Having established the relationship between the detector output $N_i(E, t)$ and the differential flux, other quantities of interest may be derived. From Eqs. (2.1) and (2.2), the differential flux normal to the surface A_p is

$$\begin{aligned} \left. \frac{d\Gamma}{dE d\Omega} \right|_{\substack{E=E_i \\ \theta=\theta_0}} &= \left[\frac{N_i}{\Delta E \Delta A \Delta \Omega \Delta t \eta_i(E_i) \cos \theta_0} \right] N_i \\ &= \left[\frac{R_{12}^2}{\Delta E_i A_1 A_2 \Delta t \eta_i(E_i) \cos \theta_0} \right] N_i \\ &= I_0(E). \end{aligned} \quad (2.3)$$

By assuming a cosine distribution, one may integrate over the outward (2π) solid angle to obtain the spectral irradiance

$$\begin{aligned}\frac{d\Gamma}{dE} &= \int_{2\pi} I_0 \cos \theta \, d\Omega \\ &= 2\pi I_0 \int_0^{\pi/2} \sin \theta \cos \theta \, d\theta = \pi I_0 . \quad (2.4)\end{aligned}$$

This is equivalent to the number of particles hitting the wall per unit area, per unit time, per unit energy interval. By tuning the analyzer to pick out different energies, one may obtain the entire energy spectrum at a particular angle θ_0 . Then, integrating Eq. (2.4) over all energies gives the flux per unit area:

$$\Gamma_0 = \int \frac{d\Gamma}{dE} \, dE = \frac{\text{particles}}{\text{cm}^2 \cdot \text{s}}$$

From this point, one is tempted to perform the final integration over area to obtain Φ_0 , the total flux to the wall. This requires the assumption of toroidal and poloidal symmetry for emission throughout the machine or an adequate model for weighting the integral based on assymetries from such sources as the limiter or gas puffing. Neither the model nor the symmetry exist at the current time, thus it is risky to extrapolate from the local measurement to a global one. We will discuss this problem further in chapter 4. For now, we discuss the hardware used in making the local measurement.

3. DEVELOPMENT OF SPECTROMETER

3.1 INTRODUCTION

In this chapter we discuss the three major components of the neutral atom spectrometer. They are (1) the cesium vapor cell, which creates a stable charge exchange target for conversion of low-energy neutrals to negative ions; (2) the electrostatic analyzer, which analyzes the energies of negative ions by deflecting different energy components into four exit channels; and (3) the detectors, which consist of conventional channel electron multipliers specially configured for high sensitivity to low-energy negative ions and for low noise. We also discuss the neutral atom detectors used in the calibration procedure. Finally, we describe the assembly of the spectrometer from the above components and briefly describe the auxiliary equipment used for data taking on the tokamak and during calibration of the spectrometer.

3.2. CHARGE EXCHANGE CELL

3.2.1. Use of Cesium Vapor as Charge Exchange Medium

From the discussion in the previous chapter, it is clear that nontraditional methods are called for to permit the analysis of neutral particle emission to be extended to energies below 500 eV. Because one of the major drawbacks of gas stripping charge exchange diagnostics is the low overall efficiency of the stripping process at low energies, it was decided to use a different system entirely—that of electron attachment in cesium vapor:

Collisions between fast hydrogen atoms or ions and alkali metal targets are of considerable interest not only from an atomic physics viewpoint but because they offer an attractive method of creating intense negative ion beams for use in neutral beam plasma heating schemes. In recent years, this latter intent has led to a sizeable body of work on the various possible reactions. In particular, the charge exchange cross sections (σ_{if} , where i = initial

charge state and f = final charge state) are well known.⁵¹⁻⁵³ Figure 4⁵² shows σ_{0-} for hydrogen and deuterium atoms incident on cesium as a function of projectile energy per atomic mass unit in the sub-keV range. The charge exchange cross sections are seen to be the same for equal velocities (or energy per atomic mass unit); thus, $\sigma_H(E) = \sigma_D(2E)$.

We may now consider what sort of conversion efficiency one might expect for a low-energy neutral deuterium beam in passing through a cesium vapor charge exchange cell. We define the fraction F_m of particles in charge state m of the total outgoing beam by

$$F_m = \frac{I_m}{I_+ + I_0 + I_-}, \quad (3.2)$$

where I_+ , I_0 , and I_- are the various emergent beam intensities. Under thin target (i.e., single collision) conditions, the probability of forming a D^- by electron capture in a cell of length l cm and cesium

Fig. 4. Electron attachment cross-section σ_{0-} for the reaction.

plotted as a function of collision energy per atomic mass unit. Triangular data points were obtained using hydrogen; circular data points were obtained using deuterium.⁵²

density $n \text{ cm}^{-3}$ is simply $P = \sigma_0 n l = \sigma_0 \Pi$, where we define the target thickness to be $\Pi = n l$ (atoms·cm⁻²). Note that the thin target assumption requires $\Pi \sigma \ll 1$.

To increase the conversion efficiency, Π must be increased to the point where multiple collision effects dominate the negative ion formation and the thin target picture is no longer valid. In general, the charge state fractions may be expressed as a set of coupled differential equations

$$\begin{aligned} \frac{dF_+}{d\Pi} &= F_0 \sigma_{0+} + F_- \sigma_{-+} - F_+ (\sigma_{+0} + \sigma_{+-}) \\ \frac{dF_0}{d\Pi} &= F_+ \sigma_{+0} + F_- \sigma_{-0} - F_0 (\sigma_{0+} + \sigma_{0-}) \end{aligned} \quad (3.3)$$

$$\begin{aligned} \frac{dF_-}{d\Pi} &= F_+ \sigma_{+-} + F_0 \sigma_{0-} - F_- (\sigma_{-+} + \sigma_{-0}), \end{aligned}$$

where we neglect the two-step processes. As Π is increased to the point where so many charge exchange collisions occur that the identity of the initial beam is lost, the exiting fractions will be independent of both the initial charge state and any further increases in target thickness. The minimum target for which this is true is called the equilibrium thickness Π_e . At equilibrium

$$\left. \frac{dF_m}{d\Pi} \right|_{\Pi > \Pi_e} = 0$$

Then from Eqs. (3.2) and (3.3)

$$\begin{aligned} F_0 \sigma_{0+} &= F_+ \sigma_{+0} \\ F_0 \sigma_{0-} &= F_- \sigma_{-0} \\ F_+ \sigma_{+0} + F_- \sigma_{-0} &= F_0 (\sigma_{0+} + \sigma_{0-}) \\ F_+ &= 1 - F_- - F_0, \end{aligned} \quad (3.4)$$

yielding

$$\begin{aligned} F_0 &= F_- \left(\frac{\sigma_{-0}}{\sigma_{0-}} \right) = F_+ \left(\frac{\sigma_{+0}}{\sigma_{0+}} \right) \\ \Rightarrow F_- &= \frac{\sigma_{0-}}{\sigma_{-0} + \sigma_{0-} - \sigma_{-0} \left(\frac{\sigma_{0+}}{\sigma_{+0}} \right)} \\ &= \frac{\sigma_{0-}}{\sigma_0 + \sigma_{-0}}, \end{aligned} \quad (3.5)$$

where we neglect stripping compared to capture ($\sigma_{0+} \ll \sigma_{+0}$).

Any further increase in Π will only increase the scattering losses and decrease the overall efficiency for any collection geometry. Π_e for the deuterium-cesium system is on the order of 3×10^{15} atoms·cm⁻².⁵² If we assume a cell length of ~ 10 cm, this implies cesium densities on the order of 10^{13} to 10^{14} cm⁻³ will be necessary. Examination of the cesium vapor pressure curve (Fig. 5) reveals that cell operating temperatures will have to be on the order of 150°C. A major practical consideration is how to satisfy these requirements in a high vacuum environment without losing excessive cesium out the cell apertures—resulting in (1) unacceptable contamination of the tokamak and analyzer and (2) unacceptably short cell availability. In addition, the cesium will tend to condense on any unheated apertures as a solid, resulting in a gradual clogging of the apertures and seriously affecting the transmission. Under these conditions, a meaningful calibration is impossible. To minimize these problems, a cell design based on the principles of a heat pipe was adopted.

3.2.2. Cesium Heat Pipe—Operating Principle

The cell used in this investigation is based upon a design by Bacal et al.^{55,56} and is similar to the one employed by Brissom et al. to observe low-energy neutrals emanating from the ELMO Bumpy Torus.³⁹ Analogous devices have been used for spectroscopic studies on metal vapors for a number of years^{57,58}—where a similar need exists for well-

Fig. 5. Vapor pressure as a function of temperature for cesium. The curve is a best fit to published data as evaluated by Schlachter.⁵⁴ Number densities (cm^{-3}) are obtained from the formula

$$n_{cs} = \frac{(2.69 \times 10^{19})(273.15) P}{(760)(273.15 + T)}$$

where T is in $^{\circ}\text{C}$; P is in torr. The operating point chosen in the current study is indicated by the dotted line $T = 122.5^{\circ}\text{C}$.

defined and stable column densities. The original development of the heat pipe as a high thermal conductance device, was performed by Grover et al.⁵⁹ and others⁶⁰⁻⁶⁵ at Los Alamos National Scientific Laboratory in the early 1960s. A good basic introduction to heat pipes was written by Eastman.⁶⁶ Although rigorous analysis of the different modes of heat pipe operation can be quite complex, the fundamental properties may be easily understood.

Basically, a heat pipe consists of an evacuated chamber, usually a tube, which is lined internally with a capillary network called a wick (Fig. 6). The wick is saturated with a fluid having a significant

Fig. 6. Adaptation of the heat pipe concept (a) to a charge exchange gas cell (b).

vapor pressure in the temperature range of interest. Substances as varied as water, mercury, fluorocarbons, and liquid alkali metals have been used successfully as working fluids; about the only requirement is that the fluid wet the wick. Thus, there is a two-phase equilibrium between the liquid phase in the wick and the vapor phase in the remaining space, with evaporation and condensation occurring at the interface. When one end of the system is heated and another cooled, there will be a net rate of evaporation at the heated end—balanced by vapor flow to the cooled end with a net rate of condensation. The condensate is then returned to the heated end via capillarity in the wick. Depending on the latent heat of vaporization of the working fluid, very high heat transfer can be achieved between the ends of the heat pipe under essentially isothermal conditions.

This mode of operation is not at all satisfactory for a cesium exchange cell design inasmuch as the vapor pressure is approximately constant throughout the pipe, and, thus, losses through any apertures will occur as before. Indeed, the use of these devices for transmitting large amounts of heat demands a closed tube to prevent significant loss of the working fluid. However, consider a heat pipe of the geometry shown in Fig. 6 being operated under

the condition of relatively low heat input and vapor pressure such that little heat transfer occurs. If we can provide a large enough heat sink at the ends, it is possible to maintain a considerable temperature gradient between the hot central section and the arms. Then, from the pressure-temperature behavior of cesium we see it is possible to achieve a high density in the center while having the apertures only a few centimeters away. This reduces the solid angle for loss out the ends by $\sim 1/r^2$, where r is the arm length between the hot center and end aperture. In addition, by clamping the arm temperature slightly above the melting point of cesium (28.5°C), we ensure condensation in the liquid phase; and, thus, the earlier problem of solid cesium clogging the apertures is avoided. The total target thickness, Π , is easily adjusted by varying the central temperature. Depending on the total thermal mass of the device, a stable equilibrium may be achieved in a

short amount of time. Note that operation of the device in this mode hardly qualifies it as a heat pipe because very little heat transfer occurs. However, the properties of stable target thickness, low vapor pressure at the apertures, and recycling of the condensation in the arms make it admirably suited for use as a charge exchange cell.

3.2.3 Design of Cesium Vapor Charge Exchange Cell

The final configuration for the heat pipe is shown in Fig. 7. (The author is indebted to J. Ray for the initial cell design as well as for considerable advice during construction.) Design parameters are given in Table 3 and some physical properties of cesium are given in Table 4.

The body was machined from a solid block of 304 stainless steel and fitted with two stainless tubes to form the vacuum container with a clear bore of

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Fig. 7. Specific design of the cesium vapor heat pipe as a charge exchange gas cell for neutral particle spectrometry.

Table 3. Cesium heat pipe—design parameters

Body	304 stainless steel block, $1 \times 10 \times 3.8 \text{ cm}^3$
Arms	304 stainless steel tubing, 12.7-mm OD $\times$ 10.9-mm ID
Wick	304 stainless steel wire cloth, 200 lines/in.; 5 turns spot welded. Length = 127 mm, 10.9-mm OD $\times$ 9.5-mm ID
Entrance aperture	8 mm
Heating	4 $\times$ 30-W cartridge heaters installed in body, nominal power input $\sim 90 \text{ W}$. Length of heated section = 3.8 cm
Cooling	Constant temperature water bath with external heat exchanger, run through 6.5-mm copper tubing on arms; 3 turns/arm, run in series
Cesium charge	6 g (3.2 cm^3)
Charge lifetime (estd)	>2000 h at operating temperature
Temperature measurement	Calibrated iron-constantan thermocouples, accurate to 0.02°C
Operating range	Central temperature T_1 — $32^\circ\text{C} < T < 200^\circ\text{C}$, nominal $122.5^\circ \pm 0.4^\circ$; arm temperature T_2 , nominal $32.1^\circ \pm 0.8^\circ$; central pressure P_1 , $3 \times 10^{-6} < P_1 < 10^{-1} \text{ torr}$ (nominal $2.8 \times 10^{-3} \pm 2.5\%$)

Table 4. Cesium data

Cesium is the most electropositive and the most alkaline element;
it combines explosively with H_2O

Atomic weight	132.8 (one stable isotope)
Atomic number	55
Melting point, $^\circ\text{C}$	28.5
Density (solid), g/cm^3	1.87
Valence	1
Work function, eV	2.14
Ionization potential (I), eV	3.89
Ionization potential (II), eV	25.1
Atomic diameter, $\text{\AA}$	5.4
Ionic diameter, $\text{\AA}$	3.38
Common oxide forms:	
Cesium oxide	CsO_2
Cesium peroxide	Cs_2O_2
Cesium trioxide	CsO_3
Cesium hydroxide	CsOH
Properties at operating temperature (122.5°C)	
Average velocity, cm/s	2.52×10^4
Vapor pressure, torr	2.8×10^{-3}
Vapor density, cm	6.7×10^{13}
Mean free path (cesium-cesium), cm	0.2

10.9 mm. This material was chosen for its good vacuum properties, high specific heat (for thermal stability), and resistance to chemical attack by cesium in the temperature range of interest. Small slide valves were installed at both ends to provide vacuum isolation and to facilitate handling after cesium was inserted. The wick itself consisted of five turns of 304 stainless steel mesh cloth (200 lines/in.) which was spot welded into a tube that fit snugly into the pipe bore. The inner wick diameter was 9.5 mm; total length of the pipe between the valves was 127 mm. The length of the central heated section was 38 mm. The central block had two small flanges providing access to the central bore for loading cesium ampules as well as a side arm assembly provided for crushing the ampules under vacuum. All gaskets on the central section were Teflon O-rings. These worked well in the operating range ($<200^{\circ}\text{C}$), but could not be reused.

Heating of the pipe was accomplished by four small (30 W) cartridge heaters that were press fitted into the central block. The heaters were wired in parallel and powered by a single Variac® auto-transformer. Cooling of the arms was provided by circulating water from a controlled temperature bath through three copper cooling coils soldered to the outside of each arm near the valves. The same water was run through the two coils sequentially; but, for the flow rates used, there was a negligible difference in the temperatures of the two arms.

A brief analysis of the thermal behavior is instructive at this point. The desired condition is to clamp the arm temperature, T_2 , at $\sim 30^{\circ}\text{C}$ while simultaneously raising the central temperature, T_1 , from ambient ($\sim 25^{\circ}\text{C}$) to operating ($\sim 120^{\circ}\text{C}$) levels, and then to hold both T_1 and T_2 constant to within a fraction of a degree. This requires removal of a varying heat load transferred to the arms by conduction through the tube walls and by cesium condensation. By coupling a heat exchanger tube to the water bath and carefully balancing the heat loss by heating the water, it was possible to achieve minimal (0.8°C) drift in T_2 as T_1 was cycled. Stability of T_1 is very important because of the steepness of the vapor pressure curve in the operating range: a 1° change in T_1 results in a 5% change in cesium density. Throughout the course of the

experiment, the thermal stability was very good because of the large mass of the central block; typically, drifts in T_1 were held to less than 0.4°C without the use of any insulation or feedback stabilization in the heating circuit. Temperatures were monitored using calibrated iron-constantan thermocouples attached to various points on the heat pipe. The reference junctions were maintained at 0°C in a Dewar flask filled with melting ice. The electromotive force generated by the thermocouples was measured using a precision potentiometer and could be converted directly to temperatures using published tables.⁶⁷ Temperature determinations could be made in this manner with a precision of better than 0.02°C .

Because the wick must be uniformly wet by the cesium to ensure satisfactory recycling of the condensate, it must be chemically clean. After being washed with soapy water and rinsed, the wick was ultrasonically cleaned in trichloroethylene (for 1 h), acetone (for 0.5 h), and ethanol (for 1 h). A final vapor rinse in hot electronic-grade isopropanol (transene) was followed by drying with a stream of dry nitrogen gas. The wick was then heated in a vacuum oven at 150°C overnight and installed in the heat pipe. Further heating in vacuo at $>200^{\circ}\text{C}$ was performed by running the central heaters at maximum power for several days prior to cesium loading. This thoroughly outgassed the heat pipe interior and eliminated any volatile impurities that might adversely affect the cesium vapor pressure. Initially, plans were made to crack the glass cesium ampule in vacuo and distill cesium up into the wick. However, single ampules having sufficient cesium to saturate the entire wick (~ 5 g) were not available; hence, a more awkward (and dangerous) loading procedure had to be adopted. A gas-tight container was erected around the heat pipe and filled with argon, allowing direct loading of the pipe through a small flange on top of the central section. Sufficient ampules (either 1 or 3 g) were cleaned carefully with alcohol, then warmed above the melting point, opened in the inert atmosphere, and the cesium carefully poured in. The heat pipe was also gently warmed to avoid clogging the opening during the filling operation. This procedure did not introduce any significant contaminants

because of the high purity (>99.98%) of the cesium ampules used.

After the flange was sealed, the heat pipe was cycled gradually to maximum temperature several times to thoroughly saturate the wick as well as to outgas any remaining volatile impurities. Measurements were then made using a hot wire surface ionization gauge to assess the actual cesium end losses before beginning the calibration (see Appendix A).

3.3 ANALYZER

To characterize the makeup or energy distribution of the observed neutral flux based on negative ion formation in the cesium cell, one must insert some sort of dispersive element—a particle analyzer—between the heat pipe and detectors. Such analyzers have played an integral role in the development of experimental physics; they range from the simple apparatus used by Thompson for his early work on positive ions⁶⁸ to the precision instruments designed today for use in such diverse areas as photoelectron spectroscopy, space physics, laser-produced plasma analysis, surface physics studies, and atomic collisions.

Particle analyzers may be characterized by the parameter of interest (e.g., mass, velocity, and energy) and by their method of dispersion (e.g., time of flight, field deflection, and energy retardation). The choice of analyzer for a specific task is based on such considerations as particle type, expected energy/momentum range, source divergence, and required resolution.

For the case of low-energy ions and for electrons, the usual choice is an electrostatic device because this eliminates the bulky magnetic systems conventionally used for higher energies. The reader is referred to two excellent reviews^{69,70} in this area in addition to detailed articles on specific geometries.⁷¹⁻⁷⁸ A drawback to the use of a purely electrostatic analyzer is that it is essentially an energy analyzer—no mass discrimination is possible without further analysis. This shortcoming is shared with such methods as time-of-flight analysis,^{40,41} which has also been used to examine neutrals in this energy range.⁴²⁻⁴⁵ Because the nonhydrogenic contribution is expected to be small in the current measurement, mass discrimination may be dispensed

with—permitting selection of the simpler electrostatic design. (For extensions of the current technique to impurity analysis, see chapter 7).

A planar geometry was chosen over the more complex spherical or cylindrical shapes for a number of reasons. Electrode construction is simpler, the precise spacing is less crucial, and the design is easily adapted to multichannel use. A sketch showing the important features of a single channel instrument is shown in Fig. 8. Two parallel plates separated by a distance, d , are biased to form a uniform electrostatic field. Slits are provided on one of the plates to allow a beam of particles in and out of the field region. This plate is generally grounded to eliminate external deflections of the beam and associated focusing effects. The other plate is biased at a voltage, $-V$, and the field has a uniform strength $E = V/d$ in the direction shown. The guard rings are suitably biased through a resistive chain to minimize fringing effects attributable to the finite size of the analyzer.

Consider a particle of charge $-e$ and energy E_0 , entering the analyzer at an angle θ as shown. Then, following Harrower,⁷² the trajectory of the particle is given by the parabolic equation

$$Y(X, \theta) = X \tan \theta - \frac{eVx^2}{4E_0 d \cos^2 \theta} \quad (3.6)$$

For the particle to pass through the exit slit requires

Fig. 8. Schematic of a parallel plate, charged particle analyzer.

$$X_0 = \frac{2E_0 d \sin 2\theta}{eV}, \quad (3.7)$$

where X_0 is the slit spacing. Thus, this geometry gives a linear dispersion in energy for both tuning voltage and distance along the ground plane. For the specific choice of $\theta = 45^\circ$, we note X_0 is a maximum for a given E_0 . In addition, from Eq. (3.7),

$$\left. \frac{dX}{d\theta} \right|_{\theta = 45^\circ} = \frac{4E_0 d \cos 2\theta}{eV} = 0. \quad (3.8)$$

Thus, this geometry is first-order focusing for the chosen angle—a useful property, because in actuality the beam entering the analyzer will have a finite divergence. The maximum height Y_m that a particle will attain in the analyzer is given from symmetry considerations by

$$\begin{aligned} Y_m &= Y\left(\frac{X_0}{2}, \theta\right) \\ &= \frac{X_0}{2} \tan \theta - \frac{eV}{4E_0 d \cos^2 \theta} \left(\frac{X_0}{2}\right) \\ &= \frac{X_0}{4} \tan \theta, \end{aligned} \quad (3.9)$$

for $\theta = 45^\circ$, $Y_m = X_0/4$. An obvious requirement of construction is that $d > Y_m$. Allowing for a reasonable range of entrance angles about $\theta = 45^\circ$ will determine the actual minimum plate separation. The resolution of an analyzer denotes the range of energy, ΔE , which particles of mean energy E may possess and still pass through the analyzer for a given tuning voltage. For an ideal parallel plane analyzer $\Delta E/E$ depends strongly upon the slit widths ΔX_1 , slit spacing X_0 , and angular acceptance $\Delta\theta$; it may be expressed as (for $\theta = 45^\circ$):

$$\begin{aligned} \frac{\Delta E}{E} &= \frac{\Delta X_1 + \Delta X_2}{X_0} (1 + \sec 2\Delta\theta) \\ &\quad - (1 - \sec 2\Delta\theta) \end{aligned} \quad (3.10)$$

Note that for a given geometry the resolution is minimized for zero divergence. In addition, it is easy to see from Eq. (3.7) that $\theta = 45^\circ$ also yields the best (i.e., the minimum) resolution (for a given E , X_0 is maximized).

Equation (3.10) is inadequate for our purposes insofar as it is derived from individual particle trajectories; it incorporates the effects of finite beam divergence but not finite beam size. It may be considered as the passband of the analyzer and as such represents an upper bound on the achievable beam resolution. Consider the situation shown at the top of Fig. 9, where a parallel beam of energy E and entrance angle $\theta = 45^\circ$ uniformly illuminates the entrance aperture. If the tuning voltage is slightly lower than required by Eq. (3.7), then the

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Fig. 9. Analyzer transmission functions for a finite-width beam for the three cases where the entrance aperture is smaller than, equal to, or larger than the exit aperture. X_0 is the distance between slit centers.

beam will be focussed as shown near the exit slit, forming an image of entrance slit. We may express the intensity I in ions per square centimeter at the exit slit as

$$I = \frac{n_0}{\Delta X_1 \Delta Z},$$

where $\Delta X_1 \Delta Z$ is the area of the slit entrance and n_0 is the total number of admitted ions. As the voltage increases (or equivalently, the incident energy decreases), the image will move across the exit slit and a fraction, f , will be transmitted. This is equivalent to a convolution of the entrance and exit slits, and a plot of f versus E is, in general, trapezoidal (triangular for the limiting case $\Delta X_1 = \Delta X_2$) as shown. We note that even though one does not have 100% transmittance for $\Delta X_1 > \Delta X_2$, in each case the full width at half maximum (FWHM) is given by $\Delta X_m/X_0$ where $\Delta X_m = \max(\Delta X_1, \Delta X_2)$. Because the total transmitted current

$$\int \frac{n_0 f}{E} dE = (n_0)(f_{\max})(\text{FWHM}), \quad (3.11)$$

the proper resolution for an ideal beam is simply

$$\rho_{\text{beam}} = \frac{\Delta X_m}{X_0} \quad (3.12)$$

This result may be modified by changes in the effective slit size attributable to fringing fields. The effect of a Gaussian input kinetic energy distribution on broadening the resolution has been examined by Rayborn and Hsaio;⁷⁹ they find little effect until the FWHM of the Gaussian distribution is of the order of the geometric resolution. Thus, for a proper calibration, one must verify that the beam is sufficiently monoenergetic, i.e., $\rho_{\text{beam}} < \rho_{\text{analyzer}}$.

For use in analyzing low-energy negative ions, several specific design precautions must be taken to ensure effective operation. The physical dimensions of the analyzer must be as small as practicable to minimize losses attributable to background gas collisions and space charge broadening of the beam.

Care must be taken to avoid having any unshielded insulators that might become charged and distort the particle trajectories; for similar reasons, all magnetic materials should be avoided. Because the particle detectors are configured to detect negative ions, they are also very sensitive to stray electrons; thus, it is imperative to minimize the production of secondary electrons inside the analyzer from whatever cause.⁸⁰ Finally, it is important to exclude any external fields such as those attributable to detector high-voltage biases or the tokamak environment. This should be done not only within the analyzer but over the entire trajectory of the ions.

With these considerations in mind, a four-channel analyzer was built for use with the cesium heat pipe (Fig. 10). Specifications are given in Table 5. All ultrahigh vacuum-compatible materials were used with the exception of small amounts of nylon and Teflon insulation. A slit geometry was adopted to increase the transmission without a corresponding decrease in resolution. The separation between exit slits (20 mm) was determined by how closely the detectors could be packed without causing problems such as arcing. The selected plate separa-

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Fig. 10. Scale drawing of four-channel analyzer used in flux measurement. Design parameters are given in Table 5. The secondary emission detector shown is used for calibration only and is replaced by a uv beam dump during measurements on the tokamak. Details of the channel electron multiplier (CEM) are not shown.

Table 5. Analyzer design parameters

Length, mm	152.4
Width, mm	50.1
Plate separation, d , mm	42.8
Ground plate	Stainless steel, 1/32-in. sheet
Guard rings	3 aluminum picture frames; 1/16-in. sheet; interior dimensions, 139.7 $\times$ 38.1 mm
Rear (deflection) plate	20 mesh copper grid on steel picture frame, 97% transmitting
Electrostatic housing	1/16-in. aluminum
Overall dimensions, mm	L:W:H — 20:75:65
Magnetic shielding	Metglas 7876 ^a
Effective entrance slit (geometric projection onto ground plane), mm	2.37 $\times$ 10.2
Angular acceptance	$\pm 1.5^\circ$

By channel number

	1	2	3	4
Base length, mm	40.64	60.96	81.28	101.6
Exit slit width, mm	1.65	1.63	15.8	1.60
Exit slit length, Z , mm	12.6	12.6	12.6	12.6
Calculated resolution, %	3.97	4.02	3.05	2.33
Tuning voltage for 100 eV beam (ideal)	210.6	140.4	105.3	84.25
Nominal trajectory length in analyzer, mm	46.64	69.97	93.29	116.61
Nominal trajectory height, mm	± 0.1	10.16	15.24	20.32
	± 0.55	± 0.82	± 1.1	± 1.36

^aTrademark, Allied Chemical Corporation.

tion was more than sufficient to satisfy the height requirement $d > Y_{\max}$ for all four channels. The three guard rings were biased using high-vacuum potted precision resistors. All parts of the analyzer, including the detector housing and electrostatic shield, were mounted on a 1/8-in. base plate for mechanical rigidity.

The rear plate was actually a window screen made of highly transparent copper mesh (20 lines/in., 97% geometric transmission). This minimized the production of secondaries from the

impact of unconverted neutrals and those ions whose energies were too high to be significantly deflected by the tuning field. For the same reason, the whole interior of the analyzer was coated with gold-black,^{81,82} a substance that has a low secondary emission coefficient as well as excellent light-absorbing qualities. The coating is prepared by evaporating gold from a hot tungsten filament onto the piece in the presence of nitrogen. For background pressures of ~ 1 torr, the gold deposit will not be a highly reflecting crystalline coating, but a

powdery structure that resembles soot. This is a result of the irregular deposition of gold crystallites attributable to background gas collisions and chemical effects at the surface.⁸³ In addition to its good optical properties, gold-black is a good conductor and this eliminates any field distortion that might result from beam charging of an insulating optical black coating. Any secondaries that are formed at the shield will be repelled by the (negative) rear grid bias and thus are not energetically favored to scatter into the detectors. One potentially serious problem is secondary electron production at the grid from the unconverted neutral beam. These electrons have a birth potential of $-V$ and are highly likely to scatter into the detectors. Even though this effect is mitigated by the use of a high-transparency grid vs a solid plate, generally the ratio of un-ionized neutrals to signal ions actually entering the analyzer is so high that substantial noise still results, as was noted during the early stages of calibration. The solution was simply to remove a strip from the grid wide enough to permit passage of the neutrals yet small enough to minimize distortion of the uniform analyzing field. From geometric projection a compromise width of 7 mm was chosen. Secondary production from other positions on the grid attributable to converted ion impact was not a noticeable source of noise during calibration. However, during observations on the tokamak, channel 1 was susceptible to noise from D^+ impact at the very lowest tuning voltages.

To minimize the stray light scattering into the analyzer and to shield the incident low-energy neutrals from various high-voltage leads within the vacuum box, the actual entrance aperture is a knife edge mounted 44.5 mm below the ground plane on a tube that is attached to the base plate. The distance from the knife edge to the center section of the heat pipe is 214 mm. Because the acceptance angle as determined by the heat pipe diameter and slit is nonzero, the effective aperture size in the ground plane is somewhat larger. In addition, the extent of angular scattering changes rapidly with collision energy in the charge exchange reaction, $D + Cs \rightarrow D^- + Cs^+$. At these low energies,⁸⁴ it is highly unlikely that the effective aperture (and hence the resolution) will remain constant as one goes to lower energies. Therefore, it is extremely

important not to naively apply Eq. (3:12) for the purposes of interpreting flux spectra. The most accurate procedure is to measure the resolution of each channel as a function of particle energy under actual operating conditions. This was performed as a part of the calibration procedure discussed in chapter 4.

3.4 LOW-ENERGY NEGATIVE ION DETECTOR

To detect the low-energy negative ions that have been analyzed, a circuit employing specially biased CEMs was developed. In the 20 years since their development,⁸⁵ CEMs (and their descendants, microchannel plates) have been used to observe photons, electrons, and heavy particles over a wide range of energies.⁸⁶⁻⁹¹ Their usefulness as generalized particle detectors is attributable to several factors: They may be operated in a gain-saturated mode, providing uniform output pulses over a modest dynamic range ($\sim 10^4 s^{-1}$) for individual particle counting.⁹²⁻⁹³ Conversely, they may be operated in an analog or continuous current mode at lower gain levels.⁹⁴ They are relatively insensitive to small ambient magnetic fields if properly oriented.⁹⁵⁻⁹⁶ They are operable over a wide range of pressures, are unaffected by exposure to the atmosphere, and are resistant to accidental high-current input impulses when properly preconditioned.⁹⁷ In addition, if care is taken to properly shape the electrostatic field at the entrance to the CEM,⁹⁸⁻⁹⁹ one can achieve essentially unit counting efficiency for either positive or negative ions that are initially of arbitrary energy.

For lower energies, enough postacceleration must be provided beyond the energy analyzer to ensure that at least one secondary is emitted per incident ion. Given a secondary emission coefficient, $\gamma^-(E)$, the probability of emitting at least one secondary may be taken as $P = 1 - \exp(-\gamma^-)$. Thus, one needs an impact energy sufficient for $\gamma^- > 3$ for $P \sim 0.95$. For the specific case of D^- ions, this turns out to be approximately 3 keV. Hence, it is necessary to maintain the front of the CEM at +3 kV with respect to ground. Great care must be taken in this region to eliminate any electrons from external sources such as beam aperturing, field emission, or photoelectrons from

stray light because these will also be accelerated into the detector, contributing a noise component to the D^- signal.

The final configuration for a single detector channel is shown in Fig. 11. (CEM tubes are drawn straightened out for clarity; their actual geometry is a planar spiral.) The grids are made from 20-mesh copper having a geometric transmission of 97%. Grid 1 is at ground potential and is provided to prevent repenetration of the high ($\sim kV/cm$) post-acceleration field back through the exit apertures into the analyzer region. Measurements made without this precaution showed a serious degradation of analyzer resolution. Grid 2 is parallel to grid 1 and biased at $+3$ kV, as is the box containing the CEMs. The front of the CEM is biased slightly (~ 100 V) negative with respect to grid 2 so that secondaries formed at the grid will not be acceler-

ated into the multiplier. The CEM output is maintained at $+6$ kV to ensure gain-saturated output pulses. A resistive divider network provides biasing for all four detector channels from a single high-voltage power supply. The output pulses are ac-coupled through a 50-pF blocking capacitor to isolate the preamplifier inputs from high voltage. This arrangement provides output pulses of approximately 10 V for D^- ions over the entire energy range of interest, as long as the count rate is less than approximately $2.5 \times 10^4 s^{-1}$.

The output from the preamplifier module (Ortec 113) is further amplified (Ortec 460, gain ~ 500) and fed into a threshold discriminator to reject low-amplitude noise. Output pulses from the discriminator are then fed to either CAMAC-controlled latching scalars for input to the ISX-B computer system or to simple scalars gated by a

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Fig. 11. Geometric and electronic configuration of CEM for D^- particle counting.

master timer for use during calibration. This arrangement, in addition to being quite sensitive to incoming ions, was found to be very noise free despite its inherent sensitivity to secondaries (as long as reasonable precautions were taken to minimize stray uv light and corona discharges inside the CEM enclosure). Interchannel cross talk¹⁰⁰ attributable to inductive coupling of the closely spaced vacuum leads was a problem until a doubly shielded arrangement was tried (Fig. 12). The capacitive shunt effectively prevents image pulses from propagating between the inner shields of adjacent channels. Noise counts for the operating system were on the order of 1 s^{-1} for any discriminator setting above 0.2 V, well below the gain-saturated signal pulse level.

Because of the slit geometry chosen for the analyzer and to allow closer detector spacing, CEMs having flattened cones* were used. During the initial calibration, one of the CEMs was discovered to have a significant dead zone attributable to a crack and had to be replaced with one having a different cone geometry.[†] This led to the lowered counting efficiency of the affected channel (channel 3). This lowered counting efficiency persisted throughout the course of the experiment. The procedure used to calibrate the spectrometer compensates for the effect and simply results in a somewhat different sensitivity curve for this channel.

3.5. SECONDARY EMISSION NEUTRAL PARTICLE DETECTOR

To perform an absolute calibration of the analyzer by using a low-energy neutral beam, it is necessary to have a method of accurately measuring the intensity of the calibrating beam. Several methods have been developed to examine beams of charged and neutral particles; a good overview of some of this area's capabilities and limitations is contained in the literature.¹⁰¹ One such method that has been used with good results for similar beams is the secondary emission detector.¹⁰² Such detec-

*Amperex type 413-BL; entrance aperture rectangular, $3 \times 15.5 \text{ mm}$.

†Amperex type 419-BL; entrance aperture circular, 10 mm diam.

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Fig. 12. Shielded electrical feedthrough employed for transferring signal pulses from the CEM through the vacuum wall.

tors are simple to use, rugged, and surprisingly accurate under the proper conditions. In its simplest form (Fig. 13), the detector consists of an insulated target that intercepts the beam and is surrounded by a cup that may be biased positively or negatively with respect to the target. One may also incorporate guard electrodes in front of the cup to suitably adjust the electric field in this region.

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Fig. 13. Configuration of the secondary emission detector.

If a beam of particles of species I and energy E is incident on a surface, electrons will be emitted from the impact region.¹⁰³⁻¹⁰⁷ Surfaces, such as copper, that form a stable oxide layer will exhibit a very reproducible secondary emission coefficient, γ , defined as

$$\gamma_i^-(E) = \frac{\text{net negative current leaving surface}}{\text{incident current of species } i, \text{ energy } E} \quad (3.13)$$

If the target is grounded through a sensitive electrometer, γ may be determined in the following way. By appropriately biasing the cup, one may either suppress the secondary emission or completely extract it. By measuring the resulting currents, the secondary emission coefficient may be determined both for positive and negative ions (Fig. 14). We consider the two cases separately:

1. Positive ions: A positive bias applied to the cup results in a current I_p through the electrometer. For biases such that all secondaries are removed and the primary I_+ is not appreciably deflected,

$$I_p = I_+(1 + \gamma_+) \quad (3.14)$$

For a negative bias such that the secondaries are returned to the target and again neglecting primary deflection, the electrometer reads

$$I_m = I_+ \quad (3.15)$$

Thus,

$$\gamma_+ = \frac{I_p - I_m}{I_m} \quad (3.16)$$

2. Negative ions: Because the primary I_- now yields a negative electrometer current, the secondary contribution must be subtracted. Hence,

$$I_p = -I_-(1 - \gamma_-)$$

$$I_m = -I_-$$

and

$$\gamma_- = \frac{I_m - I_p}{I_m} \quad (3.17)$$

For incident neutral beams, there is no net current when the secondary emission is suppressed ($I_m = 0$); thus, this method of calibrating the detector breaks down. It has been shown, however, using a different calibration procedure,¹⁰² that in the energy range of interest the ratio of coefficients for neutrals and positive ions is constant. In fact,

$$\frac{\gamma_0}{\gamma_+} = 1.15 \pm 2.8\% \quad (16 \text{ eV} < E < 1000 \text{ eV}) \quad (3.18)$$

Although these measurements were made for hydrogen, it has been verified that the secondary emission

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Fig. 14. Sketch showing the four possible configurations using the secondary emission detector to examine charged beams. In each case I_p and I_m refer to the measured current for positive and negative bias, respectively; while I_+ , I_- refer to the actual (positive or negative ion) beam currents.

coefficients are the same for hydrogen and deuterium ions at equal velocities.²¹ Thus, we may assume for deuterium,

$$\frac{\gamma_0^-}{\gamma_+} = 1.15 \pm 2.8\% \quad (3.19)$$

$$(32 \text{ eV} < E < 2000 \text{ eV}) .$$

By using this value and measuring γ_+^- as a function of energy, we may obtain an effective γ_0^- . This in turn can be used to interpret the primary neutral current from the secondary emission.

To accurately measure the emission coefficients for an actual cup, some care must be taken in the design. The cup must surround the target as fully as possible while allowing the primary beam to enter unimpeded. Because of the low-energy nature of the secondary emission (essentially all are emitted at less than 10 to 20 eV, regardless of primary energy),¹⁰⁶ it is fairly easy to extract (or suppress) the secondaries using low voltages on the cup and guard electrodes; however, at the lower beam energies (100 eV) there can be significant focussing or deflection of a primary ion beam as it passes through on its way to the target. This may lead to anomalously high or low I_p and I_m measurements attributable to the primary beam hitting the target at an oblique angle (greater secondary yield) or missing it altogether and hitting the cup instead. Careful variation of these voltages is important to verify saturation of the measured currents for each beam energy. Because of the extremely small currents needed for calibration, the support structure for the target must have a very high impedance to ground potential ($>10^{14} \Omega$). For similar reasons, the cup and surrounding region must be well-shielded and vibration free to prevent induced currents from stray electromagnetic fields or piezoelectric noise (microphonics).

Two secondary emission detectors were built for the current study using the same configuration of electrodes as shown in Fig. 13. One having cylindrical symmetry was designed for use in the neutral attenuation measurements (see Appendix B) and will be discussed later. The one used for the spectrometer calibration was a small cup designed to sit pig-

gyback on the analyzer electrostatic housing to minimize the distance to the analyzer entrance aperture. This decreased the deflection of low-energy ions during the calibration. All pieces were made from 1-mm copper sheet. The cup was a $25 \times 38 \times 38$ mm box in which the target (15.9×28.6 mm) was suspended. All apertures were 6.4×22.3 mm. The target could be rotated out of the line of sight for alignment purposes after the cup was installed.

Because of the location of the cup inside the analyzer vacuum vessel, two high-resistance feedthroughs were necessary: one to support the target on the detector housing, the second to couple the signal out of the vacuum vessel. Glazed alumina insulators with Kovar skirts were used for both feedthroughs; however, stringent cleaning was necessary to minimize leakage attributable to surface contamination. After ultrasonic cleaning in degreasers such as trichloroethylene and acetone, the ceramic surfaces were vigorously scrubbed with dilute nitric acid and cotton swabs. The feedthroughs were then boiled in distilled water for 1 h, followed by a final rinse with electronic-grade methanol. After this regimen of cleaning and upon being installed in the vacuum system, the leakage current of the ion collector to ground potential, as measured by the electrometer, dropped slowly over a period of several days to a final value of $\sim 8 \times 10^{-15}$ A. This was probably attributable to either the gradual relaxation of internal stresses in the alumina (which causes a small electromotive force in the target circuit) or to the evaporation of residual solvents from the cleaning process.

The electrometer used for these measurements was a vibrating reed electrometer (Cary model 401) operated in the resistance leak mode. In this method, the input current is routed into one of three high-value resistors and the resulting voltage drop is measured by the electrometer. Although not the most precise method of using the electrometer, the method is capable of measuring currents in the 10^{-15} A range. Moreover, the vibrating reed electrometer offers the advantage of providing a fixed output voltage for a given current. This voltage is displayed on a fast meter installed on the front of the instrument; an accurate analog signal is available for further processing if desired. The three input resistors are a possible source of inaccuracy

because of drift in their values; these were calibrated to better than 1% before beginning neutral measurements.

For the initial calibration series, target currents were measured by reading the deflection of the instrument meter. Because of the short-term jitter in the noise level as well as fluctuations in the signal, it was difficult to accurately determine the neutral current by this method, especially at lower beam energies. For the final calibration, a current digitization scheme was used wherein the analog voltage output was applied to a digital current integrator (Ortec 439) through a precision input resistor. The output pulses from the current integrator were then counted on a scaler. This method gives much better accuracy for steady or fluctuating beams because of the arbitrarily long integration times. The pulse counting technique also allows for easier averaging and error analysis.

3.6. ASSEMBLY OF SPECTROMETER AND RELATED EQUIPMENT

Fig. 15 shows the completed spectrometer as installed on the tokamak. The deflection/pumping tee provides discrimination against high-energy ions formed in the ~ 2 m flight path from the tokamak. Lower energy ions are removed by the residual tokamak fields. The small turbomolecular pump allows one to evacuate the beam tube, because one cannot pump through the high-pressure region in the heat pipe. Base pressure in the beam tube was approximately 2×10^{-7} torr between shots; however, the pressure at the machine end rose to $\sim 3 \times 10^{-5}$ torr during the shot because of filling gas flowing through the 1/4-in. collimation aperture. Possible effects of this pressure rise on the data are discussed in Appendix B.

The long flight path was necessitated by several

Fig. 15. Completed spectrometer assembly as installed on ISX-B. Collimator aperture at front of beam tube is not shown.

factors. Although the largest B -field component, B_T , falls off rapidly with distance from the tokamak, the other components decay much more slowly. Thus, there is still an appreciable field (~ 10 g) at a distance of 2 m or more from ISX-B. This field level, however, was low enough to effectively shield against. In addition, because of the crowded environment around the tokamak, it was not physically possible to locate the analyzer any closer. Finally, the long flight path serves as insurance against cesium contamination of the tokamak in the event of some catastrophe befalling the heat pipe. The beam tube was routed through a 2-in. lead shield that effectively eliminated hard x-ray noise in the analyzer. During the first day's operation, a serious uv noise problem was noted that was attributable to reflected plasma light in the analyzer; these reflections were effectively suppressed by placing a beam dump made out of a stack of stainless steel razor blades behind the exit hole in the analyzer housing. The pressure in the analyzer region was maintained at 2×10^{-7} torr or better by the large turbopump.

Vacuum controls and most of the analyzer electronics were located in a rack under the diagnostic.

Signal and control cables were run out of the machine room to the main diagnostics area, allowing remote monitoring and adjustment of cesium cell temperatures and analyzer voltage setting. The CEM discriminators were also located in the diagnostics area to simplify interfacing to the computer.

Data from the diagnostic were acquired by a PDP-8E that sampled each of the latching scalars (Fig. 11) every 1 ms for 300 ms, the nominal shot length. The PDP-8 in turn communicated with a PDP-11/34 that allowed near-real-time display of the data. The data then went to the main ISX-B data storage and analysis computer (a PDP-10) and was stored with all other shot information from the different diagnostics. This setup resulted in a 4×300 integer matrix for each shot, containing the time behavior of the detector counts synchronized to all other tokamak data. Initially, it was planned to enter analyzer voltage along with the detector outputs; however, the voltage divider/analog-digital converter combination did not have enough resolution for accurate interpretation of the data. Therefore, the voltage settings were recorded manually, along with the heat pipe temperatures.

4. CALIBRATION OF SPECTROMETER

4.1 INTRODUCTION

This chapter deals with the theory and practice of obtaining an absolute calibration of the neutral particle analyzer. The basic approach is to produce a series of known neutral atomic beams of calibrated intensity at various energies in the range 0 to 700 eV. By exposing the analyzer to these beams under conditions similar to those at the tokamak, one may obtain a response curve giving the absolute sensitivity of the device to low-energy neutrals. By folding this curve into the analysis of the tokamak data, one can obtain flux measurements sufficiently accurate for use in edge transport modeling and other theoretical endeavors.

The most difficult yet vital step in pursuing this method of calibration lies in obtaining an atomic beam of the proper characteristics in this energy range. Ideally, such a beam should be monoenergetic, highly directional (well collimated), and intense enough for the purposes of calibration. The beam should be of known shape and size in the interaction region and, most importantly, of known intensity. The component atoms should be in the ground state, with negligible metastable excited-state contamination. This ideal beam does not exist, but reasonable approximations can be obtained in one of two ways: by electron capture by a positive ion beam passing through a target gas cell or by photodetachment of a negative ion beam by a suitably intense photon flux (i.e., a laser). Both methods were employed in the current study; the former being used immediately prior to installation of the diagnostic on ISX-B and the latter being used after it was removed.

Both methods resulted in absolute calibrations of varying precision that were in good agreement over the entire energy range. Such a result not only gives us confidence in the calibration procedure per se but also attests to the good long-term stability of such a device when used for measurements over an extended period of time.

4.2 PHILOSOPHY OF THE ABSOLUTE CALIBRATION PROCEDURE

Before discussing the specifics of beam generation, it is instructive to consider in some detail the

relationship between the calibration procedure and the actual measurement.

In chapter 2, we saw that the relevant quantity, $d\Gamma/dE d\Omega$, could be expressed as a function of energy by the observables

$$\frac{N}{\Delta E(E) \left(\frac{A_1 A_2}{R_{12}^2} \right) \eta(E) \Delta t} = F(E) \cdot N,$$

where

$\Delta E(E)$ = instrumental passband, eV;

$\frac{A_1 A_2}{R_{12}^2}$ = geometric view factor, cm^2/sr ;

Δt = observation time, s;

$\eta(E)$ = conversion efficiency, D^-/D^0 ;

N = number of detected ions, D^- .

During the calibration, the goal is to identify each of these factors separately at enough different energies to permit accurate interpolations, then to recombine them to obtain a single overall function [i.e., the inverse sensitivity, $F(E)$, that expresses flux/count at energy E]. Because we have four channels, we need $F_i(E)$ for $i = 1 - 4$. If we assume that each of the factors remains constant with time and that they are not source-dependent (i.e., beam vs tokamak), then we are justified in using the derived sensitivity curves to quantify the tokamak flux based on the analyzer voltage setting and detector count rates.

The first of these assumptions is valid as long as one keeps the same geometry, maintains a stable temperature in the heat pipe, and keeps the operating characteristics constant. The second assumption—equivalence of neutrals—is not as straightforward and needs further qualification. Because we must extract the energy behavior of the analyzer from the calibration procedure, it follows that the beam energy spread needs to be much smaller than the expected analyzer resolution—essentially monoenergetic. This is hardly what one expects

from the tokamak but represents the only way to calibrate using beams. The alternative is to use a broadband source of low-energy neutrals for which the spectral intensity (i.e., energy distribution) is known accurately. This is a much more difficult prospect and would be tantamount to achieving the original measurement (i.e., determining the emissivity of a tokamak).

The other place where the question of equivalency arises is in comparing the extreme directivity of the beam with the assumed isotropic emission from the tokamak. If one puts a certain number of neutrals into the black box of Fig. 3 from a parallel beam, do these neutrals have the same quantitative effect as an equal number from an extended source that is emitting in all directions? This distinction is minimized both by the physical location of the analyzer with respect to the tokamak and by the nature of the charge-exchange region. Because of the distance from the plasma periphery to the front of the heat pipe, the flux that illuminates the entrance aperture is well collimated. If we can fill the front of the heat pipe with the calibrating beam, then despite any differences in initial divergence, the behavior at the far end of the pipe should be the same for both cases. This is attributable to the short mean free path for collisions in the cesium. On the average, a particle will undergo many collisions in traversing the cell; and the exact angular nature of the incoming beam will be quickly obscured.

Because we have previously defined the étendue $\Delta A \Delta \Omega$ of the instrument in terms of the entrance slit of the analyzer, we may define an overall conversion efficiency in terms of negative ions formed when the heat pipe is on—versus the neutral current through the slit when it is off and no cesium is present.

The reason for taking this approach is that, at these low energies, it is difficult (if not impossible) to determine an exact neutral current entering the heat pipe and to relate it unambiguously to a given negative ion count rate in one or another of the channels. On the other hand, it is possible to make a very accurate measurement of the transmitted neutrals by placing a detector as close as possible behind the analyzer entrance slit such that all neutrals are collected. As long as the heat pipe

entrance is filled (or overfilled) by the beam for given cell conditions, the count rate will be proportional to the measured neutral flux.

The principal drawback of this approach is that it introduces an unfortunate time lag in the determination of the conversion efficiencies, because one must measure the neutrals before the heat pipe is turned on and the converted ions after the heat pipe has stabilized (~ 45 min). To minimize the error in this factor requires the use of low-energy neutral beams that are stable to within a few percent on long time scales compared with the thermal cycling time of the cesium cell—a period of several hours. This turned out to be one of the major experimental challenges of the entire study. We now describe the techniques used for successfully creating stable atomic deuterium beams at energies as low as 50 eV.

4.3. DEVELOPMENT OF LOW-ENERGY ACCELERATOR

To make a neutral beam with the necessary characteristics, one must first form an ion beam of similar characteristics and then neutralize the ions in a manner that does not significantly perturb the beam. Figure 16 shows the final configuration for the accelerator used for forming the low-energy D^+ and D^- beams employed in the calibrations. Briefly, the ions are formed in the source at the nominal beam energy, extracted at some high potential, focused, velocity analyzed to select the proper species, then decelerated in a multilens array to form a roughly parallel beam of the proper energy. Immediately prior to the neutralization section the beam is deflected through 10° . This eliminates the high-energy neutrals formed upstream of the deceleration section by collisions with residual gas ions. This arrangement is very similar to the design used by Van Zyl et al.¹⁰⁸ for laser photodetachment studies, differing chiefly in the choice of source and ion species selector. The salient points of the accelerator will now be discussed in more detail.

The source used is a Colutron-type¹⁰⁹ hot filament, low-voltage arc source available commercially (Fig. 17). The source requires no magnetic fields and is simple to operate. The filament is in the

Fig. 16. Low-energy accelerator used for creating neutral beams for spectrometer calibration. Insulating breaks (dotted region) allow separate high-voltage biasing of the source and acceleration section relative to ground, simplifying beam energy changes and minimizing beam blowup. The four-element lens efficiently couples the beam into the zero field deceleration section. Pressure in the neutralization region is $\sim 5 \times 10^{-8}$ torr. Voltage polarities shown are for negative ion production (photoneutralization).

form of a tapered tungsten spiral located a few millimeters behind the anode. The desired discharge gas is admitted to the crucible through a small tube. By properly regulating the filament current, filament-anode voltage, and filling pressure, it is

possible to form in the crucible a low-voltage glow discharge of the type described by Cobine.¹¹⁰ The insulating insert confines the discharge to the region near the anode aperture. Because most of the voltage drop in the discharge occurs in the cathode fall near the filament, the positive column plasma formed near the anode is characterized by a nearly constant potential as well as an extremely low ion temperature. By appropriately biasing the extractor electrode, one may extract a beam of either positive or negative ions having an extremely narrow energy spread (< 1 eV) from the vicinity of the anode aperture. The mean energy of the ion beam is determined by the plasma potential in the extraction region; this was typically within an electron volt or two of the anode voltage. Useful extraction fields were on the order of 2 kV/cm. By floating the source along with its associated power supplies, ions having mean energies as low as 2 eV could be easily extracted.

After extraction, the ions are focused using an einzel lens. The beam then traverses a Wien filter, consisting of crossed E and B fields.¹¹¹⁻¹¹² By proper adjustment of the fields, it is possible to reject any ion not having the desired velocity.

Fig 17. Schematic of low-voltage arc source. The plasma is localized near the center of the molybdenum anode. Typical arc voltage—40 to 70 V; arc current—0.3 to 1.0 A; filament current—12 to 15 A; extraction voltage— ± 1500 V. Extraction gap is approximately 1 cm. A water jacket is provided in the mounting flange for cooling.

Because all the extracted ions have the same energy, this device serves as a mass filter allowing selection of a single ionic species.

To minimize beam blowup attributable to space charge effects^{113,114} as well as external fields, the beam is transported over most of its flight path at the extraction potential and is only decelerated to the desired energy immediately prior to the neutralization point. The lens combination (elements A through D) helps to maintain the beam quality as the ions leave the acceleration region. With this arrangement, it was possible to obtain nanoampere beams down to ~ 20 eV in the neutralization region. For proper calibration of the neutral detector, it is necessary to propagate the ion beam through the analyzer; the practical lower limit for calibration was around 50 eV.

After emerging from the neutralization region, provisions are made for deflecting any remaining ions into a small Faraday cup mounted to the side of the beam path. This serves as a convenient monitor on the primary beam intensity and helps pinpoint the cause of any drift in neutral intensity.

Prior to the calibration, a 160° spherical-sector electrostatic analyzer with high resolving power ($\Delta E/E \sim 0.26\%$) was installed immediately behind the neutralization chamber for investigating the effects of various source parameters on the energy spread and useful magnitude of the primary ion beam. Several guiding principles were obtained that helped produce beams having good intensity and small ΔE at energies as low as 20 eV. These source conditions were then reproduced during the calibration runs. Argon gas was added to the deuterium as an aid in maintaining a stable discharge; relative pressures, as measured by a thermocouple gauge on the source filling tube, were $p(D_2) \sim 100 \mu\text{m}$, $p(D_2 + Ar) \sim 300 \mu\text{m}$. It was necessary to place a ballast resistor in series with the discharge to damp out plasma oscillations in the source. These oscillations significantly affected the beam intensity downstream, in some cases completely modulating the beam at ~ 100 kHz.

Because of the use of deuterium rather than hydrogen for calibrating, precautions had to be taken to avoid hydrogen contamination of the source. Such contamination results in molecular

hydrogen ions (H_2^+) that are indistinguishable from deuterons in the Wien filter. Because of the low temperature of the discharge, a relatively larger fraction of ions are molecular rather than atomic; thus, a considerable fraction of the supposed D^+ beam may in fact be H_2^+ if any H_2 is present. This adversely affects the calibration in two ways:

1. Because the D^+ beam is used to calibrate the neutral detector, one obtains an erroneous γ .
2. If the deuterons are used to produce neutrals via electron capture in a gas cell, the molecular ions are likely to dissociate, resulting in a half-energy (H^0) component in the neutral beam. This will give an erroneous conversion efficiency.

To assess the degree of hydrogen contamination, the following procedure was followed. Every day before calibration, measurements were made of the extracted currents for $m = 1, 2$, and 4. These may be identified with the species

$$\begin{aligned} I_1 &= I(H^+) \\ I_2 &= I(D^+) + I(H_2^+) \\ I_4 &= I(D_2^+) \end{aligned} \quad (4.1)$$

Defining α as the fractional contamination, we obtain

$$I(D^+) = (1 - \alpha)I_2 \quad (4.2)$$

We now assume that for given discharge conditions, the ratio of (atomic ions/molecular ions) is isotope-independent (i.e., the chemistry is the same). Therefore,

$$\frac{I(H^+)}{I(H_2^+)} = \frac{I(D^+)}{I(D_2^+)} \quad (4.3)$$

or

$$\frac{I_1}{I_2} = \frac{(\alpha - 1)I^2}{I_4} \quad (4.4)$$

leading to the quadratic

$$\alpha^2 - \alpha + \frac{I_1 I_4}{I_2^2} = 0 \quad (4.5)$$

Normalizing to I_2 ,

$$\alpha = \frac{1 - \sqrt{1 - I_1 I_4 / I_2^2}}{2} \quad (4.6)$$

By careful conditioning of the source after filament changes and using spectroscopically pure argon and deuterium, it was possible to maintain α in the few percent range. All calibration data were taken under these conditions.

4.4 NEUTRAL PRODUCTION USING GAS CELL

The customary method of creating neutral beams from ions is to pass them through a gas cell or other target, allowing some fraction to undergo electron capture (in the case of positive ions).¹¹⁵⁻¹¹⁷ The quality of the resultant neutral beam is contingent on finding a resonant or near-resonant electron capture gas partner for the ion of interest. For low-energy protons (or deuterons), oxygen is a good choice, having reasonable neutralization efficiency¹¹⁸ and causing minimal angular scattering.²¹⁻²² For the current study, O_2 gas was introduced into a 25.4-mm long cell located midway between elements D and E in Fig. 16. The apertures were chosen to ensure complete illumination of the heat pipe entrance while minimizing the gas load on the vacuum system. No direct measurements of the cell pressure were attempted, rather the background pressure in the neutralization chamber was used as a target thickness monitor. In this way, the optimum conditions for neutralization could be identified and reproduced for various primary energies.

Figure 18 shows the conversion behavior of a 500-eV D^+ beam in the gas cell as a function of the chamber pressure. The D^+ was monitored at the side cup after being used to calibrate the neutral detector. Note the rapid drop attributable to enhanced scattering losses for both components at higher pressures. To minimize the scattering as well as adverse effects on the neutral detector and

Fig 18. Measured positive ion and neutral intensities exiting the gas cell for an incident 500-eV (7×10^{-9} A) D^+ beam plotted as a function of deceleration section pressure. Note from D^0 behavior that the operating range of 2 to 5×10^{-6} torr corresponds to single-collision conditions. Peak conversion of $\sim 30\%$ is in good agreement with values expected using published cross-section data.¹¹⁸

cesium, only enough oxygen to create a usable neutral beam was admitted to the gas cell. Typical chamber pressures were in the range 2 to 5×10^{-6} torr.

One drawback to this method of neutral production is the potential for forming neutrals in an excited state during the capture process.¹¹⁷ Such excited neutrals may have much different attachment probabilities in the cesium vapor that would result in a misleading value for the conversion efficiency.

4.5 NEUTRAL PRODUCTION USING LASER

Photodetachment of negative ions¹¹⁹⁻¹²⁰ to form neutrals has several advantages over the electron capture technique. It eliminates the need for a gas cell with the attendant differential pumping problem. There is essentially no momentum transfer to the neutral during the detachment process; hence, the scattering problem is minimized. The formation of an appreciable excited-state neutral fraction is also avoided because of two factors. First, because most negative ions have but one bound state, we

need not worry about excited states in the primary beam. In addition, because the electron affinities of most negative ions are so small, it is relatively simple to select a photon energy below the neutral excitation threshold yet sufficient for detachment. Hence, the photodetachment method can result in well-collimated neutral beams containing essentially 100% ground-state atoms. The recent advent of high-power lasers has provided the intense photon fluxes necessary for useful conversion efficiencies. The only drawbacks involve the need for slightly better vacuum conditions when working with negative ions and the relatively less intense primary beams achievable with current negative ion sources. For example, on the current apparatus the useful 500-eV D^- current at the neutralization section was typically 10^{-10} A as opposed to 10^{-9} A for D^+ .

A schematic of the photoneutralization apparatus used in the current study is shown in Fig. 19. The light source is a 100 W neodymium:yttrium-aluminum-garnet (Nd:YAG) industrial welding laser. The $1.06\text{-}\mu\text{m}$ laser line has a photon energy of 1.17 eV [more than adequate to detach the outer electron from the D^- ion (electron affinity = 0.75 eV) but insufficient to leave the D^0 in an excited state]. The laser rod itself is optically pumped by a high-intensity krypton flashtube. Laser power levels are easily controlled by varying the flashtube current (20 to 40 A).

The laser head is set up between two totally reflecting mirrors, one of which is located inside the vacuum chamber. This arrangement provides much higher photon densities inside the resultant optical cavity because no attempt is made to couple power out as in a conventional laser configuration. A micrometer x-y positioner on the vacuum mirror mount allows tuning of the optical cavity under operating conditions. A power meter mounted behind the rear mirror serves as a monitor of intracavity power (and hence photon density) by sampling the small loss through the mirror. The negative ion beam is passed directly through the intracavity region and exits the neutralization chamber as before. The vacuum window is antireflection- (AR-) coated for $1.06\text{-}\mu\text{m}$ radiation to minimize laser power losses.

To optimize the neutral yield, the ion and photon beam intensities and their overlap are of crucial

Fig. 19. A close-up of the photodetachment region in the deceleration section of the accelerator. In the drawing, the negative ion beam propagates from left to right; the photon beam is reflected at front mirror in vacuo and propagates up and down. Distance between lens elements D and E is 10 cm; distance of front mirror from ion path is ~ 2.5 cm. Note that this setup requires an intercavity window that severely limits the achievable photon density (even though AR coated). A better solution would be to make the rod face the vacuum seal, although cooling and support would be difficult. The cavity may be tuned during operation by altering the orientation of the mirror mount (arrows).

importance. By systematically adjusting the height of the laser head outside the chamber and retuning the cavity, the photon beam could be stepped vertically through the D^- beam. This allowed maximization of the beam overlap as determined by the neutral signal downstream (Fig. 20).

Figure 21 shows the increase in neutralization efficiency with flashlamp current. The enhanced yield at higher currents must be balanced against rapid lamp aging. Current levels of 30 to 32 A were sufficient for all but the lowest energy ranges. The rapid drop in efficiency for currents in excess of 36

Fig. 20. Plot of neutralization efficiency (using percentages) as the photon beam is stepped vertically through a 500-eV D^- beam. Laser flashlamp current equals 35 A. Because the ion beam axis is fixed by the requirements of the calibration procedure, this scan is necessary to ensure maximum beam overlap. The halfwidth of 1.5 mm is comparable to the ion beam width at the intersection point.

A is attributed to thermal lensing in the YAG rod. This effect has also been seen by Van Zyl.¹⁰⁸

During the development of the laser neutral source, the conversion efficiency was continually improved by moving the two mirrors closer and closer together—decreasing the cavity length. The minimum possible length of 46 cm represented one of the most important constraints on the overall yield. It was also important to keep the AR-coated vacuum window scrupulously clean to minimize cavity losses.

Once the optical system was aligned and the conversion optimized for a specific negative ion beam, the neutral beam tended to slowly drift downward in intensity for about an hour, after which it could be maintained to within a few per-

Fig. 21. Neutralization efficiency as a function of laser lamp current for a beam. The ion beam must be slightly retuned at each point to compensate for the steering effects of the large dc lamp current and its magnetic field. The limiting factor on the conversion efficiency is understood to be effective cavity length and not just power. Rapid drop in conversion efficiency at 36 to 37 A is attributable to thermal lensing in the yag rod.

cent for a period of several hours. This time stability was somewhat better than for the oxygen cell. Another more useful advantage was the ease with which the neutrals could be gated on and off by simply blocking the optical cavity. This could be done in a matter of seconds and had no effect on the long-term stability of the neutral beam. In contrast, for the gas cell setup, the oxygen had to be shut off and allowed to pump out of the cell over a period of several minutes. Then the gas flow had to be restored to its previous value. Generally, it was impossible to obtain the same neutral intensity as before because of the difficulty of resetting the gas flow.

4.6 CALIBRATION PROCEDURE

Essentially the same procedure was used for the initial and final calibration series. The spectrometer was installed to the accelerator with the heat pipe flanged directly to the neutralization tee. After optical alignment, the system was pumped down to the low (10^{-7} torr) scale. A series of beam propagation experiments was done with both positive and negative ion beams of different energies—to check alignment and acquire an initial calibration curve for the neutral detector (Fig. 22). In this way, changes in γ attributable to cesiation or vacuum openings could be monitored. Measurements were

Fig. 22. The measured negative secondary emission coefficients, γ^- and γ_+ , for the calibration neutral particle detector were obtained using negative and positive deuterium ion beams, respectively. The small values for emission below particle energies of 50 eV make measurements of neutral atoms using this technique difficult. These results are typical of those for gas-covered surfaces and compare well with data from other workers.¹⁰² During calibration, γ_+ at each energy was measured before and after the neutral beam generator to verify the stability. Barring vacuum accidents, the values were found to be fairly constant ($<10\%$) with time over periods of days.

also made of the channel resolutions and peak positions for primary negative ions for comparison with those obtained using converted negatives from the heat pipe.

The spectrometer could only be calibrated at the rate of one point per day because of the long heat pipe stabilization times necessary for good accuracy. Each morning, the source was adjusted for stable operation and a positive ion beam of the desired energy extracted. After tuning the beam down through the system to the end cup, the $m = 1:2:4$ intensity ratios were compared to verify negligible hydrogen contamination.

4.6.1 Gas Cell Calibration

The Wien filter was tuned for a deuteron beam, and γ_+ was measured several times at the end cup. The side cup deflector was then turned on and the beam steered into the side cup. O_2 gas was admitted to the gas cell, and the neutral beam through the analyzer was measured.

After the neutral beam was stabilized on target for an hour, heating of the cesium cell commenced. To minimize the thermal cycling time, a propane torch was used to help heat the central section for a few minutes. The central temperature was allowed to stabilize before the calibration proceeded.

Once the heat pipe had reached thermal equilibrium, the proper tuning voltages and resolutions for each of the four channels were measured in the following manner. The output of each discriminator was fed into a linear ratemeter (Ortec 770); which provides an output voltage proportional to the number of pulses per second. The deflection voltage on the analyzer was then scanned, and each of the peaks V_i were identified by maximizing the countrate. Figure 23 shows the peak positions for the various beam energies. Each channel curve is well fit by a straight line, verifying Eq. (3.14). It should be noted that the peak positions did not shift appreciably, whether one is looking at negatives formed in the cesium cell or primary negatives directly from the source. This is a consequence of the quasis resonant nature of the electron-capture reaction and indicates that no energy corrections need be made to data obtained on the tokamak.

After identifying the peaks, the ratemeter output

Fig. 23. Results of energy calibration of the analyzer are shown. The peak positions for each channel using different D^+ beam energies are identified. These values of tuning voltage vs energy may be used to identify the four energies observed for an arbitrary analyzer setting.

was plotted vs analyzer voltage using an x-y recorder. Figure 24 shows such a scan for channel four using a 50-eV D^0 beam. By virtue of Eq. (3.14), we may obtain the various channel resolutions from the measured peak positions and halfwidths, V_i . The results of the resolution calibration for all four channels over the energy range 0 to 700 eV are displayed in Fig. 25. The degradation (i.e., increase) in resolution at lower energies is obvious. Because the source operating parameters were picked to minimize the beam energy spread, most of this effect may be attributed to either enhanced scattering in the heat pipe or increased divergence of the negative ions after the heat pipe. However, the uncertainty in the origin of E_i/E will tend to limit the accuracy at the lowest energies using this diagnostic.

To perform the conversion efficiency measurement for each channel, the analyzer was tuned on peak and the output pulses counted for a period of 30 to 60 s. At least 10 periods were averaged together for each measurement to increase the precision. Assuming a stable neutral beam, the conversion efficiency is then simply

$$\eta_i = \frac{C_i}{n_0}$$

counts the i^{th} channeltron in T seconds

$$= \frac{\text{number of neutrals in } T \text{ seconds}}{(1.15)(1.6 \times 10^{-19})[\gamma_+^-(E)]C_i} \\ = \frac{I_p - I_l}{I_p - I_l},$$

where:

γ_+^- = secondary emission coefficient for deuterons of energy E ,

I_l = electrometer current with beam turned off (leakage current),

I_p = electrometer current with beam turned on.

Fig. 24. Output of channel four of spectrometer in counts/s for an incident 50-eV D^0 beam, plotted as a function of analyzer voltage. Calculated resolution from halfwidth is 2.2%. True resolution is slightly lower, because of finite energy spread in the D^0 beam. The measured calibration beam intensity was equivalent to about 3×10^{-12} A ($\sim 2 \times 10^7 D^0/s$).

Fig. 25. Results of resolution measurements for spectrometer at an operating temperature of 122.5°C.

After measuring all four η_i , the heat pipe was cooled down as rapidly as possible using a water line plumbed directly into the central block. The pipe was judged to be off when the count rates had dropped to below 1% of their peak values during operation. At this time, several more measurements were made of the neutral current. Finally, the oxygen was turned off and the primary deuteron beam once again tuned through the system to remeasure γ_+ . If the drift in n_0 over the course of the data run was not excessive ($<20\%$), an average of all measured currents before and after was used in calculating the conversion efficiencies. Otherwise, the data were rejected and another neutral beam formed to repeat the whole procedure.

4.6.2 Laser Photodetachment Calibration

In this case, after measuring γ_+ , the accelerator was reconfigured for negative ions. A reasonably

stable D⁻ beam of the desired energy was propagated down through the system into the rear detector. After measuring γ_- , the laser was turned on and the optical cavity adjusted for efficient neutral production. Because of the high dc current in the laser flashlamp, the negative ions were significantly steered before reaching the neutralization point. Hence, for low energies it was necessary to do the initial beam tuning with the lamp on but the photon beam blocked. This was easy to do by spoiling the cavity with a piece of cardboard. Final tuning consisted of bending the underached negatives into the side cup, then going back and forth between the beam steering controls and cavity adjustments to produce a stable neutral beam of the desired intensity down through the system. The apertures on the deceleration lens elements were again chosen so as to fill the heat pipe entrance aperture with beam. Once the neutral beam had stabilized, the calibration proceeded as before.

As mentioned earlier, during the final calibration series, the neutral detector output was digitized using the electrometer-current integrator scheme. Besides the increased accuracy for determining the initial neutral current, an additional advantage of this technique is that it allows simultaneous counting of the neutrals and negatives during the conversion efficiency measurements. By normalizing the negative ion count rate to the relative neutral signal during each counting interval, the effects of short-term beam fluctuations may be eliminated by averaging over many intervals. The use of the laser to produce neutrals also allowed accurate chopping of the neutral beam without perturbing the beam trajectories, by simply spoiling the optical cavity even at the lowest energies. This permitted measurements of background noise and leakage current when the heat pipe was on and no absolute neutral measurements could be made.

After the heat pipe was quenched and several readings taken of the neutral current, the laser was turned off and measurements were again made to determine γ_- . The accelerator was then configured to produce deuterons and γ_+ remeasured to once again determine the amount of neutral drift during the data run.

The results of both sets of conversion efficiency measurements for all four channels are shown in Figs. 26 through 29. All four show similar behavior,

Fig. 26. Results of conversion efficiency calibration for spectrometer channel 1. (White data points were obtained immediately prior to tokamak observation; black data points were obtained afterwards. The error bars were obtained by estimating each of the experimental uncertainties at 1 standard deviation of the mean and by combining in quadrature.)

Fig. 27. Results of conversion efficiency calibration for spectrometer channel 2. (White data points were obtained immediately prior to tokamak observation; black data points were obtained afterwards. The error bars were obtained by estimating each of the experimental uncertainties at 1 standard deviation of the mean and by combining in quadrature.)

including the odd channel 3. The conversion efficiency peaks around 500 eV and is on the order of 10%. These values are, of course, only absolute for the specific geometry of heat pipe and analyzer chosen. The assigned error bars are obtained from a quadrature sum of the estimated relative uncertainties in making each measurement. The smaller bars on the laser neutral data are attributable to more precise secondary emission and neutral current measurements using the digitization scheme and generally more stable beams, resulting in less neutral drift during calibration.

From the conversion efficiency and resolution curves measured during calibration and knowledge

of the viewing geometry on the tokamak, we can now calculate the absolute (inverse) sensitivity curves for each channel as outlined in section 2.2. Figures 30 through 33 show the F curves for the energy range 40 to 770 eV calculated for the viewing geometry on ISX-B.

4.7 SUPPLEMENTAL MEASUREMENTS

After obtaining the η and F curves for the spectrometer, additional measurements were made to determine the useful linear dynamic range for the detectors as well as the change in conversion effi-

Fig. 28. Results of conversion efficiency calibration for spectrometer channel 3. (White data points were obtained immediately prior to tokamak observation; black data points were obtained afterwards. The error bars were obtained by estimating each of the experimental uncertainties at 1 standard deviation of the mean and by combining in quadrature.)

Fig. 29. Results of conversion efficiency calibration for spectrometer channel 4. (White data points were obtained immediately prior to tokamak observation; black data points were obtained afterwards. The error bars were obtained by estimating each of the experimental uncertainties at 1 standard deviation of the mean and by combining in quadrature.)

ciency resulting from small drifts in the heat pipe central temperature.

4.7.1 Detector Efficiency vs Count Rate

For a given input neutral beam, a cursory pulse-height analysis may be performed on the channel electron multiplier (CEM) outputs by varying the threshold discriminators and observing the resulting count rate behavior. A drop in gain attributable to too much input will be reflected in a lowered count rate at higher settings; thus, this method gives a good indication of the dynamic range of each detector channel. Measurements were made on all four channels at various beam energies and intensi-

ties. An example is shown in Fig. 34 where the count rate for channel 1 is plotted vs discriminator setting for 150-eV particles at about $16 \times 10^4 \text{ s}^{-1}$. There is a large plateau region above the 0.01-V noise threshold showing very little degradation in gain. Contrast this behavior with that shown when the count rate has been increased to above $4 \times 10^4 \text{ s}^{-1}$. This may be interpreted as a drop in the particle counting efficiency of the detector, which has been assumed to be unity. At these count rates, one must be careful to set the discriminator as low as possible to minimize the error from uncounted pulses. Even at $4 \times 10^4 \text{ s}^{-1}$, a 0.2-V discriminator setting should result in only a few percent error;

Fig. 30. F curve for spectrometer channel 1 as obtained from the calibration data and knowledge of the viewing geometry on ISX-B. They are essentially inverse sensitivity curves, representing the flux/pulse for each of the detectors for a given tuning energy.

Fig. 32. F curve for spectrometer channel 3 as obtained from the calibration data and knowledge of the viewing geometry on ISX-B. They are essentially inverse sensitivity curves, representing the flux/pulse for each of the detectors for a given tuning energy.

Fig. 31. F curve for spectrometer channel 2 as obtained from the calibration data and knowledge of the viewing geometry on ISX-B. They are essentially inverse sensitivity curves, representing the flux/pulse for each of the detectors for a given tuning energy.

Fig. 33. F curve for spectrometer channel 4 as obtained from the calibration data and knowledge of the viewing geometry on ISX-B. They are essentially inverse sensitivity curves, representing the flux/pulse for each of the detectors for a given tuning energy.

Fig. 34. Plot of channel 1 count rate vs threshold discriminator level for two different input intensities. Gain drop in detector at high count rates causes a drop in pulse height distribution. This results in increased counting losses for a given discriminator setting and limits the useful dynamic range.

however, the noise levels around the tokamak required a somewhat higher setting (0.5 V).

4.7.2 Conversion Efficiency vs Heat Pipe Temperature Drifts

Although the stability of the central temperature was observed to be quite good because of the steepness of the vapor pressure curve (Fig. 5) in the operating regions, a small drift might have a relatively large effect on the measured conversion efficiency. Measurements were made using a 60-eV D^0 beam to see just how much of an error could be expected. Figure 35 shows the variation in negative ion count rate, cesium density, and neutral atom transmission as a function of cell temperature. That

Fig. 35. Effects of central cesium temperature (T_c) drift on low-energy (60 eV) spectrometer stability. Shown are plots of the variation in D^- production and D^0 transmission as the central temperature is varied. Also shown is the relevant portion of the vapor pressure curve. The effect of multiple scattering is to decrease the rate of change in the conversion efficiency compared to that of the cesium density. The vertical scale corresponds to cesium vapor density in units of 10^{13} cm^{-3} . The ordinates for D^+ and D^0 curves are arbitrary.

the D^- count rate does not increase nearly as fast as does the cesium vapor pressure is primarily attributable to enhanced scattering. This effect is also seen in the neutral behavior. For the observed temperature stability of $\pm 0.4^\circ\text{C}$, a drift of $\sim 2\%$ occurs in the measured count rate, a negligible error. This error may increase at higher energies as the scattering becomes less important but would still not be expected to exceed the percent change in the vapor density of approximately 4%.

5. EXPERIMENTS ON THE ISX-B TOKAMAK

After the initial calibration using the O_2 gas cell, the analyzer was installed on the ISX-B tokamak. Figure 36 is an overhead view of the device including diagnostics. The ISX-B is a moderately sized tokamak having provisions for intense plasma heating using neutral beams and plasma shaping via external coils to create noncircular cross sections. The primary goal of the project is the systematic investigation of high-beta tokamak discharges.¹²¹ Table 6 gives a list of relevant machine parameters. All data in the current study were taken for plasmas having essentially circular cross sections ($a = 26.5$

cm, $b/a \sim 1.1$). Diagnostics on ISX-B measure a wide number of plasma properties. A Rogowski coil yields plasma current; 2-mm microwave and far-infrared laser interferometers give line-averaged electron densities for a number of vertical and horizontal chords; and a four-pulse ruby laser, 90° Thomson scattering system gives time-and-space-resolved measurements of electron temperature and density. Ion temperatures may be measured at various positions by two scanning charge-exchange analyzers; in addition, these analyzers have sufficient mass discrimination to distinguish beam (hydrogen)

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Fig. 36. Overhead plan of ISX-B tokamak indicating the location of the diagnostic relative to other machine components. The two neutral beam injectors (labeled East and West) are located in sectors 1 and 16, respectively. The gas puff is located in sector 10, along with a D_α monitor. The limiter is in sector 14 (under the ohmic heating yoke).

Table 6. ISX-B machine parameters

		Typical	Maximum
Toroidal field, T	B_T	0.8–1.4	1.8
Major radius, m	R_0	0.93	0.93
Minor radius, m	a	0.27	0.27
Elongation	b/a	1.0–1.6	1.8
Plasma current, kA	I_p	90–230	230
Safety factor	q	2–4	
Electron density, cm ⁻³	n_e	$2\text{--}10 \times 10^{13}$	1.3×10^{14}
Electron temperature, keV	kT_e	1.2	1.9
Ion temperature, keV	kT_i	1.0	1.2
Confinement time, ms	τ	15	40
Pulse duration, ms		270	300
Working gas		D ₂	
Heating			
Ohmic, kW		300	
Neutral beam		2 × 1.5 MW injectors 40 keV H ⁰	
Vacuum vessel			
Volume, L		$\sim 4.6 \times 10^3$	
Surface area, cm ²		$\sim 2.1 \times 10^5$	

and background gas (deuterium) particles. Line-averaged D_α emission measurements are made at several toroidal locations around the machine. Specific measurements of edge plasma parameters have been made using a retractable pumped limiter.¹²² Additional diagnostics include Mirnov coil arrays to help analyze magnetohydrodynamic behavior, pin-diode arrays to monitor soft x-ray emission, pyroelectric detector arrays to look at radiated power, and neutron and hard x-ray detectors.

A typical operating day consists of up to 150 shots, most of which are spent in tuning up various machine parameters to obtain a reproducible discharge. Rather than wasting diagnostic effort taking data on all shots, most interest is concentrated on laser sequences, a series of assumed identical shots obtained after the tuneup period for which the Thompson scattering system and other more complex diagnostics are operated. This approach helps to average out many of the fluctuations inherent in a tokamak shot and allows one to concentrate on the parameter of interest, for example, density behavior as plasma current or toroidal field are varied.

Details of the analyzer-tokamak interface are shown in Fig. 37. The observed solid angle is exaggerated for clarity. The gate valve allowing access to the machine is connected to a 25-cm port in sector 10. The port is located in the torus midplane and is oriented at $\theta = 35^\circ$ to the plasma normal at the limiter radius. The resulting sightline has a tangency radius of 77 cm. The limiter radius is 119.7 cm, and the outer wall of the vacuum vessel

Fig. 37. Geometric arrangement of the neutral particle detection port at ISX-B.

is located at $r = 128.1$ cm. Thus, the thickness, Δ , of the edge region is ~ 8.4 cm. The rectangular nature of the ISX-B vacuum box creates a large plenum above and below the plasma in the case of circular discharges (Fig. 38). This allows good conductance of neutral gas around the torus (beyond the plasma periphery).

Previous measurements of the edge plasma in this observation region have been made using the prototype pumped limiter that was mounted on the same flange as the spectrometer.¹²² Measurements of radial profiles were made for discharges having relatively low line-averaged densities ($\sim 2 \times 10^{13}$ cm⁻³). Both temperature and density show an exponential fall for $r > a$, with e -folding lengths of

4.8 and 2.3 cm, respectively. These values are only estimates because the limiter was quite massive and certainly perturbs the scrapeoff plasma. Electron temperature, kT_e , at the limiter radius as measured by Thompson scattering was ~ 40 eV. Parallel ion fluxes at $r = a$ were measured to be on the order of 8×10^{18} cm⁻²·s⁻¹; perpendicular fluxes would be expected to be much lower.

Deposition probe measurements have been made to sample the perpendicular flux to the walls.¹²³ High-purity silicon targets were exposed at the outer wall for a certain number of discharges, then removed and analyzed for deuterium content using nuclear reaction analysis [$D(^3\text{He}, p)^4\text{He}$]. The deposition rate was measured as approximately 2×10^{15} cm⁻² per 240-ms discharge. Plasma parameters were $I_p = 170$ kA, $B_T \sim 13$ kG, $n_e \sim 5 \times 10^{13}$. These measurements were not made at the same toroidal location as the current measurement, but approximately 40° downstream (sector 8).

The 6.35-mm diameter collimating aperture A_1 is located immediately behind the gate valve. The distance L_{12} from A_1 to the analyzer entrance aperture is 235.8 cm, leading to a calculated étendue, $\Delta A \Delta \Omega$, of 1.72×10^{-7} cm²/sr. Because of the viewing angle, the distance between A_1 and the plasma edge as defined by the limiter radius is $L_{p1} = 82.6$ cm. If one assumes that the scrapeoff region does not extend into the 25-cm port much beyond the wall radius, then the thickness of the scrapeoff region as viewed by the analyzer is $(\Delta \sec \theta) \sim 11$ cm. The remainder of L_{p1} is occupied by the D₂ filling gas. The gate valve could be shut routinely to study the effects of pressure rise in the beam tube as well as various noise sources in the analyzer.

The location of the observation region relative to such items as the limiter, neutral beam injectors, and gas inlet is of great interest because these objects act as sources of neutral atoms and molecules. Such localized sources are expected to have a strong influence on the neutral flux and will tend to invalidate the concept of toroidally symmetric emission. The limiter is located in sector 14 (i.e., under the toroidal field yoke as shown in Fig. 36); in terms of the plasma current, the limiter is 80° (toroidally) upstream from the analyzer. There are two neutral beam injectors, each capable of

Fig. 38. Cross section of sector 10 of ISX-B showing plasma positioning in the vacuum vessel for circular discharges. Interior dimensions of the vessel are 113×68.7 cm. Scrapeoff distance in the horizontal plane is 8.4 cm, although in the vertical plane $\Delta \sim 29.5$ cm for circular discharges.

injecting up to 1.5 MW of 40 keV H^0 ($\sim 10^{20}$ atoms/s). They are located in sectors 16 (West beam) and 1 (East beam), corresponding to 120° upstream and 180° upstream, from the analyzer, respectively. Note that, because of the viewing and injection angles, the analyzer looks directly down the throat of the West beam injector. The inlet gas valve is located in the same sector as the analyzer. We, therefore, might expect the gas flow to have a major influence on the neutral emission measured by the analyzer. The close proximity of the gas feed leads to an additional complication in interpreting

the flux spectra. Because of the relative conductances of the first aperture and the flight tube during a tokamak shot, there will be a pressure rise in the front part of the tube despite the good vacuum at the analyzer end. This background gas may cause scattering of the neutrals on their way to the analyzer. Because this effect is more significant at lower energies, the result may be to attenuate the low-energy end of the spectrum. A series of measurements were made during the final calibration to try to assess the influence of beam attenuation on the tokamak data (Appendix D).

6. RESULTS

6.1 INTRODUCTION

This chapter presents the experimental results for flux measurements on the ISX-B using the analyzer. Most of the figures shown are data displays obtained using the PLOTCH¹²⁴ program on the PDP-10. The software will print out the contents of different diagnostic data channels vs time throughout the shot; data channels range from such basic signals as loop voltage or plasma current to reduced data such as electron density from the far-infrared interferometer. Basic data are generally available within two minutes of a shot; channels that require more involved calculations take longer. Because the four analyzer outputs are digital pulses, they fall into the former category. Because of the short time between tokamak shots during operations (150 s), most data analysis is left until the end of the day; however, it is very useful to see the raw data on a shot-to-shot basis and to verify that the diagnostic is performing as expected.

In addition to simply displaying the data, PLOTCH also allows some simple data manipulation. The time and scaling limits may be varied. Constant values may be added to each channel for offset corrections. Fluctuations or noise spikes in the data may be suppressed by smoothing the data with a Gaussian function of arbitrary time constant, or several shots may be called together and the average displayed.

6.2 BASIC SHOT DATA

Figure 39 shows the analyzer response for shot no. 40286, a typical ohmically heated discharge. The data have been smoothed with a 1 ms time constant. The four energies as determined by the analyzer voltage setting are 200, 300, 400, and 500 eV. Corresponding scale factors are (3.1, 1.5, 1.2, and 0.5) $\times 10^{10}$ D⁰/(cm²·s·eV·sr·pulse). The basic plasma parameters are shown in Fig. 40.

A cursory inspection of the data reveals several interesting aspects. At all times in the discharge, the flux is monotonically decreasing with energy, at least in the range 200 to 500 eV. Subsequent shots with different analyzer settings show this to be true over the entire energy range of the instrument. No

shot was ever observed that had a peak in the flux spectrum for E greater than about 16 eV—the lowest energy for which signals were obtained. The flux is zero at the beginning of a shot for all energies and tends to rise somewhat faster in the lower energy channels. The flux in the higher energy channels tends to decrease towards the end of the shot, while the lowest energy stays the same or increases slightly. Effects attributable to the dip in the gas puffing rate at 70 ms are also more apparent in the lower energy channels.

For comparison, Figs. 41 and 42 show a similar ohmically heated target plasma (shot no. 40288). This time, the target plasma was heated by approximately 1.5 mW of neutral beam from the East beam line. The beam is turned on 120 ms into the shot. The major effect is to enhance the neutral flux, especially at higher energies. This enhancement occurs on a time scale of ~ 20 ms.

The shot-to-shot reproducibility of the data for similar discharges was very good. The upper trace of Fig. 43 shows the flux at 250 eV obtained by averaging over ten shots in a laser sequence while the lower trace specifically shows all ten shots. This type of behavior gives more confidence in making comparisons between different energy settings and allows a flux spectrum to be built up over several shots (Sect. 6.3). Because of the rapid drop in conversion efficiency, measurements at the lower end of the energy range are much more susceptible to errors from noise counts in the channel electron multipliers. To compound this problem, the lowest energy channel, no. 1, was found to have relatively more noise counts for very low tuning voltages during operation on ISX-B. This is believed to be attributable to the formation of a small amount of D⁺ in the cesium cell that is subsequently accelerated into the rear grid of the analyzer, producing secondary electrons. These in turn accelerate back to the ground plate and will hit near the channel 1 exit slit for low tuning voltages. The noise tended to be more intense toward the end of a discharge. This effect was not noticed during calibration and results in rather large error bars for the channel 1 data at lowest energies.

Fig. 39. Raw data for ISX-B shot no. 40286, displayed as counts/ms for each spectrometer channel. Energies and full-scale flux values are listed below.

Channel	Energy (eV)	F value	Full-scale flux
		$\left(\frac{\text{particles}}{\text{eV} \cdot \text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{count}} \right)$	$\left(\frac{\text{particles}}{\text{eV} \cdot \text{cm}^2 \cdot \text{s} \cdot \text{sr}} \right)$
1	200	3.1×10^{10}	1.24×10^{12}
2	300	1.5×10^{10}	3.0×10^{11}
3	400	1.2×10^{10}	2.4×10^{11}
4	500	5.0×10^9	5.0×10^{10}

6.3 FLUX SPECTRA AND EDGE-TEMPERATURE ESTIMATES

As mentioned earlier, the availability of many shots that are essentially identical allows us to retune the analyzer and obtain the time behavior of the flux at many different energies. From this data, the local flux-spectrum, $d\Gamma/(dE d\Omega)(E, T)$, over the energy range of the diagnostic may be inferred. By averaging over several adjacent 1-ms time intervals and different shots, the signal-to-noise ratio may be substantially enhanced at the expense of temporal resolution.

Figure 44 shows such a spectrum obtained from approximately 70 shots during a density clamp documentation experiment where all plasma parameters were duplicated from shot to shot. Each point in

the flux spectrum represents an average of five or six shots having the same tuning voltage at $t = 100$ ms—somewhat before the beam is turned on. The large error bars at lower energies result from worsened signal-to-noise ratios and the need to extrapolate the conversion efficiency curves below the calibration range of 50 eV. The straight lines are obtained from a logarithmic least-squares fit to the data points. The plasma behavior is shown in Fig. 45, with the East beam line injecting 1 MW at $t = 120$ ms. Figure 46 shows the corresponding ohmically heated discharge behavior when no beam was injected.

It is obvious even with the large error bars that greater than 90% of the flux being sampled by the spectrometer is at energies below around 70 eV. This is consistent with a neutral source that is local-

Fig. 40. Some basic plasma parameters for shot no. 40286. For each plot, the upper label is a solid line, and the lower label is the dotted line. Plasma density, $\bar{n}_e$, is obtained for a central chord (diameter) and rises smoothly during the period of constant gas puffing to a level of $4 \times 10^{13} \text{ cm}^{-3}$. Plateau I_p is approximately 140 kA. The D_α signal (dotted line) is obtained from a detector located in the same sector as the diagnostic and the gas puff port. The beam current monitors are zero, indicating ohmic heating only on this shot.

Fig. 41. Raw data for ISX-B shot no. 40288 in which neutral beam heating of $\sim 1.5 \text{ MW}$ begins at 120 ms (arrow). Beam energy is 30 kV. Note the rapid increase in the signal at the time the beam is turned on, especially in the 400- and 500-eV channels.

Fig. 42. The basic plasma parameters are for ISX-B shot no. 40288. Plasma conditions are identical to shot no. 40286 up until the time of injection ($t = 120$ ms). The density clamp effect of neutral beam injection is clearly evident in the plot of central $\bar{n}_e$. The drop in $\bar{n}_e$ at 230 ms is an artifact of the interferometer. Beam power is (45 A x 33 kV) ~ 1.5 mW.

ized in a low-temperature region such as the edge. It is also apparent that there are two classes of neutrals involved because the data is well fit by two straight lines corresponding to two different exponential distributions.

Integrating the measured spectrum over energy and multiplying by the solid angle factor ($\pi/\cos 35^\circ = 3.84$) yields the total flux $\bar{\Gamma}_0$. For the energy range 65 to 500 eV

$$\bar{\Gamma} = 4.6 \times 10^{14} \text{ cm}^2 \cdot \text{s}^{-1},$$

while for the energy range 25 to 65 eV

$$\bar{\Gamma} = 1.6 \times 10^{15} \text{ cm}^2 \cdot \text{s}^{-1}.$$

A similar integration may be performed to yield the local power flux,

$$P = \int d\Omega \int E \cdot \frac{d\Gamma}{dE d\Omega} dE$$

$$= 15.9 \text{ mW/cm}^2 \text{ within the energy range 65 to 700 eV,}$$

$$= 8.6 \text{ mW/cm}^2 \text{ within the energy range 25 to 65 eV.}$$

and the average neutral energy

$$E = \frac{P_{\text{Tot}}}{\bar{\Gamma}_{\text{Tot}}} = 71 \text{ eV}$$

for the range 25 to 700 eV.

From the shape of the neutral distribution, it is tempting to infer an equivalent neutral temperature kT_0 from the logarithmic derivative. A similar procedure is widely employed to estimate central ion temperature on most past and current machines by examining the high-energy part of the neutral distribution. For relatively low densities, the high-energy tail is assumed to originate predominately in the

Fig. 43. Response of spectrometer channel 4 at 250 eV for ten assumed identical shots. The upper plot shows the average of the shots, and the lower plot superimposes all ten shots. Note the small shot-to-shot variation in the measured flux as indicated by the small amount of scatter in the data. We take advantage of this constancy to justify comparison between similar shots when the spectrometer settings have been changed to observe different energy ranges.

central core¹²⁵⁻¹²⁶ via resonant charge exchange of hot ions with residual neutrals. Profile effects on the generation and attenuation of the outgoing neutrals cause a systematic underestimation of central ion temperature using this method;⁵⁰⁻¹²⁷ accurate charge exchange measurements of T_i on present-day high-density devices calls for both localized source enhancement (diagnostic neutral beam doping) and extensive computer modeling.

The situation is somewhat better in the current case because the majority of the low-energy neu-

Fig. 44. Spectrum of low-energy neutral emission from ISX-B at $t = 100$ ms as measured by spectrometer. Points represent an average of four or five shots obtained by retuning analyzer between shots to examine different energies. Fitting lines are obtained from a logarithmic-linear-least-squares fit to the data points in the following ranges:

lower energy: ($16 \text{ eV} < E < 50 \text{ eV}$)

coefficient of regression: 0.70

higher energy: ($55 \text{ eV} < E < 500 \text{ eV}$)

coefficient of regression: 0.97

trals are formed near the edge. In addition, we are interested in the neutrals directly and are not trying to indirectly infer ion behavior from neutral behavior.

If we ignore attenuation of the low-energy flux, the temperature may be interpreted from the measured flux by assuming a distribution function

$$f_0(\vec{v}) = \left(\frac{M}{2\pi kT} \right)^{3/2} \exp \left[-\frac{mv^2}{2kT} \right] \quad (6.1)$$

Then the flux through a surface located at $\vec{x}$ at time t is given by the moment equation¹²⁸

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Fig. 45. Plasma behavior for neutral-beam-heated shots during documentation experiment of Sept. 28, 1981 (~70 shots total). Note the constant electron density after the beam was turned on (compare Fig. 46).

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Fig. 46. Plasma behavior for ohmically heated shots during $\bar{n}_e$ clamp documentation experiment.

$$\begin{aligned}\Gamma_0(\vec{x}, t) &= n \int \vec{v} f(\vec{v}) d\vec{v} \\ &= n \left(\frac{m}{2\pi kT} \right)^{3/2} \int \vec{v} \exp \left[\frac{-mV^2}{2kT} \right] d\vec{v}, \quad (6.2)\end{aligned}$$

where n is the density at $(\vec{x}, t)$. We note that for an isotropic distribution, the volume element in velocity space may be written

$$d^3\vec{v} = 4\pi v^2 dv. \quad (6.3)$$

Thus,

$$\begin{aligned}\Gamma_0(\vec{x}, t) &= n \left(\frac{m}{2\pi kT} \right)^{3/2} \\ &\cdot (4\pi) \int \vec{v} \exp \left[\frac{-mv^2}{2kT} \right] v^2 dv. \quad (6.4)\end{aligned}$$

Because we only observe a small solid angle $d\Omega$, we sample the differential flux $d\Gamma/d\Omega$ for which all $\vec{v}$ are roughly parallel. Thus, we may let $\vec{v} \rightarrow v$ and

$$\begin{aligned}\frac{d\Gamma}{d\Omega} &= \frac{n}{4\pi} \left(\frac{m}{2\pi kT} \right)^{3/2} \\ &\cdot (4\pi) \int v \exp \left[\frac{-mv^2}{2kT} \right] v^2 dv. \quad (6.5)\end{aligned}$$

Finally, letting

$$dE = mv dv \quad (6.6)$$

and

$$v^3 dv = EdE \left(\frac{2}{m^2} \right), \quad (6.7)$$

gives

$$\begin{aligned}\frac{d\Gamma}{d\Omega} &= n \left(\frac{m}{2\pi kT} \right)^{3/2} \left(\frac{2}{m^2} \right) \\ &\cdot \int E \exp \left[\frac{-E}{kT} \right] dE. \quad (6.8)\end{aligned}$$

After taking the differential,

$$\begin{aligned}\frac{d\Gamma}{dE d\Omega} &= \frac{n}{\sqrt{2m}} \left(\frac{1}{\pi kT} \right)^{3/2} \\ &\cdot E \exp \left[\frac{-E}{kT} \right]. \quad (6.9)\end{aligned}$$

The result for a surface flux may be compared to the conventional central emission, which approaches $E^{1/2} \exp(-E/kT)$, at asymptotically high energies.¹²⁸ The latter dependence arises from the assumed central temperature profile.

Figure 47 shows a semilogarithmic plot of $E^{-1}d\Gamma/(dE d\Omega)$ from Fig. 44. The two-component nature is still evident, but it is now the slope in which we are interested. From Eq. (6.9), we see

$$kT \sim - \left[\ln \left(\frac{1}{E} \frac{d\Gamma}{dE d\Omega} \right) \right]^{-1}.$$

For the lower energy component, the inverse slope yields an equivalent temperature of

$$kT_1 = 7.1 \text{ eV}.$$

For the higher,

$$kT_2 = 82 \text{ eV}.$$

Both of these values are subject to a certain amount of error. The lower temperature is limited by the uncertainty in and scarcity of the data points; however, this is mitigated somewhat by the logarithmic dependence of the slope. The higher temperature, which is based upon particle energies of a few hundred eV that are presumably born farther inside the plasma, is subject to the same attenuation problems as conventional central flux measurements. Based on the calibration accuracy and the relative number of counts generally obtained during shots, the absolute temperature values are judged to be accurate to within 50%. However, the relative error in comparing two sets of data at the same energies is much smaller.

Fig. 47. A plot of $E^{-1}d\Gamma/(dE d\Omega)$ vs energy at $t = 100$ ms is shown. Inverse slopes of the two fitting lines are $kT = 7.1$ eV and $kT = 82$ eV.

The origin of the low-energy particles is quite possibly molecular dissociation of the filling gas resulting from successive electron impact. That is,

The above reactions have relatively large cross sections in the sub-keV energy range, and (if one assumes the Franck-Condon dissociation energy of 10 to 20 eV¹²⁹ to be shared equally between the resulting ion and atom) the consistency with the measured neutral energy distribution is quite reasonable. As to the higher energy particles, their origin is less clear. The inferred temperature is somewhat higher than expected for the edge, although kT_e is measured to be ~ 40 eV at the limiter radius. It is doubtful that the observed neutrals come directly from ion recycling at the main limiter because of the large toroidal separation. They are more likely attributable to charge exchange by edge ions with

the copious number of neutrals supplied by the gas feed in the line of sight of the analyzer. However, there are two factors that indicate that at least part of the observed neutrals are attributable to wall/limiter recycling. One factor is the possible existence of a virtual limiter (i.e., a material projection near or even past the limiter radius of 27 cm) near the observation region. For example, the bundle divertor flange in sector 13 is only 50° toroidally upstream of the diagnostic. The vacuum vessel design resulted in a scrapeoff distance, Δ , at this point of only 4.2 cm or less. From the profile results of the pumped limiter measurements, we still expect a substantial fraction ($e^{-4.7/2.3} \sim 15\%$) of the parallel ion flux at this radius to impact the wall and recycle as neutrals. The other factor is the relatively large scrapeoff distance on the machine, especially in the vertical direction ($\Delta \sim 30$ cm). This results in a longer mean free path for neutrals to wander toroidally about the machine without hitting either the wall or the plasma. Taken together, it seems reasonable that the higher energy component is attributable in part to both causes—charge exchange of edge plasma ions and neutralization at limiter-like surfaces.

6.4 EFFECTS OF NEUTRAL BEAM HEATING

In conjunction with the high- β studies being conducted on ISX-B, up to 3 MW of energetic ($E_{\text{beam}} > 30$ keV) hydrogen atoms are routinely injected into ohmically heated plasmas using two beam injectors. As shown earlier, the major effect of such injection on the low-energy neutral measurements is to increase the flux by a substantial amount. Figures 48 and 49 show plots of $d\Gamma/(dE d\Omega)$ at $t = 200$ ms obtained from the same series of discharges discussed in the last section. Figure 48 is based on those shots having ~ 1 MW of neutral beam heating using the East beam line. The beam was turned on at 120 ms. Figure 49 is based on the corresponding ohmically heated shots. In the case of injection, we note that both slopes are somewhat reduced—indicating that heating has occurred. Comparisons of the logarithmic derivatives of the

Fig. 48. Illustration of flux spectra at $t = 200$ ms for the neutral-beam-heated case.

Fig. 49. Illustration of flux spectra at $t = 200$ ms for ohmic heating only.

$E^{-1}d\Gamma/(dE d\Omega)$ plots, Figs. 50 and 51, show that the inferred temperatures have increased from 7.2 to 8.4 eV and from 86 to 112 eV, respectively. However, the increased curvature of the data at higher energies indicates that the distribution is nonthermal (i.e., this portion of the flux can no longer be characterized by a single temperature). Other effects of beam injection are summarized in Table 7. The increase in flux occurs predominantly at both the higher ($E > \sim 500$ eV) and lower ($E < 25$ eV) ends of the energy range. This dual enhancement is seen as additional evidence for the two-component nature of the measured flux.

Because of the difference in toroidal location and injection direction for the two neutral beam injectors, one might expect a noticeable difference in the low-energy neutral flux as measured in the observation region. This did not prove to be the case, at least in those instances for which direct comparisons could be made. Figure 52 shows the spectrometer output for shot no. 40963, a beam-

Fig. 50. $E^{-1}d\Gamma/(dE d\Omega)$ is plotted for neutral beam heating.

Fig. 51. $E^{-1} d\Gamma/(dE d\Omega)$ is plotted for ohmically heated case.

Table 7. Comparison of flux measurements for ohmically heated and neutral-beam-heated discharges at $t = 200$ ms

Each particle and power flux value has been multiplied by a factor of 3.84 to account for the integral over solid angle for an assumed cosine emission profile

	Ohmically heated	Neutral beam heated	Fractional increase
<i>kT</i> , eV			
For lower energy distribution	7.2	8.4	0.17
For higher energy distribution	86	117	0.30
Flux in range, $D^0 \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$			
$25 < E < 85$ eV	2.1×10^{13}	9.7×10^{13}	3.60
$85 < E < 500$ eV	4.4×10^{14}	4.5×10^{14}	0.02
$500 < E < 700$ eV	2.3×10^{13}	7.7×10^{13}	2.30
Total flux in range, $D^0 \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$			
$25 < E < 700$ eV	2.6×10^{15}	1.0×10^{16}	2.85
Power flux in range, $\text{mW} \cdot \text{cm}^{-2}$			
$25 < E < 85$ eV	11.7	55	3.70
$85 < E < 700$ eV	16.8	23.5	0.40
Total power flux, $\text{mW} \cdot \text{cm}^{-2}$			
$25 < E < 700$ eV	28.5	78.3	1.75
Mean particle energy in range, eV			
$25 < E < 700$ eV	68.6	49	-0.29

heated discharge using the East beam line. Figure 53 is for shot no. 40957, which was identical except that in this case the West beam line was used. For the energy range 200 to 500 eV, there is essentially no difference in the neutral outflux, despite the fact that the West beam line is injecting directly along the observation chord of the diagnostic (see Fig. 36).

The level of neutral emission does not seem to scale with increased beam power at least for the higher energy component. Figure 54 shows the spectrometer output for a discharge having staggered injection, with the East and West beam lines firing at 80 ms and 120 ms, respectively. Plasma parameters for the shot are shown in Fig. 55. Total injected power is over 3.5 MW. In comparison with the enhancement attributable to the first beam, there is little or no effect by the second beam at all, even though the injected power doubles. This may simply be caused by a saturation effect in the interaction of the beam with the edge plasma (i.e., the neutral emission may scale with P_{beam} at much lower power levels.

Because of the lack of mass resolution in the current device, it is not possible to say exactly what fraction of the observed flux is hydrogen (as opposed to deuterium), but it is expected to be negligible for several reasons. First, because the beam current $I_b \ll I_p$ and the major sources of neutrals (wall and gas puff) are deuterium, there is only a small amount of hydrogen in the torus—assuming no recent vacuum openings. Secondly, the analyzer is tuned to be sensitive to low energies—any hydrogen would have to come from beam ions ($E > 30$ keV) that had thermalized in the bulk plasma sufficiently to be in the energy range of the analyzer ($E < 1$ keV). We neglect entirely the small amount of hydrogen adsorbed on the walls between shots. Finally, for a given energy, hydrogen has a lower conversion efficiency than deuterium in the cesium cell.

6.5 INFLUENCE OF GAS PUFFING ON LOW-ENERGY FLUX

From the shape of the flux spectra, it appears that a large percentage of the low-energy emission

Fig. 52. Spectrometer response for neutral beam injection using East beam line only. Energies shown are 200, 300, 400, and 500 eV. $P_{inj} = 1$ MW into a 150-kA, $5.5 \times 10^{13} \text{ cm}^{-3}$ ohmically heated discharge at $t = 120$ ms.

Fig. 53. Spectrometer response for neutral beam injection using West beam line only. Identical settings and plasma conditions as above.

Fig. 54. Spectrometer response for staggered two-beam injection at 80 and 120 ms. Beam firing times are shown as arrows. Energies shown are 200, 300, 400, and 500 eV.

Fig. 55. Plasma parameters for two-beam injection are shown.

may be attributed to a roughly Maxwellian source having temperatures corresponding to molecular dissociation energies. Because of the close proximity of the gas puff value to the observation region, it is natural to try to discover what relationship if any exists between this intense localized source of molecules and the low-energy neutral emission.

Gas puffing is the principal method of fueling discharges in present-day tokamaks. Successful fueling involves the introduction of an amount of gas suitable for initiating the discharge and adding additional gas to maintain the discharge when particles are lost because of effects such as wall loading and pumpout by the vacuum system. Because of the nature of the experiments performed on the ISX-B while data was being taken with the spectrometer, the gas puffing was fixed and could not generally be varied. In particular, for the series of shots examined in the last two sections, a preprogrammed flow was used that consisted of a prefill, a large "superpuff" at 40 ms, and steady puffing at 100 ms until the end of the shot. Figure 56 shows the time behavior of the gas puff in $\text{torr} \cdot \text{L} \cdot \text{s}^{-1}$ along with the D_α intensity measured by a detector pointing at the gas inlet.³¹ For $T_e \sim 40$ eV, the

most likely channel for formation of deuterium atoms in the $n = 3$ state from molecules is the two-step process:¹³¹⁻¹³²

Dissociative

The extremely good time correlation between molecular gas input and D_α emission is indicative of the speed with which molecular dissociation occurs in the edge region.

Because of the lack of control over gas puffing, an effort was made to compare the low-energy neutral emission at the peak of the first puff ($t = 40$ ms) to that immediately following the peak ($t = 70$ ms), using the same series of shots as before. Figures 57 and 58 show the flux spectra at 40 and 70 ms, and Figs. 59 and 60 show the corresponding $E^{-1} d\Gamma/(dE d\Omega)$ plots.

The interpretation of the flux behavior is complicated not only by the fact that we are comparing

Fig. 56. D_2 gas puff (solid line) and D_α intensity (dotted line) in sector 10 for Sept. 28, 1981, shots on ISX-B. Steady-state flow of $10 \text{ torr} \cdot \text{L} \cdot \text{s}^{-1}$ corresponds to a fuelling rate of 7×10^{19} atoms/s at STP.

Fig. 57. Flux spectrum very early in the discharge ($t = 40$ ms) obtained from same series of shots as before. Time corresponds to peak of superpuff shown in previous figure.

Fig. 59. $E^{-1} d\Gamma/(dE d\Omega)$ is plotted for $t = 40$ ms.

Fig. 58. Flux spectra for $t = 70$ ms in Sept. 28, 1981, sequence. Time corresponds to minimum in D_2 gas puffing.

Fig. 60. $E^{-1} d\Gamma/(dE d\Omega)$ is plotted for $t = 70$ ms.

the emission at two different times but also by the rapid changes going on in the plasma as a whole at these early times in the discharge (see Fig. 45). It is not at all clear whether the differences in the 40 ms and 70 ms data are attributable to the effect of the gas puff or to such things as heating effects, increased or decreased density, better plasma confinement, and so forth. At the time of minimum gas input, the inferred temperature for the higher energy component of 85 eV is above that for either 40 ms (69 eV) or 100 ms (82 eV); this may be attributable to cooling of the edge by the increased gas flow or an increased transparency for charge exchange neutrals emerging from the core.

For the few shots in which the gas puff was varied at later times in the discharge, the low-energy emission shows a much clearer behavior. Figure 61 shows the gas puff and D_α signals for two neutral-beam-heated shots, nos. 40319 and 40335. Note that the fueling rate is lower than in the previous cases and that the gas is completely off after the $t = 40$ ms puff. In the latter shot, the gas flow is also turned completely off from $t = 145$ ms to $t = 190$ ms. Again, the D_α intensity is seen to closely follow the fueling rate and drops to the same minimum for the two periods of no gas input.

Figure 62 shows the spectrometer output for the same two shots—corresponding to emission at 200, 300, 400, and 500 eV. In this case, the emission drops in all four channels as soon as the gas is turned off, then returns to the same level as before when the gas flow is resumed. At least in this energy range, the gas puff is seen to account for ~70% of the neutral emission. The behavior of the

emission is identical to that of the D_α intensity, suggesting that the same group of atoms is involved in both phenomena.

Fig. 61. Gas puff and D_α signals for shot nos. 40319 (solid line) and 40335 (dotted line). Gas is turned off at 145 ms at the latter shot, and the D_α intensity drops rapidly during this time to essentially zero. As gas is turned back on at 190 ms, D_α intensity rises rapidly.

Fig. 62. Neutral flux measured by spectrometer for shot nos. 40319 and 40335. Energies for the four channels are 200, 300, 400, and 500 eV, respectively. Flux behavior in this energy range is identical to that of D_{α} emission when the gas puff is turned off and on late in the shot.

7. SUMMARY AND CONCLUSIONS

7.1 DISCUSSION OF RESULTS AND SOME IMPLICATIONS

A summary of the current work may be divided into three parts: consideration of the diagnostic *per se*, discussion of the specific results obtained on the ISX-B, and comparison with other experimental results on both the ISX-B and other machines. The data presented in the previous chapter indicate that charge transfer in alkali metal vapor is a viable technique for directly observing the low-energy neutral outflux from present-day tokamaks. The calibration procedure described earlier enables one to relate the spectrometer output to the incident neutral atom intensity in an accurate and meaningful way. The good agreement between the two calibrations that were performed using different methods and at different times attests to the long-term stability of the diagnostic; in addition, the agreement gives us confidence in the quantitative results obtained on the tokamak. In the next two sections, methods of systematically extending the useful energy range of the spectrometer and possible applications to diagnosing impurity fluxes are discussed.

The primary results of the measurements on the ISX-B were as follows:

1. For the type of discharge described earlier, the low-energy ($25 \text{ eV} < E < 700 \text{ eV}$) neutral deuterium flux exhibited behavior indicating the existence of two distinct populations that were well fit by Maxwellian velocity distributions having equivalent temperatures of ~ 8 and $\sim 80 \text{ eV}$, respectively. This behavior was observed at times as early as 40 ms into the discharge and at all subsequent times. Neutral beam injection enhanced the tails of both distributions, implying heating of both components. These effects were not dependent on either beam location or beam power for the range $P_{\text{inj}} > 1 \text{ MW}$.
2. The magnitude of the measured flux indicates that only a small fraction of the energy content of ISX-B is being lost directly in low-energy ($25 \text{ eV} < E < 700 \text{ eV}$) neutrals. This is true of both ohmically and beam-heated discharges. A crude overestimate of the losses in this energy range is

obtained by simply multiplying the calculated values for power flux by the surface area of ISX-B ($\sim 2 \times 10^5 \text{ cm}^2$). For the values listed in Table 7, the result is only 6 kW in the case of ohmic heating and 15 kW in the case of neutral beam heating. Energy losses at the limiter that are attributable to ion recycling and higher energy charge exchange neutrals will be a far more serious problem. On the other hand, the large particle fluxes at low energies play a substantial role in fueling and the particle balance. Unfortunately, no data with pellet injection were available to assess the relative merits of this mode of fueling compared to gas puffing.

3. In view of what is known about recycling, charge exchange, molecular dissociation, and similar atomic processes, there are several plausible explanations for the evolution of the two components. Because of the proximity of the gas puff to the viewing region, there is a large local source of D^0 atoms resulting from two-step dissociation of the feed gas. Depending on the population of the various vibrational states of the D_2^+ intermediate and the corresponding Franck-Condon dissociation energies, the resulting atoms may have an energy distribution quite similar to that measured for the lower energy group. A second possibility is charge exchange of these same neutrals with a low-energy ion component existing in the edge region; a third is neutralization of edge ions at a material projection and their subsequent reemission as neutrals. Based on the measurements, there is no way to decide which mechanism is the correct one; most likely, it is a combination of all.

A similar situation exists for the high-energy component. Although one can, in this case, rule out the possibility of dissociation products being observed directly, it is obvious from the results of the density decay experiment (Fig. 62) that these dissociation products are indirectly responsible for the major ($\sim 70\%$) portion of the flux measured in the 200- to 500-eV energy range. Next, a distinction must be made between charge exchange and wall recycling as the dominant mechanism. The rapidity

with which the flux tracks the D_α signal would seem at first to favor charge exchange; however, isotopic exchange measurements¹³² have shown that wall recycling in the ISX-B occurs in a very short time. Again, a combination of these effects is the most likely answer.

To gain further insight into the emission behavior, an attempt was made to combine the current results with higher energy data obtained from the nitrogen stripping cell magnetic energy analyzer (MEA). This device is described in the literature³⁰ and is calibrated for absolute flux measurements down to about 350 eV for deuterium. Figure 63 replots the $t = 100$ ms data discussed earlier (Fig. 44) on an expanded energy scale along

with the corresponding data from the MEA. For these measurements, the MEA was located in sector 6, approximately 80° in the ion-drift direction from the low-energy analyzer. The angle of observation was approximately the same for both diagnostics. (The author wishes to thank Dr. Steve Scott for providing the relevant MEA data and analysis.)

As can be seen, the agreement between the two sets of data is quite good, despite the different viewing locations. The absolute flux values agree to within a factor of two in the overlap range of approximately 350 to 700 eV. Using an asymptotic fitting procedure on the 100-ms MEA data, the equivalent temperature is estimated at 195 eV—somewhat higher than the 82 eV deduced from

Fig. 63. Spectrum of neutral emission from the ISX-B at $t = 100$ ms in the energy range 16 to 1500 eV, using data from both the low-energy spectrometer (solid points) and the conventional stripping-cell charge exchange analyzer (open triangles). [Low-energy data points are the same previously shown in Fig. 44. Note the good agreement between diagnostics in the overlap range (350 to 700 eV).]

the low-energy data. Because the MEA fit is not based on spectrum energies below 350 eV, the discrepancy is not too worrisome. The similar curvature in the two sets of data in the overlap range is encouraging and creates the image of a single smooth emission spectrum. The emission spectrum is not, however, characterized by a single temperature (in the energy range above about 100 eV) but by a series of increasing temperatures; this is a consequence of the increasing optical depth for neutrals of higher energies. The described behavior is quite similar to that seen in other plasma devices. Brissom³⁷ employed a cesium analyzer to observe the neutral particle spectrum of Elmo Bumpy Torus (EBT) plasmas shown in Fig. 64. The only essential difference seen in the flux spectra of ISX-B and EBT is the lack of the very-low-energy component in the case of EBT. This is attributable to the narrow bandwidth of the EBT analyzer, which restricted measurements to energies greater than 100 eV.

Fig. 64. Energy spectrum of neutral emission on EBT, as measured by the cesium analyzer of Brissom et al. Note that the spectrum does not extend below about 100 eV.³⁹

The results for total flux integrated over the energy range 25 to 700 eV compare favorably with the extensive deposition probe measurements of edge particle fluxes on ISX-B which have been performed by Roberto, Zuhr, and co-workers.¹²³⁻¹³³ For ohmically heated discharges similar to the ones discussed in the previous chapter, they measure a total fluence to the wall of $\sim 2 \times 10^{15} \text{ D} \cdot \text{cm}^{-2}$ per 240 ms discharge. Additional measurements¹³⁴ using rotating probes for time-resolved flux measurements yielded an average neutral flux of approximately $2 \times 10^{16} \text{ D} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ at positions 1 to 5 cm outside the limiter radius. Their observations are made in sector 8, 40° toroidally away from the spectrometer. Considering that the current measurements ignore the energy range below 25 eV, the agreement is satisfactory. In addition, the data for fluxes to the wall^{123,133} are consistent with a bimodal energy distribution having a low-energy Maxwellian component along with a high-energy tail.¹³⁵ This behavior is also quite similar to the two-component distribution seen by the low-energy analyzer, despite the toroidal separation in the two measurements.

Comparisons may also be made with the low-energy neutral measurements done on PLT.⁴²⁻⁴³ Roberto, Zuhr, et al. also made observations at a position separated 100° toroidally from the limiter, similar to the observations in the current study. In this case, however, the gas puff was also separated toroidally from the diagnostic location by about 100° . Thus, the PLT results should be typical of the neutral outflux in regions that are remote from major neutral sources and might be expected to be different from the gas-puff-dominated results of the ISX-B measurements. In addition, there are significant differences in the physical dimensions (for PLT, $R = 130 \text{ cm}$, $a = 40 \text{ cm}$, $\Delta = 10 \text{ cm}$) and the plasma conditions (in PLT, $1.2 \times 10^{13} \text{ cm}^{-3}$, 450 kA, 29 kG, 800 eV for ohmically heated T_i , pulse length 1 s, hydrogen filling gas) and, finally, viewing geometry ($\theta \sim 15^\circ$, as opposed to 35° on ISX-B.)

Despite all these differences, the two sets of measurements compare favorably in several respects. Although the data show no evidence of the lower energy component seen in the current study, the flux behavior is in reasonable agreement with that

of the higher energy component. In particular, at ≤ 200 ms in their discharge—when the primary neutral source is the toroidally symmetric gas prefill of approximately 3×10^{-4} torr—Roberto, Zuhr, et al. obtain the following values in the energy range $20 \text{ eV} < E < 1000 \text{ eV}$: particle flux $\Gamma_0 = \sim 3 \times 10^{15} \text{ cm}^{-2} \cdot \text{s}^{-1}$, power flux of $\sim 40 \text{ mW/cm}^{-2}$, mean particle energy expressed as of 120 eV. These values may be compared with those of Table 7. [At later times in the discharge, the PLT flux is seen to drop by a factor of ~ 25 , as the fill gas is burned out and the dominant source for the low-energy flux becomes recycling at the toroidally distant limiter.] A similar enhancement (three times) of the total flux is seen for neutral beam injection. This enhancement occurs in 50 ms as opposed to 20 ms in ISX-B. The fact that one sees such similar results under such widely varied plasma and machine parameters is intriguing. It tends to indicate that the flux behavior is machine-independent to a certain extent, at least for the current generation of devices. In view of the fact that the low-energy flux is basically an edge phenomenon, this is perhaps not too surprising. Despite the varied central plasma conditions found in different present-day confinement experiments, parameters such as edge electron temperature, neutral density, vacuum materials, and filling pressure are generally similar. It would be of interest to investigate the edge fluxes under circumstances in which the above is not true. Some possibilities include: intense gas puffing; edge heating by radio frequency (either by design or because of inefficient coupling to the core plasma); cryogenic walls (which might modify the molecular dissociation and/or recycling processes); special material walls and limiters; and, of course, magnetic diverters.

In attempting to interpret the results of chapter 6 and to relate them to the plasma behavior in ISX-B, warnings should be heeded:

1. The current measurement is a local one of a parameter having several sources that are known to have toroidal and poloidal asymmetries.
2. Because of the viewing angle of 35° , the spectrometer accesses components of neutral flux emanating both parallel and perpendicular to the

magnetic field. Depending on the origin of the neutrals (for example, resonant charge exchange), these components might exhibit significantly different behavior, as is seen at higher energies.¹³⁶ A diagnostic capable of scanning in the toroidal midplane at different θ would help in determining how important this effect is.

3. The lack of an accurate neutral density profile in the edge region makes it hard to predict to what extent the measurement is optically thin (implying a chord-integral measurement) or optically thick (implying a surface measurement). This may be contrasted with the case of high-energy neutral flux measurement in which the determining factor is not the neutral profile but rather the electron (ion) density profile. This is because, for neutral atoms emerging from the core, attenuation occurs primarily from electron and ion impact ionization or charge exchange with ions. As lower and lower energies are approached, the neutral source is located nearer to the limiter radius, where both n_i and T_i are small. Thus, the question of attenuation is not as important as that of the exact source location (i.e., the neutral profile).

In conclusion, it may be stated that negative ion formation in alkali vapors is a useful tool for investigating low-energy neutral atom behavior under conditions encountered in the edge region of tokamaks. As such, it is complementary to other diagnostic techniques such as material probes, time-of-flight analysis, and atomic fluorescence and can help in acquiring a more integrated picture of the edge region. The experimental results presented in the previous chapter, although not extensive, serve to point out the efficiency of this method.

7.2 METHODS TO EXTEND THE LOW-ENERGY RANGE OF THE SPECTROMETER

The decreased count rate at lower energies is the major current constraint on low-energy measurements. This is in part unavoidable because of the falloff in the electron attachment cross section in cesium at low energy, but several improvements in the apparatus are possible for future efforts.

1. Increase area of front aperture: This is the simplest remedy and should increase the signal in the proportion $A_{\text{new}}/A_{\text{old}}$. By the use of suitable tubes or multiple apertures, the gas conductance may be kept low and suitable low pressures may be maintained in the transit tube.
2. Move apparatus closer to machine: This will increase the signal in the proportion $(r_{\text{old}}/r_{\text{new}})^2$. It would be straightforward to increase the magnetic shielding (e.g., by enclosing the apparatus in a soft iron box) sufficiently to move it forward as much as one meter and still accurately analyze the low-energy ions. For the current case, this should result in an enhancement of about $(235/135)^2$.
3. Increase heat pipe operating temperature: This will increase the electron attachment rate in the heat pipe for lower energy neutrals somewhat but will also result in increased scattering, as was evident in Fig. 35. In addition, the cesium loss rate and cell lifetime will decrease accordingly. Therefore, it is unlikely that the low-energy performance of the current setup could be substantially improved by increasing the operating temperature, although a small increase might be worthwhile.
4. Increase the transmission of the energy analyzer: Widening the entrance aperture would allow more negative ions to be counted at the expense of worsened energy resolution. Because the current device has such high resolving power, this is quite tolerable. An additional advantage of widening the aperture would be to increase the effective acceptance angle. Because of the focusing effects of the analyzer, the scattering in the cesium cell would not then be as detrimental to the low-energy conversion efficiency.
5. Eliminate noise in analyzer from positive ions: Secondary electrons formed by positive ion impact on the repeller grid will tend to fall back to the ground plane along the field lines. Because of the current spacing of grid and detector slits, positive ions tend to hit the grid opposite the first slit when the analyzer is tuned for low energies. This results in the noise seen in

channel 1 at the lowest energies examined on the tokamak. Solutions would be to move the grid or increase the distance of the exit slits from the entrance slit.

If these steps are taken, the overall increase in efficiency for high as well as low energies will tax the current detector capabilities. In conjunction with increasing the low-energy count rate, the dynamic range must be improved. As shown earlier, the current system response is linear up to only a few times 10^4 pulses/s. By choosing different detectors such as high-current channeltrons and using more sophisticated electronics capable of higher speed, it should be possible to increase the linear range by between one and two orders of magnitude. This would require more expensive electronics but would certainly increase the useful energy range, in addition to the enhancing data quality (because of better statistics). The current sampling rate of the PDP-8 setup is 1 kHz; however, this could also be increased (at increased cost), yielding a better time resolution and allowing studies of sub-ms phenomena in the low-energy flux.

7.3 EXTENSIONS OF DIAGNOSTIC METHOD TO EXAMINE IMPURITY NEUTRALS

Up until now, we have neglected to consider impurity (nonhydrogenic) atoms and their role in the low-energy neutral flux for a number of reasons. Such impurity fluxes would be expected to be much smaller than the ones measured here because the relative cleanliness (low Z_{eff}) of current machines. The necessary charge transfer cross sections are not as well known (if at all) as those for hydrogen, and a calibration similar to the one performed above would require the preparation of well-behaved impurity atomic beams. In addition, the diagnostic should resolve differing masses as well as energies, requiring a more complex instrument. Each of these considerations makes the measurement an exceedingly difficult one.

On the other hand, impurities play an important part in many of the physics problems associated with fusion research. Because the wall (including the limiter) is the most important source of impuri-

ties (neglecting grid sputtering during neutral beam injection or impure fueling gas), most of the impurities in tokamak plasmas are low-energy edge neutrals at one time or another. Thus, the observation of impurity fluxes is of intrinsic interest; in this section we discuss some methods of extending the current measurements to include nonhydrogenic species.

Impurities may be classified as either high Z (e.g., iron or molybdenum) or low Z (e.g., carbon or oxygen). The former are usually attributable to plasma sputtering or erosion of structural members, and the latter tend to come from adsorbed layers of surface contaminants (an exception is the growing use of carbon or carbide limiters). High- and low- Z impurities may be further distinguished by their degree of ionization in present-day tokamaks. Although the lighter ions are often completely stripped at the center of the plasma (e.g., O^{8+}), the heavier species are generally only partially stripped. Of course, the temperature profile implies each ionization stage below the maximum will also exist for some minor radius.

Observations of edge impurity fluxes have been made using resonant fluorescence spectroscopy and desorption probe techniques similar to those used in the deuterium measurements. In particular, measurements in the edge of ISX-B¹³⁴⁻¹³⁵ have shown oxygen concentrations typically 1% of the plasma edge density, with iron and carbon a factor of ten lower. Thus, it may be possible to extend the electron attachment technique to examine these three impurities—assuming the modifications mentioned in the last section are adopted. The main uncertainty in feasibility is in regard to the electron attachment cross section for these species in cesium because the mass analyzing techniques are well-known from atomic physics studies (see references called out in Sect 3.3). Nagata¹³⁷⁻¹³⁸ has measured both the equilibrium fraction F_- and the total electron capture cross section σ_{0-} for both carbon and oxygen in alkali metal vapors, including cesium, at energies down to 1 keV. The cross sections at this energy are measured to be $\sim 5 \times 10^{-16} \text{ cm}^{-2}$ for oxygen in cesium and $\sim 8 \times 10^{-16} \text{ cm}^{-2}$ for carbon in cesium. These values may be compared to

$\sim 1 \times 10^{-15} \text{ cm}^{-2}$ for deuterium at the same energy (Fig. 4). Even more encouraging, however, are Nagata's results for the equilibrium fraction measurements, where F_- for both carbon and oxygen are found to be significantly higher than for hydrogen (0.92 for oxygen and 0.85 for carbon at 1 keV). The maximum conversion efficiencies he achieved were $\sim 15\%$ for oxygen and $\sim 25\%$ for carbon at 1 keV, whereas his value for hydrogen was $\sim 8\%$. From this data, it seems likely that the electron attachment technique would work for both oxygen and carbon, at least for the keV range. The conversion efficiencies for lower energies are unknown.

Table 8 shows some information on negative ions of typical tokamak impurities, along with deuterium. It is noted that calibration for oxygen using

Table 8. Negative ions for atomic species of interest in tokamaks

Negative ions	A	Configuration	Electron affinity (eV)
$H^-(^1S)$	1	$1s^2$	0.754
$C^-(^4S)$	6	$2s^2 2p^3$	1.263
$C^-(^2D)$		$2s^2 2p^3$	0.034
$O^-(^2D)$	8	$2s^2 2p^5$	1.463
$Fe^-(^4F)$	26	$3d^2 4s^2$	-0.16
$Mo^-(^6G)$	42	$4d^3 5s^2$	$\sim 1.1 \pm 0.2$
$W^-(^6S)$	74	$5d^3 6s^2$	$\sim 0.5 \pm 0.3$

Source: B. M. Smirnov, *Negative Ions*, McGraw-Hill, New York, 1982.

the photodetachment technique will require a different laser because the yttrium-aluminum-garnet (YAG) photon energy of 1.17 eV is insufficient to detach the valence electron [electron affinity (E.A.) = 1.46 eV]. Substitution of an argon laser ($h\nu \geq 2.35 \text{ eV}$) should suffice. At first glance, a similar problem exists for carbon; however, it is possible to produce a large fraction of C^- in the long-lived 2D state¹³⁹ that has an E.A. of only about 35 meV. Thus, the YAG laser would be sufficient for photo-neutralization in this case.

Appendix A MEASUREMENT OF CESIUM LOSS USING A HOT-WIRE SURFACE IONIZATION GAUGE

As was emphasized in chapter 3, the *raison d'être* for the heat pipe design of the charge exchange cell was to minimize the cesium loss through the cell apertures. Thus, it is instructive to attempt to determine the actual loss under operating conditions—not only to verify the operation of the heat pipe but also to set some limits on expected cell lifetime and cesium flux into the tokamak.

Consider the situation in Fig. A.1 where we idealize the heat pipe as having cesium density, n , and temperature, T , only in the central section as shown. The loss of cesium through the ends may be estimated by¹⁴⁰

$$dN = A_2 d\Phi_{cs} = \frac{nv}{4} \left(\frac{d\Omega}{2\pi} \right) A_2 \quad (A.1)$$

$$= \frac{nvA_1}{8\pi} \cdot \frac{A_2}{R_{12}^2},$$

where v = rms velocity at temperature T .

For our operating conditions,

$$T = 122.5^\circ\text{C}$$

$$v = \sqrt{\frac{3kT}{m}} \sim 2.7 \times 10^4 \text{ cm/s}$$

$$dN = 5.2 \times 10^{16} \left(\frac{A_2}{R_{12}^2} \right) \times (2 \text{ ends})$$

$$= 3.7 \times 10^{15} \text{ atoms/s} = \sim 2.9 \text{ mg/h}.$$

Thus, a charge of 6 g should last up to 2000 h at our nominal operating temperature. From this model, we see that the flux through any aperture should drop as R_{12}^{-2} , where R_{12} = distance from central section to aperture. For example, the

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Fig. A.1. Geometry for calculating the loss of cesium out the end of the heat pipe. A step function is assumed for the density profile.

amount of cesium going back through the collimating aperture into the tokamak should be no more than

$$\frac{nvA_1}{8\pi} \cdot \left(\frac{0.317}{(2.12)^2} \right) = 3.7 \times 10^{11} \text{ s}^{-1} < 0.3 \mu\text{g/h} \quad (\text{A.2})$$

This model is not rigorous; the derivation of Eq. (A.1) assumed the mean free path for collisions to be $L \gg$ cell dimensions, but they are approximately equal for the operating temperature range. Because we expect the outflux to be typical of conditions within 1 mtp of the aperture (i.e., somewhere in the arm), the hot center is shielded and the loss should be even lower than that predicted by Eq. (A.1). The question is, how much less.

Note that there is a simple yet elegant method of accurately measuring the loss flux at an arbitrary distance from the heat pipe. Because of the low (3.89 eV) ionization potential of cesium, it is easy to make a sensitive detector based on surface ionization on a hot wire. This method is similar to that used in the original cesium vapor pressure measurements by Langmuir and others.¹⁴¹⁻¹⁴² The setup is shown in Fig. A.2. The hot wire is a tungsten filament with a diameter of 0.0254 cm that is stretched between two support posts. The collector is a thin-walled stainless tube ($d = 1.91$ cm) supported independently of the filament and grounded through a current meter as shown. The entrance aperture is 0.635 cm in diameter and exposes a length, L , of the central section of the wire to the cesium flux. The exit aperture is slightly larger than the entrance; this allows the cesium that does not hit the wire to pass through without depositing on the inner wall of the collector. For a parallel flux, Γ_{Cs} , we may set $L = 0.635$ and

$$\Gamma = \frac{dN/dt}{w \cdot L}, \quad (\text{A.3})$$

where

dN/dt = number of cesium atoms striking the wire/s,

w = wire diam = 2.54×10^{-2} cm,

L = exposed length = 6.35×10^{-1} cm.

When the filament is heated to a temperature greater than ~ 1400 K, almost all of the atoms striking the filament will evaporate as ions. If we now apply sufficient bias voltage to overcome the space charge surrounding the filament, the collector will count all of the positive ions; and one can say that

$$\Gamma = \frac{I^+}{ewL}, \quad (\text{A.4})$$

where I^+ is the collector current in amperes.

Fig. A.2. Top and side views of the hot-wire surface ionization gauge. The filament and its power supply are biased positively to permit efficient collection of the positive ion. The gauge is enclosed in a shield during operation to minimize electrical noise in the microammeter.

Several limitations must be taken into account to justify this simple picture:

1. Space-charge current limitation: For a given voltage V_B , the maximum current that can be extracted is given by¹⁴³

$$I_B = 1.46 \times 10^{-5} \frac{L}{r_{\text{coll}}} \left(\frac{V_B^{3/2}}{\beta} \right), \quad (\text{A.5})$$

where r_{coll} = radius of the cylindrical collector and β is a geometric factor ~ 1.08 . This yields the following saturation fluxes:

$$1 \text{ V: } \Gamma_{\text{max}} \leq 3.48 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1},$$

$$10 \text{ V: } \Gamma_{\text{max}} \leq 1.1 \times 10^{17} \text{ cm}^{-2} \text{ s}^{-1},$$

$$25 \text{ V: } \Gamma_{\text{max}} \leq 4.4 \times 10^{17} \text{ cm}^{-2} \text{ s}^{-1}.$$

Fig. A.3. Measurements (points) and calculated gauge currents (line) for cesium flux measurements at 26 cm from the central section of the heat pipe. At operating temperatures of 122.5°C, the corresponding measured flux is approximately $3.9 \times 10^{13} \text{ cm}^{-2} \cdot \text{s}^{-1}$.

We see that only very small voltages are required for expected fluxes.

2. Shielding of ends: Because the wire ends are cooled by the mounting posts, they may not be hot enough to guarantee 100% ionization. This is the reason for a well-defined aperture in the middle of the collector. Shielding of the ends also prevents leakage currents attributable to cesium coating of the insulators.
3. Wire purity: Various drawing processes involved in manufacturing the wire can coat the tungsten with a carbon/carbide layer that can severely limit the ionization efficiency and should be avoided. Such coatings are difficult if not impossible to remove once applied.¹⁴⁴ Even pure tungsten generally has dissolved alkali impurities;

Fig. A.4. Measured (points) and calculated gauge currents (line) for cesium flux measurements at 44 cm for central section of heat pipe. At operating temperature of 122.5°C, the corresponding measured flux is approximately $1.3 \times 10^{13} \text{ cm}^{-2} \cdot \text{s}^{-1}$.

at the typical operating temperatures, these will slowly diffuse to the surface and ionize, giving a leakage current (usually small) that must be subtracted.

4. Limitations on filament current: Although the wire must be hot enough ($T > 1400$ K) for 100% ionization efficiency, if the current is raised too high ($T \sim 1800$ K), the light from the filament will begin ejecting photoelectrons from any cesium atoms deposited on the interior of the collector tube. This photocurrent may become a substantial fraction of the measured positive ion current. Note that this effect is minimized by avoiding cesium coating of the interior, hence the use of a large exit aperture.

One must also be careful to minimize the evaporation of the filament because this causes changes in the value of w . Because this only becomes a problem at $T > 2500$ K, the temperature should be kept in the range 1400 to 1800 K—as noted above.

Nominal values for I_{fil} for given wire diameters are available in the literature.¹⁴⁵ For our device, $I \sim 2.5$ A is sufficient.

After incorporating the above limitations, the following procedure was adopted. The detector was set up a distance from the heat pipe. For every flux measurement made, it was easy to verify proper operation by varying V_{bias} and I_{fil} to ensure that the collector current was saturated.⁵¹ Leakage current was minimized by flashing the filament to ~ 2500 K for a few minutes, then reducing to operating range. This resulted in I_l typically $< 1\%$ of the measured currents.

Figures A.3 and A.4 show collector currents as a function of heat pipe temperature for $R_{12} = 26$ cm and 44 cm, respectively. The solid curves give the expected current based on Eqs. (A.3) and (A.4), and are seen to overestimate the actual measurements. Presumably, the confinement properties of the heat pipe are somewhat better than predicted by the simple slab model.

Appendix B

EFFECTS OF BACKGROUND GAS ON LOW-ENERGY NEUTRAL FLUX MEASUREMENTS

A factor that tends to complicate any measurements of neutral flux from tokamaks is the effect a background of D_2 molecules has on the transmission. For the case of ISX-B measurements, such a background exists in the volume between the plasma edge and the first collimating aperture and to a lesser extent in the beam tube behind the collimation aperture.

It is not possible to separate out the purely attenuative effects (such as scattering of the D^0 in D_2) from the general interaction between plasma edge and neutral gas blanket, nor should we want to for the purposes of measuring the flux to the walls. We do wish, on the other hand, to minimize transit effects in the beam tube itself because these will change the measured flux magnitude and energy distribution.

To investigate this effect, measurements of the pressure rise in the tube were made during operations on ISX-B. An attenuation experiment was later run during the postcalibration to measure the transmission losses under similar conditions.

The transit tube between the first aperture and the pumping tee is of length (l) = 170 cm and internal radius (a) = 1.9 cm so that the conductance for molecular flow of deuterium ($m = 4$ amu) at temperature (T) = 300°K is

$$C_T = 30.48 \left(\frac{a^3}{l} \right) \left(\frac{T}{m} \right)^{1/2} = 10.6 \text{ L/s} ,$$

and for the aperture A_1

$$C_A = 3.64 (A_1) \left(\frac{T}{m} \right)^{1/2} = 10.0 \text{ L/s} .$$

A fast ($t = 1$ ms) ionization gauge was placed directly behind the front aperture and measurements

were made for gas puffing with no discharge or toroidal field operation to eliminate magnetic field effects on the ionization gauge. The measured pressure rose smoothly with time to a peak of approximately 3×10^{-5} torr. The pressure measured at the far end of the tube near the pumping/deflection tee showed no appreciable rise in pressure from the base value of 2×10^{-7} torr. Assuming a linear pressure drop along the length of the tube and correcting for the gauge sensitivity of deuterium implies a target thickness of approximately

$$\Pi_{D_2} = 2.69 \times 10^{19} \left(\frac{P}{760} \right) \left(\frac{T}{T + 273.15} \right) \left(\frac{1}{2} \right) \\ \sim 2 \times 10^{14} \text{ cm}^{-2} .$$

The target thickness during an actual discharge is expected to be significantly less than this because of the pumping effects of the plasma. Measurements made with a shielded ion gauge tube indicated a relative drop in pressure of approximately 50% during a discharge. However, it is not known how well the shielding functioned in the transient magnetic fields. Thus, we choose $2 \times 10^{14} \text{ cm}^{-2}$ as an upper limit.

The setup used to measure neutral attenuation using the low-energy accelerator is shown in Fig. B.1. The attenuation cell was a 75-cm long, 3.8-cm diameter pipe having small apertures at either end. The same fast gauge that was used for the tokamak measurements was installed on the pipe. When the pumping valve was closed, it was a simple matter to vary the cell pressure over four orders of magnitude without appreciably increasing the pressure in the aft section of the accelerator or the detector chamber.

The secondary emission detector used for these measurements was quite similar to the calibration

Fig. B.1. Illustration of experimental setup to determine scattering attenuation losses on D^0 transmission through a background of D_2 . The cell length of 75 cm was a compromise between duplicating the solid angle used on the tokamak and maintaining good differential pumping between the cell and the high-vacuum detector and accelerator section.

detector described in chapter 3 except for having cylindrical symmetry and the substitution of sapphire for alumina as the target support insulator. This resulted in significantly lower leakage currents. The detector was arranged so as to subtend essentially the same solid angle as did the heat pipe entrance aperture on the tokamak.

Attenuation measurements were made on neutral deuterium beams of 800, 200, and 100 eV energies. Before each run, the secondary emission detector

Fig. B.2. Illustration of percent transmission of 800 eV D^0 through D_2 plotted as a function of target thickness in the attenuation cell. The estimated range of target thickness attributable to background gas in the tokamak measurements is indicated by the arrow.

Fig. B.3. Illustration of percent transmission of 200 eV D^0 through D_2 (same conditions as for 800 eV).

was calibrated using a D^+ beam as described in chapter 4. The necessity of propagating a charged beam through the 75-cm cell precluded measurements below 100 eV. After establishing a stable neutral beam, the pressure in the cell was raised and the resultant neutral intensity measured. A magnet near the end of the gas cell served to remove any charged particles formed by stripping collisions. The cell was then evacuated and the neutral intensity remeasured. The transmission was calculated by normalizing the intensity at pressure P to the average intensity I_0 before and after adding gas to eliminate short-term drift effects. Results are shown in

Fig. B.4. Illustration of percent transmission of 100 eV D^0 through D_2 (same conditions as for 800 eV).

Figs. B.2, B.3, and B.4, where the target thickness Π_T now is given by

$$\Pi_T = 3.22 \times 10^{16} P(\text{torr}) \text{ cm}^{-2} .$$

For all three energies investigated, scattering outside the detector solid angle does not become significant until relatively large Π_T . Within the error limits, there is less than a 10% effect—even at 100

eV for the estimated 2×10^{14} target thickness on the tokamak. These results are similar to those found by Fleishmann and Tuckfield²² for an 80 eV H^0 beam in helium and oxygen. There may still be a problem for lower energies, but the lack of substantial difference in the 800 eV vs 100 eV data (at least for $\Pi_T \leq 3 \times 10^{14} \text{ cm}^{-2}$) seems to indicate a weak dependence on energy for the measured target thickness range.

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