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MASTER

JANUARY 1979

PPPL-1478

UC-20f

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S. L. DAVIS, S. S. MEDLEY, M. BRUSATI

PLASMA PHYSICS LABORATORY

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THE CHARGE EXCHANGE ANALYZER FOR MASS RESOLVED
ION TEMPERATURE MEASUREMENTS ON PLT

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S. L. Davis, S. S. Medley and M. Brusati*

Plasma Physics Laboratory, Princeton University

Princeton, New Jersey 08540

ABSTRACT

A five channel, mass resolved, radially scanning charge exchange diagnostic system was calibrated over an energy range of $0.75 \leq E \leq 40$ keV and installed recently on PLT. The system provides either passive measurements with facility to correct for neutral density profile effects or active charge exchange diagnostics using a vertically aimed Berkeley ion source which is normally operated at 15 keV, 5 A. This report describes the analyzer and presents typical measurements obtained during high power neutral beam injection heating.

*Present Address: Comitato Nazionale Per L'Energia Nucleare Laboratorio Gas
Ionizzati, Frascati, Italy

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I. INTRODUCTION

As is well known, one method for determining the plasma ion temperature in magnetic confinement devices is based on analysis of the energy distribution of escaping fast neutrals produced by resonant charge exchange between ions and the residual neutral atoms. For PLT, where the minor radius ≤ 45 cm and the line average density reaches $\sim 1 \times 10^{14} \text{ cm}^{-3}$, the mean free paths for neutral diffusion into – and escape of moderately energetic charge exchange neutrals from – the plasma can be substantially smaller than the minor radius. To correct for distortion of charge exchange measurements due to these effects, the previous analyzer system on PLT employed a diagnostic neutral beam which, in conjunction with a scanning detector, provided a radial profile of the ion temperature¹. With the introduction of neutral beam heating, the need arose for an analyzer with mass resolving capability as well as an extended energy range. A mass analyzing, five channel energy analyzer was designed, constructed and calibrated to satisfy this requirement. The new analyzer, which preserves the scanning capability of the previous one, employs channel electron multiplier detectors operated in the pulse counting mode.

A description of the analyzer is presented in Section II. Section III describes the calibration procedure and Section IV presents a Monte Carlo model used to estimate the absolute efficiency factor. Typical measurements obtained during recent high power neutral beam heating on PLT are displayed in Section V to illustrate the data acquisition and analysis procedure.

II. ANALYZER DESCRIPTION

The main components of the analyzer are indicated on the photograph shown in Fig. 1. The stripping cell (A) is 10 cm in length with entrance/exit apertures in the form of cylindrical channels, each of diameter 0.3 cm and length 2.5 cm. Two

tubes of 0.32 cm bore provide access to the cell interior from an external flange for a gas inlet (B) and pressure measurement (C). The cell is normally operated with helium gas at 0.5 - 2 mTorr, the pressure being measured with an ionization gauge*. For helium gas at ~1 mTorr and tube dimensions noted above, the total conductance of the two apertures is ≈ 1 l/sec. The gas load presented by the stripping cell is pumped with a 200 l/sec Airco TMP-212 turbomolecular pump located at port D. Taking into account the conductance of the pump access and the degraded speed for helium, the effective pumping speed is ~ 100 l/sec. During operation the analyzer chamber is maintained at a pressure of approximately 10^{-5} Torr.

The zeroth order focusing, 120° deflection magnet (E) provides a maximum field of 4 kG in a 1 cm vacuum gap between the pole faces. The 1 inch thick steel walls of the vacuum chamber provide both the return yoke for the magnet as well as shielding against the magnetic field in the environment of the PLT. The cylindrical electrostatic deflection plates (F) have a separation of 1 cm and radii of curvature chosen to provide five channels with multiples of 1, 2, 3, 4 and 5 times the energy of the lowest energy channel. The detectors (G) are channel electron multipliers (Galileo Electro-Optic Model 4800) operated in the pulse counting mode. Signal interfacing through the vacuum wall is provided by a BNC connector array (H).

Ions entering the magnetic field are deflected according to $mv/r = qB$. The radius of curvature, r_n (cm), for a singly charged ion of mass, m (AMU) and energy, E_n (keV), in the n th analyzer channel satisfies the equation

$$B^2 = 20.7 \frac{mE_n}{r_n^2} \quad , \quad (1)$$

where B is the magnetic field strength in kilogauss. After emerging from the magnet, the zeroth order focused particles have effectively straight trajectories

*True pressure after correction for the gauge factor (~ 6) is approximately 3-12 mTorr.

into ~ 0.32 cm diameter apertures located near the entrance to the electrostatic deflection plates. The electric field between the plates $\epsilon(r) = (V_0 - V_i)/r \ln(r_0/r_i)$ causes the ions of the proper energy to follow an approximately circular path of radius r from the entrance to the exit apertures satisfying the force equation:

$$M \frac{v^2}{r} = q \epsilon(r) \quad , \quad (2)$$

where V_0 , V_i are positive and negative voltages of amplitude, V , applied to the plates and r_0 , r_i are the radii of the outer and inner plates, respectively. Introducing the notation: $r_n = n r_i$ where r_i is the centerline radius of the lowest energy channel, r_{on} and r_{in} being the outer and inner radius of the n th channel where $r_{on} = n r_i + 0.5d$ and $r_{in} = n r_i - 0.5d$ and d is the plate separation common to all channels, one may write

$$V = \ln \left(\frac{n r_i + 0.5d}{n r_i - 0.5d} \right) E_n \quad , \quad (3)$$

where the amplitude of the plate voltage, $V(\text{kV})$, is the same for all channels (E_n in keV).

Details for the electrostatic plates are given in Table I.

Although the electrostatic plates conventionally provide energy analysis and the magnet mass separation, the role of these components has been reversed in the present application. This is made possible by the requirement to separate only hydrogen and deuterium ions and, as will be discussed further in the next section, relaxes the accuracy to which the deflection plate voltages must be set. From Eq. (1), the energy resolution of the magnet for any mass is given by

$$\frac{\Delta E}{E} = 2 \frac{\Delta B}{B} \approx 2 \frac{\Delta r}{r} \quad , \quad (4)$$

where r is the radius of curvature for the ion trajectory corresponding to a given channel and Δr is the diameter of the apertures at the entrance to the

electrostatic plates. Only two mass separation scenarios require consideration: 1) if the magnetic field is adjusted to align a particle of mass M and energy E onto a given channel aperture, then particles of mass $M/2$, energy $2E$ or mass $2M$, energy $E/2$ giving the same ME product will also be aligned at the same aperture. However, if the energy resolution of the electrostatic plates satisfies

$$\Delta E < E/2 < E \quad (5)$$

(i.e., if $\Delta E/E < 50\%$), then particles with the above parameters will not be transmitted. This effectively provides the mass separation capability of the analyzer.

III. CALIBRATION

The arrangement used for calibration of the analyzer is shown schematically in Fig. 2. An ORTEC Model 358B ion source with a modified extraction gap provided a continuous ion current of $\approx 200 \mu A$ over an energy range of 0.75-40 keV. The hydrogen species mixture (H^+ , H_2^+ , H_3^+) from the source was mass analyzed using a 90° deflection magnet to focus H^+ on the neutralizer cell apertures. Electrostatic deflection plates served to remove the residual ions at the neutralizer exit as well as to quench excited metastable states² of H^0 . A permanent magnet (not shown) was used to apply a well localized magnetic field across the drift tube near the analyzer to remove particles reionized during flight through the drift tube.

Calibration of the analyzer required determining the magnetic field and deflection plate settings, the resolution of the magnet and deflection plates, and the detection sensitivity for the five channels as a function of neutral H^0 energy. The data were obtained using the pulse counting circuitry shown in Fig. 3. The entrances of the channel electron multiplier detectors were biased at -3 keV. This eliminates the drop in detection efficiency for charged particles at low energies,

since all ions impinge on the detector entrance with a minimum energy of 3 keV. Neutral particles collected by the detector aligned on the axis of the calibration beam (CHANNEL "O" in Fig. 2), however, are not post accelerated. Thus a correction to the neutral signal must be applied at energies below 3 keV. The manner of accomplishing this will be discussed shortly. The detector pulses were processed using Galileo Electro-Optic PAD 400 pulse amplifier-discriminators which provided a 100 nsec long, 5 volt signal output into a terminated 50 Ω coaxial cable. The pulses were accumulated using a conventional scaler paralleled with a rate meter which drove the ordinate of an X-Y plotter. The plotter abscissa was driven either by the amplitude of the magnetic field or the deflection plate voltage, depending on which of these was being varied. This circuitry was used to examine separately each of the five analyzer channels while an identical system (except for the X-Y plotter) was dedicated to the straight-through (CHANNEL "O") detector. Each channel was provided with a dedicated pulse amplifier-discriminator.

The following procedure was used to calibrate the field settings. For a selected beam energy, an approximate deflection plate voltage setting was calculated using Eq. (3). The magnetic field was varied to obtain the "B field scan" on the X-Y plotter as illustrated in Fig. 4A. With the magnetic field set for the peak of this scan, the deflection plate voltage was varied to provide the "E field scan" shown adjacently. Experience quickly confirmed that this procedure was not sensitive to the deflection plate setting provided the setting fell within the FWHM range of the E field profile. The above procedure was carried out with an arbitrary, but constant, stripping cell pressure (He) over a wide range of energies to generate the magnet and deflection plate calibration curves shown in Figs. 5 and 6, respectively.

The above profiles also provided the magnetic and electrostatic resolution calibrations. A collated set of profiles is illustrated in Fig. 7. As discussed earlier, the narrow bandpass of the magnet provides the energy resolution. The FWHM energy resolution obtained from profile measurements of the quantity $2 \Delta B/B$ are listed in Table II. Also shown are values calculated from $2 \Delta r/r$ [Eq. (4)]. Only rough agreement between calculated and measured values can be expected because the magnet exit apertures are not located close to the magnet exit face (see Fig. 2). The FWHM resolution for the deflection plate varied from $\sim 30\%$ for the lowest energy channel (CHANNEL 1) to $\sim 50\%$ for the highest energy channel (CHANNEL 5). This satisfies condition (5) and hence provides the required mass separation between hydrogen and deuterium atoms. For the highest energy channel, Fig. 7 exhibits the B field profile corresponding to H_2^0 at energy $E/2 \sim 10$ keV (dense hatched profile) simulating the deuterium case and illustrating satisfactory mass separation for the most stringent mass resolution case.

The following procedure was used to determine the efficiency of each analyzer channel. With a neutral hydrogen beam of known energy E but arbitrary intensity $N_0(E)$ entering the stripping cell, the counting rate of the zeroth channel with the cell evacuated to $\sim 10^{-5}$ Torr and in the absence of magnetic field is

$$\epsilon_0^T = \xi_0(E) N_0(E) \quad , \quad (6)$$

where ξ_0 is the overall efficiency of this channel, including collection efficiency and detector sensitivity. The gas cell was then set at a gauge pressure of 0.5, 1.0, 1.5 or 2.0 mTorr helium and the magnetic/electrostatic fields adjusted to maximize the counting rate of the n th channel. The resulting field values were checked against the calibration values of Figs. 5 and 6. Under these conditions, the n th channel counting rate is

$$\epsilon_n^+ = \xi_n(E) n_+(E) \quad , \quad (7)$$

where $n_+(E)$ is the ionized component of the incoming neutral intensity, $N_0(E)$. At the same time, the zero channel counting rate is reduced to

$$\epsilon^0 = \xi_0(E) n_0(E) , \quad (8)$$

where $n_0(E)$ is the residual neutral component. Introducing $\eta(E)$, the stripping efficiency of the gas cell including scattering losses, one can write

$$\begin{aligned} n_+(E) &= \eta(E) N_0(E) \\ n_0(E) &= [1 - \eta(E)] N_0(E) . \end{aligned} \quad (9)$$

Furthermore, putting $\xi = \gamma \cdot \beta$ where γ is the detector efficiency and β is the collection efficiency, the counting rates are normalized as follows:

$$\frac{\epsilon^+}{\epsilon^T} = \frac{\gamma_n \beta_n}{\gamma_0 \beta_0} \eta(E) , \quad (10)$$

and

$$\frac{\epsilon^0}{\epsilon^T} = 1 - \eta(E) . \quad (11)$$

The ratio

$$\frac{\epsilon^+}{\epsilon^0} = \frac{\eta(E)}{1 - \eta(E)} \cdot \frac{\gamma_n \beta_n}{\gamma_0 \beta_0} , \quad (12)$$

depends primarily on parameters associated with the stripping cell. The sum of the zero and n th channel signals is

$$\frac{\epsilon^+}{\epsilon^T} + \frac{\epsilon^0}{\epsilon^T} = 1 - \left(1 - \frac{\gamma_n \beta_n}{\gamma_0 \beta_0} \right) \eta(E) . \quad (13)$$

The calibration procedure described above was used to determine ϵ^+/ϵ^T , ϵ^0/ϵ^T , ϵ^+/ϵ^0 and $(\epsilon^+ + \epsilon^0)/\epsilon^T$ for each analyzer channel at numerous beam energies over the range of 0.75-40 keV and stripping cell pressures noted earlier. The results for 1 mTorr helium cell pressure are given by the data points in Fig. 8. The solid curves are polynomial fits to the data.

As a consistency check, it is of interest to compare the calibration results against theoretical predictions. To model the analyzer performance, we start with the equations governing the stripping cell. With a beam N_0 of atomic hydrogen entering the stripping cell, the conversion efficiency, η , is given by³

$$\begin{aligned} \eta &= \frac{n^+}{N_0} \\ &= \frac{\sigma_{01}}{\sigma_{01} + \sigma_{10}} \exp(-\ell C_1 p \sigma_s) \\ &\quad \left\{ 1 - \exp \left[-\ell C_1 G p (\sigma_{01} + \sigma_{10}) \right] \right\} \quad (14) \end{aligned}$$

where

$$C_1 = 3.243 \times 10^{13} \text{ cm}^{-3} \text{ mTorr}^{-1}$$

p = cell gauge pressure (mTorr)

ℓ = cell length (cm)

G = gauge factor

and σ_{01} , σ_{10} , σ_s are atomic cross sections (cm^2) for ionization, recombination and scattering. The gauge factor, G , corrects the gauge reading for sensitivity to helium. An empirical scattering cross section given by

$$\sigma_s = F_s \times 10^{-16} E^{-1/2}, \quad (15)$$

where E is the particle (ion or neutral) energy in keV and F_s is a fitting parameter was adopted as a reasonable approximation to information available in the literature^{3,4}. Values for σ_{01} , σ_{10} were obtained primarily from Atomic Data for Controlled Fusion Research, ORNL-5206 (1977) supplemented by other^{5,6} sources for stripping cross sections, σ_{01} , at energies below 5 keV. The cross sections are plotted in Fig. 9 with a factor $F_s \sim 3$ for the stripping cross section.

Before plotting the experimental points shown in Fig. 10, the data points were adjusted for detector efficiency in the following manner. The sensitivity curve available from the detector manufacturer⁷ and the literature⁸ was fitted by the expression:

$$\begin{aligned}\gamma_+ &= F_D \left[1 - \exp - \left(\frac{E + 3.0}{2} \right) \right] \\ \gamma_0 &= 1 - \exp - \left(\frac{E}{2} \right),\end{aligned}\quad (16)$$

where γ_+ applies to the n th channel charged particle detectors and γ_0 applies to the neutral particles detected by the zeroth channel. F_D is a relative sensitivity parameter the order of 0.9. The expression for γ_+ takes into account the 3 keV post acceleration due to the bias applied at the detector entrance. The data were then corrected by multiplying ϵ^+ by γ_0/γ_+ before plotting. The sum $(\epsilon^+ + \epsilon^0)/\epsilon_0^T$ and the ratio ϵ^+/ϵ^0 are determined from the corrected values.

A computer code was written to apply the correction of Eq. (16) to the data and generate curves corresponding to ϵ^+/ϵ_0^T , ϵ^0/ϵ_0^T , ϵ^+/ϵ^0 and $(\epsilon^+ + \epsilon^0)/\epsilon_0^T$ using Eq. (14) with the cell gas pressure, $P(\text{mTorr})$, the scattering cross section parameter, F_S , and the detector sensitivity factor, F_D , as fitting variables. The fitting variable values corresponding to the curves displayed in Fig. 10 are presented in Table III. As can be seen, an acceptable fitting to all channels over most of the data energy range was obtained by a fixed gauge pressure of 1.2 mTorr, a scattering factor, F_S , of 5.0 with the detector factor, F_D , varying from 0.57 to 1.75. The latter variation is somewhat artificial since it effectively includes not only the energy dependence of the detector sensitivity, but also the sensitivity factor, F_D , which reflects the "collection efficiency" for the various channels [i.e., the product $\gamma_n \beta_n$ in Eq. (10)]. The 20% correction to measured cell gauge pressure of 1 mTorr is reasonable in view of uncertainty in the gas correction factor required to convert the ion gauge reading for helium.

A discrepancy between the data and the model exists in the energy range around 5 keV, which eludes explanation at present. However, since the effect appears to some degree for all channels, its presence is regarded as real. For this reason, in reducing the charge exchange data for experimental measurements, rather than using the convenient model, the data were fit by polynomials of order up to six. The fitted polynomials (Fig. 8) were subsequently used for data reduction rather than the calibration points.

As a final remark on the analyzer calibration, the stripping cell pressure was varied to examine the sensitivity of calibration results. As an example, Fig. 11 shows the value of ϵ^+/ϵ_0^T as a function of cell pressure with H^0 energy as a parameter for CHANNEL 1.

IV. ANALYZER ABSOLUTE EFFICIENCY ESTIMATE

Except for the usual experimental uncertainties, the calibration procedure described in the previous section provided calibration of the analyzer for a beam of well-collimated neutrals relative to the counting efficiency of the CHANNEL O detector. In the pulse counting mode, the efficiency quoted by the manufacturer⁷ can be accepted with reasonable reliability ($\pm 10\%$) especially for particle energies exceeding ~ 3 keV. Even with the efficiency of the CHANNEL O detector known, however, absolute calibration of the analyzer system does not result due to geometrical factors associated with the neutral source. Specifically, calibration was performed using a collimated beam source whereas in actual application, the neutrals derive from a spatially distributed isotropic source within the vacuum vessel of the P.I.T. machine. Controlled simulation of these conditions is impractical. As an alternative, a Monte Carlo code was written to simulate numerically the essential features under applied conditions. A description of the code and its use to obtain an estimate of absolute calibration factors is given below.

In practice, the first analyzer aperture encountered by the charge exchange efflux is flooded with particles dispersed in energy and direction of flight. The code was initiated at this aperture using a random number generation to simulate particles over the entire aperture area characterized by an assigned energy spread, $\pm \Delta E$, around energy, E , and an assigned angular spread, $\pm \Delta \psi$, relative to the axis of the analyzer collimation apertures. The angle $\Delta \psi$ was chosen to be in excess of the limiting acceptance angle calculated from the known dimensions of the analyzer apertures. A large fraction of these particles was lost as the code advances their trajectories through the apertures of the stripping cell. Surviving particles were advanced through the analyzer magnetic field. Fringe field effects were examined by using various empirical field shaping expressions to simulate field distribution in the edge region of the pole pieces. Further particle loss on the apertures at the entrance of the electrostatic analyzer plates (see Fig. 2) occurs while most of the remaining ones, upon being advanced through the electrostatic plates and their exit aperture, reach the detector.

As a check on the validity of the code output, a comparison was made between the measured energy resolution of the five analyzer channels and that generated by the Monte Carlo calculation. For this purpose, the initial angular spread on the particles was set to zero in order to simulate the collimated neutral beam used for calibration. The results are shown in Table IV with good agreement evident. In addition, the table presents the code-generated energy resolution corresponding to imposition of angular spread on the source particles. As expected, the effect is only a slight variation in energy resolution.

To extract the absolute calibration factor from the code results, it is first necessary to determine the ratio of the first aperture of the stripping cell to the area in the plane of this aperture accessible to source particles from any source

point with the maximum assigned angular spread. The desired factor is then the product of this ratio with the ratio of the number of detected to launched particles. The resulting absolute calibration factor for each channel is presented in the extreme right column in Table IV.

It is of interest to compare the code results with that calculated from the equation

$$F = A \frac{d\Omega}{4\pi} \cdot \frac{\Delta E}{E} \quad (17)$$

where A is the area (taken at the plasma center) viewed by the analyzer, $d\Omega$ is the solid angle subtended by the detector aperture at the plasma center, ϵ is the measured analyzer efficiency (see Fig. 8) and $\Delta E/E$ is the energy resolution (see Table I). From geometrical considerations, $A \approx 38 \text{ cm}^2$ and $d\Omega \approx \pi a^2/L^2 \approx 1.4 \times 10^{-6}$ for $L = 240 \text{ cm}$ and $a = 0.16 \text{ cm}$. Taking CHANNEL 3 as an example, $\Delta E/E = 0.06$ which yields a calculated value $F = 2.5 \times 10^{-7} \text{ cm}^2$. Although this value agrees reasonably well with the code results, the latter are usually smaller than estimates based on Eq. (17) for all channels. This discrepancy is attributed to the more accurate treatment of the Monte Carlo code. Where an absolute calibration factor is required in the data analysis described in the following section, the code generated values have been adopted.

V. RESULTS

First measurements with the new analyzer (called MACE for mass analyzed charge exchange diagnostic) were obtained on PLT in early July 1978. At present, high power ($\sim 2 \text{ MW}$) neutral beam heating experiments are in progress. Representative charge exchange measurements are described here to demonstrate operation of the analyzer for these experiments.

The data acquisition process is performed as follows. The channel electron multiplier signal is conditioned by the pulse amplifier discriminators described earlier. The output of these units are fed via ~ 30 meter lengths of 75Ω coaxial cable directly into a Tracor Northern TN 1207 scalar interfaced to a PDP-11 scalar channels as illustrated in Fig. 12. A clock gates the five scalar channels to accumulate pulses for 1 ms time intervals. After each shot the accumulated data is sent to the PDP-10 computer for permanent archiving. The analysis program accesses the raw data, time averages over a 10 ms interval, performs quality analysis of the data, corrects for the zero level due to noise counts, applies the energy dependent calibration calculations, and finally performs a least squares fit to the resulting data on a semilog plot of the points as a function of energy. Three basic displays are then available at the charge exchange system control terminal.

The display shown in Fig. 13 is automatically provided after each discharge. Shown on the left are the raw data signals from the five channels with the energy setting of each channel indicated in the left corner of the plot. The other two plots show the semilog energy distribution of the analyzed data points corresponding to the raw data. The times during the discharge, displayed at the top, are selectable from the control console.

To obtain the ion temperature measurement for a given set of discharge conditions, it is necessary to accumulate from 5-10 such shots under reproducible conditions. The cumulated shots provide a semilog data display such as the one shown in Fig. 14. The energy limits for the line fit shown are selected by inspection of the built up display of data. Such line fits, the slope of which yields the ion temperature, can be provided for each 10 ms time slice throughout the discharge. The resulting display of ion temperature versus time during the discharge is shown in Fig. 15.

Certain features of the charge exchange system were not in use at the time the measurements shown were taken. Specifically, these were the diagnostic neutral beam's radial scanning capability. The data shown are viewing a horizontal diameter line-of-sight.

At this point it is instructive to examine the data analysis procedure in more detail, particularly the method used to correct the central ion temperature for attenuation and neutral density profile effects.

The neutral flux detected by the analyzer represents a line integral through the plasma. This presents a two-fold complication in the interpretation⁹ of the charge exchange measurements. First, the plasma neutral density profile is quite hollow. Consequently, the source density of charge exchange neutrals at the center of the plasma is small ($\lesssim 10^8 \text{ cm}^{-3}$). Second, considerable attenuation of the charge exchange flux occurs as the neutrals leave the plasma. The net result of these effects is to cause an underestimate of the central ion temperature. The PLT charge exchange system is equipped with a diagnostic neutral beam providing an active diagnostic which circumvents the first of these problems, but description of this is beyond the scope of the present report. Alternatively, the analysis of the passive measurements for PLT utilizes a procedure to correct for the ion temperature underestimate. In previous work¹⁰, comparison of the corrected passive measurements against those obtained using the active system showed excellent agreement.

The passive analysis is performed as follows. If the detector is set to view particles at the energy E_j , the charge exchange particles created in a plasma volume element at radius, r , are attenuated on the way out by $\exp(-\lambda_j)$ where

$$\lambda_j = \int_a^r n_e(r') \sigma_T(E_j) dr' \quad (18)$$

For the quantity $\sigma_T(E_j)$, an empirical fit to the total attenuation cross section which includes the effects of impurities was used (see Appendix I). The total flux detected by CHANNEL "N" of the analyzer is then:

$$J_N(E_j) = \int_{-a}^a K_N(E_j) n_0(r') n_+(r') f_+(E_j, r') \times E_j \left(\frac{\Delta E}{E} \right)_{jN} \langle \sigma_{cx}(E_j) E_j^{1/2} \rangle e^{-\lambda_j} dr' \quad (19)$$

where n_+ is the ion density, f_+ is the ion distribution, $(\Delta E/E)_{jN}$ is the energy resolution, σ_{cx} is the charge exchange cross section and n_0 is the neutral density. The factor $K_N(E_j)$ contains all of the calibration parameters for a given analyzer channel, except for the energy resolution noted separately. If attenuation and radial profile effects were negligible, one could write

$$n_0 n_+ f_+(E_j) = J_N(E_j) \left[E_j \left(\frac{\Delta E}{E} \right)_{jN} \langle \sigma_{cx}(E_j) E_j^{1/2} \rangle K_N(E_j) \right]^{-1} \quad (20)$$

Assuming a Maxwellian energy distribution

$$f_+ = \frac{2}{\sqrt{\pi}} \left(\frac{E_j^{1/2}}{(kT_j)^{3/2}} \right) \exp \left(-\frac{E_j}{kT_j} \right), \quad (21)$$

the ion temperature is obtained from the derivative of the natural logarithm of the right-hand-side of Eq. (20) divided by the term $(E_j/kT_j)^{1/2}$. In general, however, one cannot neglect the attenuation and radial profile effects.

The correction procedure starts with experimental profiles for electron density and temperature. The ion density profile is assumed to be identical to that of the electrons. Using an empirical profile of the form

$$T_i(r) = T_i(o) \left[1 - \left(\frac{r}{a} \right)^n \right]^m \quad (22)$$

for the ion temperature, an analytic model computer code¹¹ is used to calculate the neutral density profile. A separate code then uses this density profile to

determine the charge exchange production in a volume element at a specified radius. The attenuation of this flux from the specified radius to the plasma periphery is calculated. This procedure is carried out over the plasma radius to construct the charge exchange energy distribution, from which a scaling factor is obtained. The scaling is then applied to the RHS of Eq. (20) to produce a corrected central production rate and a corrected central ion temperature is evaluated. The results of this correction procedure are displayed as the curve shown in Fig. 13. Typically the uncorrected temperature under estimates the central ion temperature by 10-20%, though at low ion temperatures and high densities the correction can be significantly larger. Plasma density and temperature limits to the correction procedure are established by comparison of the corrected ion temperature against active measurements.

Having obtained the ion temperature, the Maxwellian factor, $f_+(E_j)$, can be separated from the LHS of Eq. (20) to yield the product $n_0 n_+$ as a function of time. By introducing an estimate for n_+ information can be obtained on the time evolution of the central value of n_0 , the neutral density. Inclusion of this feature in the charge exchange analysis is in progress and will be the subject of a future report.

ACKNOWLEDGEMENTS

The authors appreciate the support of H. P. Eubank and the excellent technical assistance of the Neutral Injection Group, particularly Dennis Carr, Ed Ryan, John Tobin, and Dick Yager. The assistance of R. Smith during the design phase and the contributions of R. J. Goldston throughout the project, particularly in use of his Monte Carlo code to estimate the analyzer absolute efficiency, is gratefully acknowledged.

This work was supported by the United States Department of Energy Contract No. EY-76-C-02-3073.

REFERENCES

- ¹Eubank, H. P., "Course on Diagnostics and Data Acquisition Systems," Sept. 1975, Varenna, Italy, 152.
- ²Morgan, T. J., Berkner, K. H., Graham, W. G., Pyle, R. V., and Stearns, J. W., Phys. Rev. A 14, 664 (1976).
- ³Adlam, J. H. and Aldcroft, D. A., "The Measurement of the Efficiency of a Helium Gas Cell for the Conversion of a Beam of Energetic Hydrogen Into a Proton Beam," CLM-R100 (1969).
- ⁴Amdur, I. and Mason, E. A., J. of Chem. Phys. 25, No. 4, 630 (1956).
- ⁵Tawara, H., "Cross Sections for Charge Transfer of Hydrogen Beams in Gases and Vapors in the Energy Range 10 eV-10 keV," Nagoya University, Japan, Institute of Plasma Physics Report IPPJ-AM-1 (1977).
- ⁶Tawara, H. and Russek, A., Rev. Mod. Phys. 45 No. 2 Part 1, 178 (1973).
- ⁷Galileo Electro-Optics Corp., Sturbridge, Mass. 01518, Data Sheet 4000A (1977).
- ⁸Egidi, A., Marconero, R., Pizzella, G., and Sperli, F., Rev. Sci. Inst. 40, No. 1, 88 (1969).
- ⁹Parsons, C. R. and Medley, S. S., "On the Interpretation of Charge-Exchange Ion Temperature Measurements in Tokamaks," Plasma Physics 16, 267 (1974).
- ¹⁰Brusati, M., Davis, S. L., Eubank, H. P., Moriette, P., Smith, R., and Goldston, R. J., Bull. Am. Phys. Soc. 22, 1076 (1977).
- ¹¹Goldston, R. J., "A Simple Neutral Density Profile Calculation for Tokamaks with $\lambda_{mfp} \ll a$," PPPL-1443 (1978).
- ¹²Freeman, R. L. and Jones, E. M., "Atomic Collision Processes in Plasma Physics Experiments," CLM-R 137 (1974).
- ¹³Goldston, R. J., private communication.

TABLE I

ELECTROSTATIC PLATE PARAMETERS

Channel	Outer Radius r_o (cm)	Inner Radius r_i (cm)	Exit Aperture Radius Δr (cm)
1	4.5	3.5	0.45
2	8.5	7.5	0.36
3	12.5	11.5	0.24
4	16.5	15.5	0.24
5	20.5	19.5	0.11

TABLE II

MAGNET ENERGY RESOLUTION ($r = 0.35$ cm)

Channel	r (cm)	Δr (cm)	$2 \Delta r/r$ (%) Calculated	$2 \Delta B/B$ (%) Measured
1	4.0	0.165	8.3	9.0
2	5.7	0.165	5.8	6.4
3	6.9	0.159	4.6	6.1
4	8.0	0.140	3.5	5.6
5	8.9	0.127	3.0	4.4

TABLE III

PARAMETERS FOR DATA FITTING MODEL

Channel	Cell Factor P	Scattering Factor F_S	Detector Factor F_D
1	1.2	5.0	.570
2	1.2	5.0	.650
3	1.2	5.0	.800
4	1.2	5.0	.850
5	1.2	5.0	1.75

TABLE IV

MONTE CARLO CODE CALCULATION OF ABSOLUTE CALIBRATION FACTORS

Channel	Measured* ($2 \Delta B/B$)	Monte Carlo* ($\Delta \psi = 0$)	Monte Carlo* ($\Delta \psi \neq 0$)	Absolute Factor
1	9.0 ± 0.4	9.7	9.2	7.0×10^{-8}
2	6.4 ± 0.4	6.9	6.7	4.9×10^{-8}
3	6.1 ± 0.4	6.5	6.0	4.0×10^{-8}
4	5.6 ± 0.4	5.6	5.7	3.3×10^{-8}
5	4.4 ± 0.4	4.4	4.1	2.0×10^{-8}

*FWHM energy resolution (%).

FIGURE CAPTIONS

1. Interior components of the charge exchange analyzer.
 - A. Stripping Cell
 - B. Gas Inlet
 - C. Ion Gauge Access
 - D. Turbo Pump Port
 - E. Magnet
 - F. Electrostatic Plates
 - G. Channel Electron Multiplier Detectors
 - H. Signal Interface
2. Analyzer calibration arrangement.
 - A. Ortec 538B Ion Source
 - B. Turbo Pumps
 - C. Source Mass Analyzing Magnet
 - D. Neutralizer Cell
 - E. Electrostatic Deflection Plates
 - F. Drift Tube
 - G. Gas Inlet
 - H. Ion Gauge Access for Cell Pressure
 - I. Electrostatic Plates
 - J. CEM Detectors for Five Energy Channels
 - K. CEM Zero Channel Detector for Calibration
 - L. Ion Gauge for Analyzer Pressure
3. Block diagram of signal processing circuitry used for calibration.
4. Illustration of the magnetic (A) and electrostatic (B) field calibration profiles.

5. Calibration curves for the analyzer magnet: plot of $B^2 = a_n mE$ for $m = 1$ (hydrogen) where a_n is the calibration factor of the n th channel.

$$a_1 = 1.70 \times 10^{-2}$$

$$a_2 = 8.28 \times 10^{-3}$$

$$a_3 = 5.58 \times 10^{-3}$$

$$a_4 = 4.15 \times 10^{-3}$$

$$a_5 = 3.26 \times 10^{-3}$$

6. Calibration curves for the analyzer electrostatic deflection plates: plot of $V = b_n E$ where b_n is the calibration factor for the n th channel.

$$b_1 = 2.06 \times 10^2$$

$$b_2 = 1.19 \times 10^2$$

$$b_3 = 6.55 \times 10^1$$

$$b_4 = 5.33 \times 10^1$$

$$b_5 = 3.71 \times 10^1$$

7. Illustration of the magnetic and electrostatic energy/mass resolution characteristics.
8. Polynomial fits to the calibration data for the five analyzer channels.
9. Ionization (σ_{01}), recombination (σ_{10}), and scattering (σ_s) atomic cross sections used in the analyzer model.
10. Comparison of experimental calibration data against analyzer model results.
11. Dependence of the calibration factor on stripping cell pressure for CHANNEL 1.
12. Schematic of the data acquisition system.
13. Charge exchange analyzer raw data display.
14. Typical semi-logarithmic charge exchange energy distribution showing least squares fit to cumulate data (Ti = 4 keV at 550 ms).
15. Display of charge exchange ion temperature measurements as a function of time during discharge. Time resolution is 10 msec.

APPENDIX I

The total attenuation cross section, σ_T , used in Eq. (18) to calculate the attenuation of the charge exchange efflux is obtained from an empirical fit to the cross sections for charge exchange¹² (σ_{cx}), and impact ionization on electrons (σ_{ie}), protons (σ_{ip}), and impurity ions (σ_{ii})¹³. The fitting equations used are presented here. All cross sections are in units of cm^2 .

The cross section for charge exchange of protons on hydrogen atoms is given by:

$$\sigma_{cx} = \frac{0.6937 \times 10^{-14} \left(1 - 0.155 \log \frac{E}{M} \right)^2}{1 + 0.1112 \times 10^{-14} \left(\frac{E}{M} \right)^{3.3}} \quad (\text{A-1})$$

where M is the proton or deuteron mass in AMU and E is the particle energy in electron volts (used throughout this section).

The proton impact ionization cross section is given by $\sigma_{ip} = 10^{x_{ip}}$

where

$$x_{ip} = -34.833 + 8.156 \left(\log \frac{E}{M} \right) - 0.8712 \left(\log \frac{E}{M} \right)^2 \quad (\text{A-2})$$

The electron impact ionization cross section is given by $\sigma_{ie} = 10^{x_{ie}}$ where

$$x_{ie} = \left[\frac{0.5051 + 0.0274 \left(\log \frac{T_e}{200} \right) - 0.1901 \left(\log \frac{T_e}{100} \right)^2}{1.38 \times 10^6 \text{ E/M}} \right] \times 10^{-8} \quad (\text{A-3})$$

and T_e is the electron temperature (eV).

The plasma ion depletion (ratio of proton to electron density) is

$$\frac{n^+}{n_e} = \frac{Z_1 - Z_{\text{eff}}}{Z_1 - 1} \quad (\text{A-4})$$

and the impurity ion density fraction is

$$\frac{n_1}{n_e} = \frac{Z_{\text{eff}} - 1}{Z_1 - 1} \cdot \frac{1}{Z_1} \quad (\text{A-5})$$

Here Z_{eff} is the effective plasma Z and Z_1 is the charge state of the designated dominant impurity species.

Combining the above relations gives the total cross section expression

$$\sigma_T = \left(\sigma_{\text{ip}} + \sigma_{\text{cx}} \right) \left(\frac{n^+}{n_e} + \frac{n_1}{n_e} \cdot Z_1^{5/4} \right) + \sigma_{\text{ie}} \quad (\text{A-6})$$

As can be seen, the cross sections of charge exchange and ionization on the impurity population is accounted for by scaling the proton cross sections as the impurity charge state to the power $5/4$.

Fig. 1. 786347

Fig. 2. 783992

Fig. 3. 783991

Fig. 4. 786181

Fig. 5. 783985

Fig. 6. 783988

Resolution of Magnet (Shaded)
and Deflection Plates (Profiles)

Fig. 7. 783889

Fig. 8. 783990

Fig. 9. 783979

Fig. 10. 783994

Fig. 11. 783984

Fig. 12. 783993

Fig. 13. 780113

Fig. 14. 783883

FIG. 15. 78G182

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B. Grik, Universite de Quebec, Canada
 G. Horikoshi, Nat. Lab. for High Energy Physics,
 Japan

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T. J. Boyd, Univ. College of North Wales
 Culham Lab., Abingdon, England (2)
 M. H. Brennan, Flinders Univ., Australia
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 S. Screenivasan, Univ. of Calgary, Canada
 J. Radet, Fontenay-aux-Roses, France
 Prof. Schatzman, Observatoire de Nice, France
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