THE MASS-RESOLVING CHARGE-EXCHANGE SYSTEM ON PDX

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PPPL--1940

DE83 002336

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ABSTRACT

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The PDX charge-exchange system is comprised of four, ten channel, mass-resolved, charge-exchange analyzers. Each analyzer is constructed with parallel electric and magnetic fields and is calibrated over an energy range of 0.5 to 40 keV. The mass rejection between hydrogen and deuterium has been measured as better than 1000 to 1. For ohmic heated discharges the system can provide single shot radial ion temperature profiles (4 point) with 1 msec time resolution. For neutral beam heated discharges complete radial and temporal profiles can be obtained in 2 to 4 shots. The system is also equipped with a vertically aimed diagnostic neutral beam to allow local ion-energy distribution measurements. This report describes the analyzer system and its calibration, and presents results from ohmic and neutral beam heated discharges.

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I. INTRODUCTION

In order to provide ion temperature and ion energy distribution measurements for PDX,¹ the design of the PLT charge-exchange system² was modified and expanded. The basic vacuum and magnet systems were retained, while the electrostatic system was redesigned to allow easier alignment, and the number of energy channels was increased from 5 to 10. The overall PDX system design was also expanded to include five mass sensitive analyzers, each with a different vertical line of sight (Fig. 1). The uppermost of these five analyzers is presently on loan to the MIT magnet laboratory, leaving a system of four analyzers, each viewing a different radial chord. The dashed boxes shown at the top of the analyzer stand indicate alternate analyzer positions. These positions extend the range of possible sightlines to one which passes through the outer divertor throat. Use of a diagnostic neutral beam in conjunction with the analyzers allows local charge-exchange measurements.³ The diagnostic beam was built from a Berkeley 15 keV - 5A field-free ion source⁴ and is mounted below PDX on a support which allows the beam to tilt through about 12 degrees. This tilting capability allows the beam to pass through either the center of a circular plasma ($R = 140$ cm) or through the center of an inside "D" diverted plasma ($R = 120$ cm). Access to radii outside of this range is limited by internal coil structures in PDX.

A description of the analyzer is presented in Section II. Section III describes the calibration procedure and calibration results. Section IV describes the passive ion temperature measurement technique, and Section V describes the use of the diagnostic beam.

II. ANALYZER SYSTEM DESCRIPTION

The geometry of the PDX analyzer system including the Diagnostic beam is shown in Fig. 1. Each of the analyzers is capable of moving slightly about a pivot point which is located near the vacuum vessel flange. In practice these motions are performed manually with some difficulty, so that in general it is planned to leave the analyzers fixed except in response to special needs. The radial tangents which are viewed by the analyzers are shown by the solid lines in Fig. 2. This figure indicates the minor radius of tangency versus major radius of the plasma for the present position of all four analyzers. The dashed lines in this plot indicate the minor radius of intersection of the four analyzer sightlines with the diagnostic beam. The dashed curves shown are for a beam tilted 11.5 degrees toward the center line of PDX. This angle aims the beam at the center of a plasma whose major radius is roughly 140 cm (close to center for most PDX plasmas).

The main components of the analyzer are shown in Fig. 3. The analyzer consists of a 15 cm long, differentially pumped stripping cell (A) which is normally operated with helium gas at 0.5 - 3.0 mtorr (gauge pressure). Helium is used because it has adequate stripping efficiency, and a small amount does not adversely affect the tokamak operation. The cell is apertured on both ends by 3.8 cm long cylinders, each of which contains a series of 5 smaller equally spaced apertures. The outermost apertures are 0.23 cm in diameter. The apertures reduce scattering along the cylinders and improve mass resolution. Two copper tubes provide separate access to the stripping cell for gas feed and pressure measurement. Each analyzer is equipped with a 450 l/sec turbo molecular pump (Leybold-Heraeus TMP-450) which maintains both the analyzer box and drift region in the range of 5×10^{-6} torr or less during analyzer operation.

The magnet pole pieces (B) are mounted on the top and bottom lids on the vacuum chamber with the electrical windings sealed outside the vacuum. The magnet gap is 1 cm and provides a nominal maximum field of 4 kg at 12 amps of current. The vacuum chamber walls are constructed of 2.5 cm thick soft iron which provides both a return path for the magnet flux and a magnetic shield against the tokamak fields.

A single negatively biased electrostatic deflection plate (C) provides an electric field parallel to the magnetic field.⁵ This plate is located 3.5 cm above a ground plane which is mounted parallel to but slightly below the bottom magnet face. A template for the electrostatic plates was made from a full-scale drawing of the trajectories of the ions through the magnet and into the electrostatic drift region. The projection of this drawing in the plane of the magnet pole faces shows straight trajectories in the electrostatic region. The length of the electrostatic plate, l_j , along the j th trajectory was fixed to allow the flight time of an energetic ion to be equal for all particles of the same mass which exit from the magnet ($l_j/l_1 = v_j/v_1$). The vertical displacement is then proportional to the acceleration in the electric field and dependent only on the mass of a particle and not its energy (assuming $q=1$). This allows all ten detectors (D) to view particles of the same mass while mounted at approximately the same height above the center line of the magnet faces (2.5 cm). With this geometry, the magnetic field selects the desired energies, and the electrostatic deflection separates these energies into rows of different mass (Fig. 4). By choosing the proper deflection voltage for a given magnet current, the desired mass species may be selected. Presently this system has been used to observe only hydrogen or deuterium, but there is speculation that under some circumstances helium neutrals may also be detectable.^{5,6}

The system uses channel electron multipliers (Galileo Electro-Optics Corp. Model 4830) covered with 90% transmission nickel mesh to improve detection uniformity, and it operates in a pulse counting mode. A ground plane (E) of 90% transparent mesh is located between the detectors and the electrostatic region to shield the -3 kV bias of the detectors.

There are several minor improvements which were added to the systems to improve stray light rejection and mass resolution capabilities.

- 1) Although the vacuum chamber and most of the components in the box were painted with a black conducting paint (Flat Black resistive paint, RS-170B, Microcircuit Co., New Buffalo, Mich.), it was found necessary to add two baffles (F) to improve stray light rejection.
- 2) The solid electrostatic plate was replaced in critical regions with a transparent nickel mesh (G) to reduce reflection of ions. The mesh does not alter the electric field, but it allows ions of the wrong mass to pass through without reflecting toward the detectors.
- 3) A baffle (H) was added at the high energy end of the magnet to stop energetic particles which might reflect from the ceramic that supports the electrostatic plate.
- 4) Exit slits (I) were added to the magnet to improve the mass rejection (the exit aperture is about 0.35 cm).

The signal handling and data acquisition system is depicted in Fig. 5. The detector output is sent into a combination pulse amplifier and

discriminator which provides a TTL level pulse (Galileo Electro-Optics Corp. Model 400 or Lecroy 7790 with an ECL/TTL convertor). This TTL pulse is sent through an isolation pulse transformer to a camac scaler unit with local memory (Lecroy models 8590 and 8801). The scalers are normally gated at a 1 kHz rate by a programmable clock (Lecroy model 8501), allowing 1 msec time resolution. The analyzer deflection voltage and current are set remotely by computer using a camac DAC (Kinetic Systems Model 3110 - 10 bit DAC). The deflection voltage, magnet currents, and pressures are all continuously monitored with ADCs (Lecroy Model 2232 - 32 channel ADC).

III. CALIBRATION

The arrangement used for calibration of the analyzers is shown in Fig. 6. An Ortec model 358B ion source provides a beam over the energy range 0.5 to 40 keV. The species mixture from the source was mass analyzed by a 90° deflection magnet. The selected ions were then partially neutralized by the residual gas in the drift tube ($\sim 2 \times 10^{-5}$ torr). A second magnet placed directly in front of the analyzer was used to remove the remaining ions from the beam. Both a channeltron and a Johnston electron multiplier were used at different times as the straight through detector (channel 0). Both detectors were operated in a pulse counting mode to monitor the transmitted neutral flux. In general, the larger area and more stable gain of the Johnston multiplier gave more reproducible results and the Johnston multiplier was subsequently used for the absolute efficiency measurements. The data acquisition was computerized by employing a Camac DAC to control the magnet and deflection settings while monitoring the various detector count rates with Camac scalers.

The mass and energy calibrations were performed first by varying the magnet current and deflection voltage to determine the peak settings for hydrogen at several energies. The detector heights were adjusted slightly to ensure that for a given magnetic field the deflection voltage may be set to adjust one mass species on the face of all detectors. After this adjustment in height, the deflection and magnet values were recalibrated. Typical results from one such scan are shown in Fig. 7. The magnet current is measured from the voltage drop across a 0.05 ohm precision resistor in series with the magnet coil. The magnet current is expressed throughout this paper in terms of the voltage drop measured across this resistance (i.e., 1.0 volt = 20.0 amps). The scan yields not only the centroid values for the magnet current and deflection voltage but also their widths. The energy resolution is determined from the full width at half maximum of the peak in the magnet scan and varies from ~ 4 to 12% (better for the higher energy channels). The width of the voltage scan is about 20% and has been designed to allow only enough resolution to ensure mass selection. This feature allows the voltages and currents of the system to be set easily without concern about loss of count rate. The relative energy and energy resolution of each channel is shown in Table 1. The centroid values for the magnet current and deflection voltage versus energy have been fit with the following equations:

$$mE_1/R_1^2 = A_1 + B_1 I + C_1 I^2 ,$$

$$E_1/R_1^2 = A_V + B_V V ,$$

where E_1 is the energy of the i th channel in keV, m is the particle mass in amu, and R_1 is the radius of curvature of the i th trajectory in the magnet.

The coefficients to these fits are also shown in Table 1. The dominant terms on the right hand sides of these equations are the $C_1 I^2$ and $B_v V$ terms. The other terms are used to "tune the fit" to allow for such things as magnet hysteresis and nonlinear resistor effects. To avoid anything except a small constant direction hysteresis in the magnet, the magnet current is always increased slowly from zero to reach a particular field.

Figures 8 and 9 show a pair of typical fits to all detectors at numerous energies and demonstrate the feasibility of this grouped approach to energy and mass calibration.

To enable accurate ion temperature measurements under a variety of plasma conditions, good mass rejection capabilities are critical. For example, under conditions of intense neutral injection, where $f_b \gg f_{\text{thermal}}$ in the range 7-15 T_1 , poor mass resolution may cause considerable uncertainty in the ion temperature measurement. For this reason the PDX analyzer system was carefully built and tested to ensure good mass rejection capabilities.

To determine the mass rejection of the analyzers, several experiments were performed. First, an H^0 beam of fixed energy was injected into the analyzer. The deflection voltage and magnet current of the analyzer was scanned in such a way as to move the beam horizontally across the face of the detectors. The results of this scan were compared to a second scan in which the deflection voltage was doubled with all other parameters remaining fixed. This second scan mimics the effect of trying to mass reject a full energy distribution of deuterium neutrals from detectors set to view hydrogen. The comparison for one of the detectors is shown in Fig. 10. By integrating the count rate in the lower spectra and comparing this value to the peak value in the upper spectra, a mass rejection capability of greater than 1000:1 is estimated. A similar comparison can be made with half the

deflection voltage to simulate rejection of hydrogen while the analyzer is set to view deuterium (Fig. 11). A similar result of $\geq 1000:1$ is obtained. This mass rejection was obtained only after the addition of the apertures and baffling to the analyzer as described in Section II. Before the addition of these baffles the rejection was of the order 500:1.

A test of the mass rejection capabilities under actual operating conditions is shown in Figs. 12 and 13. These figures were produced by setting the analyzer to look between hydrogen and deuterium and observing that the count rate is comparable to background levels. The figures demonstrate that during neutral beam injection, the analyzer can reject the beam species while being used to observe the thermal distribution of the background plasma.

Although only relative efficiencies are needed for the ion temperature and ion energy distribution measurements, to obtain the absolute neutral flux (and thus to be able to make an estimate of the local neutral density) the absolute efficiencies of the analyzers are needed. An important factor in determining the absolute efficiency is the measurement of the stripping efficiency. This was performed as follows. A Johnston electron multiplier was used in the straight through port because of its large area and reproducible results. With the stripping cell gas flow off the Johnston multiplier efficiency, ϵ_m , for operation in a pulse counting mode was determined. This was done by comparing the operation of the multiplier in the pulse mode to its operation in the current mode. At high energies ($E \approx 20$ keV), the detection efficiency is nearly one ($\epsilon_m \approx 1$)⁷, and the multiplier count rate, ϕ_m , is equal to the number of incident neutrals per sec, ϕ_0 . In the current mode, the incident flux, ϕ_0 , is related to the multiplier current, I_m , through the multiplier gain, G , and the secondary emission coefficient, γ , by

$$I_m = e G \gamma \phi_0.$$

Since $\phi_m = \epsilon_m \phi_0,$

then $\phi_m/I_m = \epsilon_m/(e G \gamma).$

At $E \sim 20$ keV, with $\epsilon_m \approx 1$, we deduce $G \gamma = I_m/\phi_m$. From the published values of the secondary emission coefficient^{8,9} and the measured multiplier count rate and current, the value of $G \gamma$ can be determined for all energies. The multiplier detection efficiency ϵ_m can be determined at all accessible energies from

$$\epsilon_m = e G \gamma \phi_m/I_m.$$

A plot of ϵ_m deduced in this manner is shown in Fig. 14. We assume throughout that the energy dependence of the secondary emission coefficient is the same for neutrals of deuterium and hydrogen at the same velocity.⁸ We also assumed that the secondary emission from the grid in the Johnston multiplier has the same energy dependence as for CuBe.⁷

Having determined the efficiency of the multiplier, the flux of neutrals which pass through an evacuated cell, ϕ_0 , can be measured by operating the multiplier in a pulse counting mode. The flux detected by one of the ten channels, ϕ_j , is related to the incident flux by the stripping efficiency, ϵ_s , the collection efficiency, ϵ_c , and the channeltron detection efficiency, ϵ_D , by

$$\phi_j = \epsilon_s \epsilon_c \epsilon_D \phi_0.$$

The collection efficiency is 0.81 (due to the transmission of the nickel meshes) for the calibration beam and is slightly reduced (~5%) when the source of neutrals is the plasma. This is because the plasma subtends a larger solid angle than the beam. The correction to ϵ_j has been calculated using a Monte Carlo particle following code¹⁰ and is applied when analyzing data from PDX. The channeltron detection efficiency has been taken from Ref. 11. The stripping efficiency can be measured as follows. The incident neutral flux ϕ_0 is measured with the stripping cell evacuated. The cell is then filled with He gas at the desired pressure and the resulting transmitted neutral flux ϕ_t is measured. This is repeated several times to obtain ϕ_t/ϕ_0 to about 5% accuracy. The largest uncertainty in ϕ/ϕ_0 is due to the beam intensity fluctuation. Then ϕ_j/ϕ_t is measured by scanning the magnetic and electric fields for the peak value of ϕ_j/ϕ_t . The resulting stripping efficiencies, $\epsilon_s = (\phi_j/\phi_t) (\phi_t/\phi_0)/\epsilon_c\epsilon_D$, are plotted versus energy for both hydrogen and deuterium in Fig. 15 for a gauge pressure of 0.8 mtorr. Figure 16 shows the variation in stripping efficiency with cell pressure.

To compare these results with theory,¹² we write

$$\epsilon_s = \frac{\sigma_{01}}{\sigma_{01} + \sigma_{10}} \exp(-\lambda_{\text{eff}} PC_1 \sigma_s).$$

$$\{1 - \exp[-\lambda_{\text{eff}} PC_1 (\sigma_{01} + \sigma_{10})]\},$$

where $C_1 = 3.243 \times 10^{13} \text{ cm}^{-3} \text{ mtorr}^{-1}$ (at $T = 25^\circ\text{C}$).

In this equation σ_{01} and σ_{10} are the usual cross sections for charge transfer,^{13,14} σ_s is the scattering cross section, and $\lambda_{\text{eff}} P$ is an effective length times the pressure of the stripping cell. To obtain the latter term, a 20 keV neutral beam was used at various cell pressures to measure the ratio ψ_t/ψ_0 as a function of pressure. This ratio is given by

$$\psi_t/\psi_0 = \frac{1}{\sigma_{10} + \sigma_{01}} \exp(-\lambda_{\text{eff}} P C_1 \sigma_s)$$

$$\{\sigma_{10} + \sigma_{01} \exp[-\lambda_{\text{eff}} P C_1 (\sigma_{01} + \sigma_{10})]\}$$

At 20 keV, σ_s is expected to be small^{12,15} and at low pressures the variation of ϵ_s with pressure yields the constant of proportionality between gauge pressure and $\lambda_{\text{eff}} P$. A reasonable fit was obtained with $\lambda_{\text{eff}} = 10.2$ cm while using the manufacturer's gauge factor of 7.3.¹⁶

Although the scattering of ions and neutrals may be slightly different and the geometry of the detectors is different, at low pressures the scattering cross sections has little effect on the stripping efficiency. If we assume that σ_s is the same in the equations for ϵ_s and ψ_t/ψ_0 , then we can write

$$\frac{\psi_j}{\psi_t} = \epsilon_c \epsilon_D \frac{\sigma_{01} \{1 - \exp[-\lambda_{\text{eff}} P C_1 (\sigma_{01} + \sigma_{10})]\}}{(\sigma_{10} + \sigma_{01} \exp[-\lambda_{\text{eff}} P C_1 (\sigma_{01} + \sigma_{10})])}$$

Note that ψ_j/ψ_t is independent of σ_s . In order to improve the fit to the data for ψ_j/ψ_t , it was necessary to reduce the values used for σ_{01} and σ_{10} at energies below 10 keV to 80% of the published values.^{13,14} The cross section was reduced in a manner which joined smoothly with the data above 10 keV. This reduction is comparable to the uncertainties in the published cross sections.

The remaining variable, σ_s , can be found from the measured stripping efficiencies and transmitted flux at a given energy by using the equation

$$\sigma_s = \frac{-\ln(\epsilon_s + \psi_t/\psi_o)}{l_{\text{eff}} PC_1}.$$

Data taken at a variety of energies and pressures exhibit a large variation in σ_s . The variation is particularly large above 10 keV where the effect of scattering is small and hence the statistical reliability is poor. In addition, for otherwise similar analyzers, different sized stripping cell apertures result in different values for σ_s . Figure 17 shows the variation with energy of σ_s for analyzers with 0.3 cm and 0.236 cm apertures. In either case we find $\sigma_s \propto E^{-0.65}$ which is in good agreement with Adlam and Aldcroft¹² and Amdur and Mason¹⁵ who found $\sigma_s \propto E^{-0.58}$. For the 0.236 cm apertures used in the final design we find $\sigma_s = (0.93 \pm .3) \times 10^{-16} E^{-0.65} \text{ cm}^2(\text{keV})^{0.65}$. The solid lines in Figs. 15 and 16 compare ϵ_s with the above theory using the previously specified values for l_{eff} , σ_s and ϵ_m . The 20% variation of the data about the curves appears to be due mainly to the fluctuation of σ_D and/or ϵ_m with vacuum history. Sets of data taken after long (more than three weeks) undisturbed vacuum conditions yield more reproducible results. Data taken one or two days apart and shortly after opening the box exhibited large (> 30%) variations in efficiencies. Despite these difficulties the relative efficiency as a function of energy agrees quite well with what is expected down to ~ 0.5 keV and represents a small (< 5%) error in the inferred temperatures. The error in the absolute efficiency due to the above problems is about 30%.

With the overall detector efficiency known, the count rate, C_1 , of the i^{th} detector of a charge-exchange analyzer can be related to the neutral source rate through the equation

$$C_i = \epsilon_i \int \Delta E_i \frac{\Delta \Omega}{4\pi} \langle \sigma v \rangle_{cx} n_o n_+ g_+ e^{-\lambda_i} A dl$$

where $\epsilon_i = \epsilon_s \epsilon_{ci} \epsilon_D$.

The term $\Delta \Omega$ is the solid angle of the analyzer system, A is the area viewed by the analyzer, $\langle \sigma v \rangle_{cx}$ is the rate coefficient for charge-exchange reactions,¹⁷ n_o is the neutral density, n_+ is the ion density, g_+ is the ion energy distribution function (see Appendix I), $e^{-\lambda_i}$ is the attenuation factor for neutrals leaving the plasma (see Appendix I), ΔE_i is the energy bandwidth of the i^{th} detector, and dl indicates an integration along the appropriate chord of the plasma.

We can define an energy independent geometric efficiency, F_i , of the i^{th} detector as

$$F_i = \epsilon_{ci} \frac{\Delta \Omega}{4\pi} A \cdot \frac{\Delta E_i}{E_i}.$$

Noting that F_i is independent of the integration variable ($A \Delta \Omega$ does not vary along l), we can write

$$C_i = F_i \epsilon_s \epsilon_D \int E_i \langle \sigma v \rangle_{cx} n_o n_+ g_+ e^{-\lambda_i} dl.$$

The values of F_i for each of the analyzers can be calculated from the calibration stand results for $\Delta E_i/E_i$ and ϵ_{ci} . The values of F_i shown in Table 2 have been corrected for the larger aperture and solid angle effects on

$\Delta E_i/E_i$ and ϵ_{ci} which are not observed on the test stand, but which are present on PDX. A Monte Carlo particle following code¹⁰ was used to study the particle trajectories in the analyzer with both a small circular entrance aperture, to model from the test stand geometry, and with a larger entrance aperture, to model from the PDX geometry. This correction is included in the values shown for $\Delta E/E$ in Table I. The values of $\Delta E_i/E_i$ as measured on the test stand were found to need a correction of only about 0.002 to compensate for the PDX geometry. The collection efficiencies, ϵ_{ci} , were found to drop from ~ 0.81 to ~ 0.76 for the PDX geometry. The values of F_i shown in Table 2 take into account these effects. The values of F_i were calculated by taking the Monte Carlo value for $F_i/(\Delta E_i/E_i)$ and multiplying this by the measured $\Delta E_i/E_i$ from Table I. Although $\Delta E/E$ depends on the actual shape of the response function, for simplicity we have used the full width at half maximum. The value of $A \Delta\Omega/4\pi$ is the same for all analyzers except for analyzer #1 which has a factor of 2 larger aperture area. The detector to detector variation of $F_i/(\Delta E_i/E_i)$ is comparable to the statistical error of 5% in the Monte Carlo results.

The knowledge of F_i completes our calibration of the analyzer system and enables a connection to be made between the basic plasma parameters of the tokamak with the count rate. Although an absolute calibration of the analyzers is not necessary for measurements of the ion temperature profile, the calibration may be used to make estimates of the local neutral density.

IV. Passive Charge-Exchange Measurements

Clearly, the primary purpose of the charge-exchange analyzer system is to measure ion temperature profiles under various PDX plasma conditions. The ion temperature measurements are made in two ways, which are referred to as the active and passive techniques.

The passive technique for measuring the ion temperature involves assuming that at high enough energies the neutral flux detected by the analyzer comes primarily from a small region at the hottest point along the sightline. This assumption works reasonably well for PDX when the line average electron density remains less than about $4 \times 10^{13} \text{ cm}^{-3}$. Above this density the charge-exchange signal from the center of the plasma becomes weaker because of increasing attenuation of both ingoing and outgoing neutrals.

Using the assumptions described in Appendix I, we can define

$$f_i \equiv \frac{C_i}{F_i \epsilon_s \epsilon_D E_i^{3/2} \frac{2}{\sqrt{\pi}} \langle \sigma v \rangle_{cx}} (\text{cm}^{-5} \text{ eV}^{-3/2}) = \frac{G}{T^{3/2}} \exp\left(-\frac{E_i}{T}\right)$$

where $G = n_0 n_+ e^{-\lambda_1} \Delta l (\text{cm}^{-5})$ and where C_i is the detector count rate.

By fitting $\ln f_i = \ln G/T^{3/2} - E_i/T$ with a straight line, the slope can be used to extract the ion temperature, T , and the intercept can be used to extract the "amplitude", G . A typical " $\ln f$ vs: E " plot is shown in the left half of Fig. 18. The triangular data points marked passive were fit to obtain the ion temperature during D^0 neutral beam injection into a H^+ plasma. The temporal profile during injection is shown in the left half of the figure. To measure ion temperatures reliably during neutral beam injection, we typically need three or more reproducible plasma shots including a background shot to measure X-ray, light, and neutron noise levels. For ohmically heated discharges, single shot ion temperature profiles can generally be obtained. The background levels during ohmic heating are generally negligible.

The amplitude, G , which is derived from the fitting of $\ln f$ versus E also provides useful information. The ratio of attenuation for hydrogen and deuterium for reproducible discharges provides a rough estimate of the hydrogen to deuterium ratio in the plasma. It has been observed, for example, during gas changeover (D to H or H to D), it takes roughly five shots for the changeover to occur. After 20-50 shots the plasma still contains a large fraction (10-20%) of the previous hydrogen isotope. The fraction of the unused hydrogenic isotope present seldom goes below 5%, even after a large number of pulses.

The amplitude can also be used directly to observe changes in the neutral density, but this is complicated by penetration effects. It is perhaps better for the purposes of neutral density estimates to calculate the expected count rate for a given analyzer from the measured plasma parameters (see Section VI).

V. ACTIVE CHARGE-EXCHANGE MEASUREMENTS

Active charge-exchange measurements involve the use of the diagnostic neutral beam to enhance the neutral density locally along the sightline of the analyzer. The assumptions of the passive technique are not needed, and a less controversial measurement of the local ion temperature can be made. High energy tails on the ion energy distribution, which have been observed on the exterior of the plasma and cause considerable problems with the passive technique, can be handled easily with the active technique. Further, in higher density cases where the central charge-exchange signal is weaker, the ion temperature can be measured more reliably with the active system. In high temperature cases, it is necessary to take into account the Shafranov shift¹⁸ in order to know where the localized temperature measurements are being made

with respect to the hottest part of the plasma. In some PDX cases, this shift can be larger than 10 cm. It is this effect that generally accounts for the values of ion temperature measured using a diagnostic beam being lower than those made with the passive technique.

In general, the diagnostic beam is pulsed once during a discharge for 10-15 msec at a particular time of interest. The raw charge-exchange signal typically responds with an increased count rate during the beam on time (Fig. 19). The enhanced count rate is determined by subtracting the background count rate, which is determined from the count rate before and/or after the diagnostic beam is fired. The enhanced count rate can then be related to the plasma parameters and beam neutral density, n_o^b , through

$$C_i^b = F_i \epsilon_s \epsilon_D E_i v_o(E_i) n_i g_+(E_i) e^{-\lambda_i} w/\sin\alpha,$$

where the terms are described in more detail in Appendix II. The term $v_o(E_i)$ is the rate with which plasma ions of energy E_i charge exchange with beam induced neutrals. In reality $v_o(E_i)$ includes contributions both from direct interactions with beam neutrals and from interactions with secondary halo neutrals.¹⁹ The secondary halo neutrals are produced when plasma ions charge exchange with primary beam particles. The halo neutrals can roughly double the number of beam induced neutrals present along an analyzer sightline, and can broaden the region of enhanced neutrals by a few centimeters. The effect of the halo neutrals on the energy dependence of $v_o(E_j)$ is very weak and affects the temperature measurement only slightly when compared to other effects (such as shot to shot reproducibility). For this reason, the exact magnitude of the halo neutrals is not needed for useful temperature measurements. In general the magnitude of the halo neutrals is taken to be

equal to the number of primary beam neutrals, and the average energy of the halos is assumed equal to the average ion energy in the intersection volume. This allows a quick but fairly accurate treatment for $v_0(E_1)$.

The temperature calculation is performed by dividing the count rate by the calculable parameters on the right side of the above equation to produce

$$f_1^b = C_1^b / \{ F_1 \epsilon_S \epsilon_D E_1^{3/2} v_0(E_1) e^{-\lambda_1} \frac{2}{\sqrt{\pi}} w / \sin \alpha \}.$$

Again assuming a Maxwellian distribution, we obtain

$$f_1^b = n_+ e^{-E/T} / T^{3/2},$$

where

$$n_+ = f_1^b(0) T^{3/2}.$$

To obtain an ion temperature, we fit the $\ln f_1^b$ versus E_1 data with the linear function

$$\ln f_1^b = \ln n_+ / T^{3/2} - E/T.$$

Figure 18 shows a typical fit to a near central energy distribution function as measured with the diagnostic beam.

VI. FURTHER RESULTS

The primary purpose of this paper has been to describe the construction and calibration of the PDX analyzer system. For the sake of completeness, the following section is presented to describe some of the more important results from the analyzer system. It is beyond the scope of this paper to go into detail concerning the interpretation of these results.

Both active and passive charge-exchange measurements have been relied on heavily during PDX experiments to provide reliable ion temperature measurements. Figure 20 shows a comparison of active and passive ion temperature measurements with a doppler broadening measurement of a Ti XXI k_{α} line.²⁰ The agreement is remarkable and gives us confidence in both types of temperature measurement.

The main reason for providing a diagnostic beam with a charge-exchange diagnostic is to allow centrally localized ion temperature measurements. However, another valuable use of such a system can be seen in Fig. 18. Under some conditions of neutral beam injection into PDX, the passive charge-exchange system detects a charge-exchange efflux of the target species which shows a strongly curved energy spectrum. This strong curvature can make passive ion temperature measurements unreliable without further information. The diagnostic beam has been used under these circumstances to provide a local measurement of the ion energy distribution. After this technique has been applied to several discharges, the passive technique can be interpreted to produce reliable ion temperatures. The local measurement, as can be seen in Fig. 21, demonstrates that a tail in the distribution function has been created in the outer regions of the plasma during neutral beam heating. The origin of the tail is still not understood, but it appears to have an energy dependence which is inconsistent with knock-ons.²¹

The ion temperature has been measured under a variety of neutral beam injection cases on PDX²², and results of these measurements have been tabulated. A scaling of these results can be seen in Fig. 22. The quantity P_{abs} is the injected power minus the power loss due to shine through. The scaling, although having considerable scatter, indicates improved heating quality with higher current levels. Diverted and circular discharges give similar results at the same plasma currents. The dashed lines in Fig. 22 represent constant values for the ion heating efficiency, $\eta_i \equiv \bar{n}_e \Delta T / P_{abs}$, for comparison to results from other tokamaks. The PLT ion heating efficiency, for example, is generally in the range $3.0 < \eta_i < 4.5$.²³ Figure 23 shows radial profile measurements made with the active beam during both ohmic and neutral beam heated discharges. As the figure indicates, the radial profiles appear to be roughly parabolic raised to second or third power.

Some estimates have also been made of the neutral density observed in front of the analyzer, but these estimates give quite low numbers for the neutral density ($10^6 - 10^7 \text{ cm}^{-3}$). It is quite possible, given the present level of understanding regarding the spectroscopic measurements of τ_p , that these neutral densities are realistic.²⁴ However, values are too low to explain the values needed in energy balance codes to maintain the particle source rates, even considering possible toroidal asymmetries in the neutral influx. Work on this subject is continuing.

The analyzer has also been used occasionally to view the slowing down spectra during high power neutral injection,²⁵ but in general this task has been left to the horizontally scanning fast ion diagnostic which has an energy resolution and fast detection electronics more suited to the problem.²⁶

V. SUMMARY

The PDX charge-exchange system has been constructed and fully calibrated to allow passive and active charge-exchange measurements. The analyzers were calibrated over an energy range of 0.5 to 40 keV for both hydrogen and deuterium. The stripping and scattering efficiencies were measured during the calibration and were found to be in fairly good agreement with the published cross sections. The analyzers have been used extensively on PDX to provide ion temperature measurements during ohmic and neutral beam heating experiments. The results of these measurements have indicated a strong dependence of ion heating with plasma current and a roughly linear dependence with $P_{\text{abs}}/\bar{n}_e$. The diagnostic beam has been used to measure local ion energy distributions, which show a clear indication of an energetic tail in the outer plasma regions during neutral beam heating experiments.

ACKNOWLEDGMENTS

We would like to express our appreciation to the following people: Ed Ryan, John Tobin, Frank Polem, Jeff Abramson, Dick Yager, Bob Shoemaker, Jim Bailey, and George Constantine for their fine technical support; Jack O'Sullivan for the engineering design and construction; D. Miller, V. Braco, and the DAS group for their programming efforts; S. Schweitzer, M. Gensamer, and J. Mayercak for their electronic support; H. Eubank and D. Meade for guidance and continuing budgetary support; R. Goldston, R. Kaita, S.S. Medley, L. Roquemore, and J. Strachan for many useful discussions; and the PDX group whose hard work has made the measurements on PDX possible.

This work was supported by the United States Department of Energy, Contract No. DE-AC02-76-CHO-3073.

Appendix I - Passive Charge-Exchange Data Reduction

The count rate, C_i , is related to the flux at the analyzer, Γ_i , through

$$C_i = F_i E_i \epsilon_S \epsilon_D \Gamma_i = \epsilon_i A \Delta\Omega/4\pi \Delta E_i \Gamma_i ,$$

where the units of Γ_i are $\text{cm}^{-2} \text{sec}^{-1} \text{eV}^{-1}$. The flux can be related to the plasma parameters by

$$\Gamma_i = \int e^{-\lambda_i} \langle \sigma v \rangle_{cx} n_o n_+ g_+ dl ,$$

where $e^{-\lambda_i}$ is exit attenuation (Appendix II), and g_+ is the ion energy distribution (see below).

To produce ion temperatures, several assumptions need to be made.

- (1) The neutral temperature is assumed to be small compared to the energies of the neutrals being used for temperature measurements so that

$$\langle \sigma v \rangle_{cx} = \sigma_{cx}^H(E_H) \cdot v_i ,$$

where $v_i = \left(\frac{2E_i}{m_i}\right)^{1/2}$ $E_H = \frac{1}{2} m_H v_i^2$, where m_H is the proton mass, and σ_{cx}^H is the hydrogen charge-exchange cross section.¹⁷

- (2) The ion energy distribution is Maxwellian:

$$(g_+ = \frac{2}{\sqrt{\pi}} \frac{E^{1/2}}{T^{3/2}} e^{-E/T}) .$$

- (3) The neutrals used for temperature measurement come from a localized region around the hottest spot along the analyzer sightline

$$(\Gamma_i = e^{-\lambda_i} \langle \sigma v \rangle_{cx} n_o n_+ g_+ \Delta l)$$

and that the attenuation, $e^{-\lambda_i}$, and the source length, Δl , do not depend on the energy, E_i .

We now define the energy distribution function

$$f_i \equiv \Gamma_i / (\langle \sigma v \rangle_{cx} \frac{2}{\sqrt{\pi}} E^{1/2}) (\text{cm}^{-5} \text{ev}^{-3/2}).$$

Using the assumptions made above,

$$f_i = e^{-\lambda_i} n_o n_+ e^{-E/T} T^{-3/2} \Delta l (\text{cm}^{-5} \text{ev}^{-3/2}).$$

To produce an ion temperature, T , logarithmic derivative of f_i is taken over the appropriate energy range,

$$T = - \left(\frac{1}{f_i} \frac{\partial f_i}{\partial E} \right)^{-1}.$$

The temperature is, of course, produced simply from a linear fit to a $\ln f$ versus energy plot. In practice the energy limits of the fit are critical in determining a reasonable "passive" temperature. The method used is to restrict the energies in the fit to the range of roughly 2 to 10 T_i . In the computer code which does the actual calculation, it is necessary to iterate the fit several times to get the appropriate energy limits. The temperature from each successive fit is used to yield better energy fit limits. The "intercept" of this fit yields the amplitude, G , which we define as

$$G \equiv \int \frac{2}{\sqrt{\pi}} E^{1/2} f(E) dE \text{ (cm}^{-5}\text{)}.$$

Under the assumptions made above this becomes

$$G \equiv f(0) T^{3/2} = e^{-\lambda_i} n_o n_+ \Delta l \text{ (cm}^{-5}\text{)}.$$

On each $\ln f$ vs: E plot, the amplitude, G , is output in these units for the displayed temperature fit. The quantity G is useful for comparison with any codes which attempt to predict the charge-exchange signal that we observe. It will allow a direct comparison with the charge-exchange measurements and the neutral densities which are needed to produce these fluxes. Also the ratio of amplitudes, measured by observing hydrogen and deuterium, yields the ratio of the concentration of the two species (if one takes into account the difference in attenuation).

Appendix II - Active Charge-Exchange Data Reduction

The enhanced count rate from the beam plasma charge-exchange reactions can be written

$$C_i^b = F_i \epsilon_S \epsilon_D E_i \Gamma_i,$$

$$\text{with } \Gamma_i^b = v_o(E_i) n_+ g_+(E_i) e^{-\Lambda_i} w/\sin\alpha,$$

where w is the width of the beam along the analyzer sightline, and α is the angle between the beam and detector sightlines.

$$v_o(E_i) = \sum_{j=1}^3 \sigma_{cx}^H(E_{rel}^{i,j}) v_{rel}^{i,j} n_o^j + \sigma_{cx}^H(E_{rel}^{i,halo}) v_{rel}^{i,halo} n_o^{halo},$$

where j is the index of the beam energy component,

$$v_{rel}^{i,j^2} = \frac{2E_j}{m_j} + \frac{2E_i}{m_i} + 4 \left(\frac{E_i E_j}{m_i m_j} \right)^{1/2} \cos \alpha$$

$$E_{rel}^{i,j} = \frac{1}{2} m_H v_{rel}^{i,j^2} \quad (m_H = \text{proton mass}),$$

σ_{cx}^H is the hydrogen charge-exchange cross section,¹⁷

$$v_{\text{rel}}^{i,\text{halo}^2} = 2 \left(\frac{E_i}{m_i} + \frac{8}{\pi} \frac{T}{m_p} \right) \quad (m_p = \text{average plasma mass}),$$

$$E_{\text{rel}}^{i,\text{halo}} = \frac{1}{2} m_H v_{\text{rel}}^{i,\text{halo}^2},$$

T is the halo temperature at the point of intersection of the beam and analyzer sightline, and n_o^{halo} is the halo density. The halo neutral density is generally taken to be equal to the beam neutral density ($n_o^{\text{halo}} = \sum_j^3 n_o^j$), but can be calculated in other codes²⁷ and input if desired. In general, the density of halo neutrals assumed makes a negligible difference on the final calculation of the ion temperature. The contribution of the j^{th} energy component of the beam to the local neutral density is written

$$n_{o,j}^s = \frac{h_j j^{1/2} m^{1/2} P_b \exp(-\delta_j)}{\sqrt{2} A (eV_b)^{3/2} \sum_i (h_i/i)},$$

where $h_j = 0.38, 0.25, 0.38$ for H and $0.56, 0.22, 0.22$ for D are the neutral current fractions of the various beam energy components.⁴ The quantity, P_b , is the diagnostic beam power at the entrance to the vacuum vessel, A is the beam area, and V_b is the primary beam voltage.

The plasma entrance and exit attenuations, $\exp(-\delta_j)$ and $\exp(-\lambda_1)$, respectively, have similar forms and differ mainly because of differences in energy and trajectory. For both cases we used $\beta_k = (\delta_j \text{ or } \lambda_1)$, where

$$\beta_k = \int (n_i \sigma_{\text{cx}}^H v_{\text{rel}}^{i,k} + n_e \langle \sigma v \rangle_{ei} + n_i \sigma_{ii} v_{\text{rel}}^{i,k} + n_j \sigma_{\text{loss}} v_{\text{rel}}^{j,k}) \frac{dl}{v_k},$$

where k denotes the particles being attenuated, i denotes the plasma ions, j the impurity ions,

$$\sigma_{\text{loss}} = 4.6q \times 10^{-16} \cdot \{ (32Z/E_{\text{rel}}^{i,k}) [1 - \exp(-E_{\text{rel}}^{j,k}/32Z)] \},^{28}$$

$$(v_{\text{rel}}^{j,k})^2 = 2 \left\{ \frac{E_k}{m_k} + \frac{8}{\pi} \frac{T_j}{m_j} \right\},$$

$$(v_{\text{rel}}^{i,k})^2 = 2 \left\{ \frac{E_k}{m_k} + \frac{8}{\pi} \frac{T_i}{m_i} \right\},$$

$\sigma_{\text{cx}}^{\text{H}}$ is the hydrogen charge exchange cross section evaluated at

$$E_{\text{rel}}^{i,k} \approx \frac{1}{2} m_{\text{H}} v_{\text{rel}}^{i,k^2},$$

σ_{ii} is the hydrogen ion impact ionization cross section¹⁷ also evaluated at $E_{\text{rel}}^{i,k}$, $\langle \sigma v \rangle_{ei}$ is the electron ion impact ionization rate,¹⁷ n_i is the hydrogenic ion density, n_e is the electron density, v_k is the velocity of the attenuating particle, Z is the impurity charge, and $\int d\lambda$ is the integral over the appropriate path.

For the case of the diagnostic beam we define a different value of f_i than is used for passive analysis.

$$f_i^b \equiv \Gamma_i^b / \left(\frac{2}{\sqrt{\pi}} E_i^{1/2} v_o(E_i) e^{-\lambda_i} w/\sin\alpha \right).$$

For a Maxwellian distribution

$$f_1^b = G^b e^{-E/T} / T^{3/2} ,$$

where

$$G^b \equiv \frac{2}{\sqrt{\pi}} \int f^b(E) E^{1/2} dE . ,$$

$$\text{or } G^b = f^b(0) T^{3/2} ,$$

If all of the parameters and assumptions we make to calculate f_1^b are correct, then $G^b = n_+$.

Again the ion temperature is obtained from

$$T = - \left(\frac{1}{f^b} \frac{\partial f^b}{\partial E} \right)^{-1} .$$

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Table 1.

Detector	Analyzer #1		Analyzer #2		Analyzer #3		Analyzer #4	
	E/E ₁	ΔE/E	E/E ₁	ΔE/E	E/E ₁	ΔE/E	E/E ₁	ΔE/E
1	1.00	0.122	1.00	0.110	1.00	0.092	1.00	0.106
2	1.54	0.086	1.45	0.076	1.45	0.063	1.38	0.087
3	2.05	0.077	2.14	0.094	2.16	0.074	1.87	0.080
4	3.02	0.084	2.96	0.079	2.98	0.068	2.56	0.091
5	4.17	0.071	3.92	0.075	3.86	0.062	3.41	0.075
6	5.26	0.073	5.10	0.080	4.86	0.066	4.19	0.070
7	6.26	0.066	6.41	0.066	5.97	0.059	5.46	0.066
8	7.77	0.073	8.00	0.057	7.27	0.057	6.76	0.062
9	9.36	0.050	9.60	0.061	8.94	0.056	8.17	0.053
10	10.87	0.042	11.20	0.056	10.93	0.051	9.52	0.041

A _I	0.4304 x 10 ⁻²	0.7844 x 10 ⁻²	0.5212 x 10 ⁻²	0.3876 x 10 ⁻²
B _I	-0.3515 x 10 ⁻¹	-0.7527 x 10 ⁻¹	-0.9855 x 10 ⁻¹	-0.2963 x 10 ⁻¹
C _I	0.2588 x 10 ¹	0.2190 x 10 ¹	0.2556 x 10 ¹	0.2444 x 10 ¹
A _V	-0.1787 x 10 ⁻²	-0.1386 x 10 ⁻²	-0.1695 x 10 ⁻²	-0.1550 x 10 ⁻²
B _V	0.7353 x 10 ⁻⁴	0.5893 x 10 ⁻⁴	0.6319 x 10 ⁻⁴	0.6792 x 10 ⁻⁴
R ₁ (cm)	4.00	4.24	4.24	4.24

$$R_1^2 \equiv R_1^2 (E_1/E_1)$$

$$\frac{E_1^M}{R_1^2} = A_I + B_I I + C_I I^2$$

$$\frac{E_1}{R_1^2} = A_V + B_V V$$

Table 2

DETECTOR	F (10 ⁻⁸ cm ²)			
	ANALYZER #1 ^{a)}	ANALYZER #2 ^{b)}	ANALYZER #3 ^{b)}	ANALYZER #4 ^{b)}
1	5.47	2.76	2.31	2.66
2	3.85	1.91	1.58	2.18
3	3.45	2.36	1.86	2.01
4	3.76	1.98	1.71	2.28
5	3.18	1.88	1.56	1.88
6	3.27	2.01	1.66	1.76
7	2.96	1.66	1.48	1.66
8	3.27	1.43	1.43	1.56
9	2.24	1.53	1.41	1.33
10	1.88	1.41	1.28	1.03

- a) If we assume $\epsilon_i = 0.76$ and a 3.8 cm diameter circular aperture 225 cm from the stripping cell exit, we can estimate by hand

$$\frac{\Delta\Omega}{4\pi} \epsilon_{ci} A = 5.96 \times 10^{-7} \text{ cm}^2,$$

which compares well with the value found from the Monte Carlo code of $4.48 \times 10^{-7} \text{ cm}^2$.

- b) If we assume $\epsilon_c = 0.76$ and a 2.54 cm diameter circular aperture 225 cm from stripping cell exit, we can estimate by hand

$$\frac{\Delta\Omega}{4\pi} \epsilon_{ci} A = 2.65 \times 10^{-7} \text{ cm}^2,$$

which compares well with the value found from the Monte Carlo code of $2.5 \times 10^{-7} \text{ cm}^2$.

FIGURE CAPTIONS

- Fig. 1 Schematic of the charge-exchange system and the PDX cross section.
- Fig. 2 Plot of the minor radius of tangency versus the PDX plasma major radius assuming circular flux surfaces. Solid lines indicate passive measurements, and dashed lines indicate active measurements with a beam tilt of 11.5° .
- Fig. 3 Photograph of the interior of one of the charge-exchange analyzers.
- Fig. 4 Plot showing the relative spatial positions of particles in the detector plane.
- Fig. 5 Schematic of the charge-exchange electronics and the interface to the DAS computer system.
- Fig. 6 Schematic of the calibration stand setup.
- Fig. 7 Plot of the ratio of the count rate in one of the detectors to the straight through count rate versus magnet current and plate voltage. The scan was performed to determine the energy and mass calibration of the detector.
- Fig. 8 A cumulative plot of deflection voltage calibration data for analyzer #1. The data shows the centroid of the deflection voltage for various energies of particles. The width of the data indicates a $\pm 5\%$ variation in the energy. This width is plotted to demonstrate how closely the solid line fits the data. Typical full widths to half maximum are 20-40%, and it is deemed necessary to set the deflection voltage to within roughly $\pm 5\%$ to prevent significant loss of count rate.
- Fig. 9 A cumulative plot of magnet current calibration data for analyzer #1. The data shows the centroid of the magnet current for various values of EM/R_1^2 (see text). The width of the data points is 2.5% and is plotted to indicate the accuracy of the fit (solid line).
- Fig. 10 Comparison of the H^+ count rates for two horizontal scans along the detector plane with the beam positioned at two different heights. The comparison demonstrates the ability of the analyzer to reject deuterium while observing hydrogen.
- Fig. 11 Comparison of the H count rates for two horizontal scans along the detector plane with the beam positioned at two different heights. The comparison demonstrates the hydrogen rejection capability.
- Fig. 12 Raw data from PDX of count rates versus time during $D^0 \rightarrow H^+$ injection for five channels. The deflection voltage is set to look at deuterium, hydrogen and between the masses.
- Fig. 13 Raw data versus time for two channels during $H^0 \rightarrow D^+$ injection. The deflection voltage is set to look at hydrogen, deuterium, and between the masses.

- Fig. 14 Johnston multiplier efficiency versus energy per amu.
- Fig. 15 Measured hydrogen and deuterium stripping efficiencies versus energy per amu. The error bars reflect both statistical uncertainties and the variation of efficiencies with vacuum history.
- Fig. 16 Measured hydrogen stripping efficiencies for three different stripping cell gauge pressures. The curves are the calculations discussed in the text. The error bars reflect both statistical uncertainties and the variation of efficiencies with vacuum history.
- Fig. 17 Scattering cross section versus energy. The open circles are hydrogen with stripping cell apertures of 0.3 cm, while the solid circles and x's are hydrogen and deuterium, respectively, with stripping cell apertures of 0.24 cm diameter.
- Fig. 18 Sample active and passive ion temperature measurements showing $\ln f$ versus energy and temporal ion temperature behavior. The data is taken for a $D^0 > H^+$ injection case with $P_b = 5.1$ MW absorbed, $I_p = 500$ kA and $n_e \approx 3.9 \times 10^{13}$ (during injection).
- Fig. 19 Sample raw charge-exchange data taken during a diagnostic beam pulse showing the enhancement in signal. The data was taken during 3.0 MW $D^0 > H^+$ neutral beam injection with a line average density of $2.3 \times 10^{13} \text{ cm}^{-3}$ and a plasma current of 490 kA.
- Fig. 20 Temporal behavior of a 5 MW $D^0 > H^+$ neutral injection heating case shows a comparison between active, passive, and doppler broadening ion temperature measurements. The active charge-exchange data point is ~ 6 cm off axis because of the Shafranov shift during heating, while the point taken during the ohmic phase is ~ 3 cm off axis.
- Fig. 21 Plot of the active measurement of $\ln f$ versus energy for three different radii. The measurement shows the presence of a tail which arises during high power neutral injection and appears to originate from large minor radii.
- Fig. 22 Summary of active and passive ion temperature measurements from the high neutral heating experiments, showing ion temperature scaling with the neutral beam power absorbed by the plasma (excluding shine-through and beam duct losses) divided by the line average electron density.
- Fig. 23. Radial ion temperature profiles as measured with the active beam. The dashed lines indicate profiles calculated from $T_i(1-r^2/a^2)^n$ with $n = 2.0, 2.5, 3.0$.

FIG. 1

82X0019

FIG. 2

82X0017

FIG. 3

FIG. 4

ANALYZER SYSTEM COMPUTER INTERFACE

FIG. 5

FIG. 6

82X0020

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

MASS REJECTION FOR D⁰-H

Magnet = 0.223
Deflection = 0.878 kV

Magnet = 0.223
Deflection = 1.303 kV

Magnet = 0.223
Deflection = 1.783

FIG. 12

MASS REJECTION FOR $H^0 \rightarrow D$

FIG. 13

82X0068

FIG. 14

#82X0071

FIG. 15

FIG. 16

82X0069

FIG. 17

FIG. 18

82X0218

FIG. 19

FIG. 20

FIG. 21

#81X1432

FIG. 22

FIG. 23