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CHARACTERISTICS OF SOLID-TARGET CHARGE-EXCHANGE ANALYZERS FOR ENERGETIC ION DIAGNOSTICS ON TOKAMAKS

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Abstract

Compact electrostatic charge-exchange analyzers have been constructed for installation in areas of high magnetic fields and restricted access near tokamak fusion devices. The analyzers employed carbon stripping foils, and have been calibrated for proton energies between 1 and 70 keV. They have been successfully used to study charge-exchange losses in auxiliary-heated tokamak plasmas.

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INTRODUCTION

Charge-exchange analyzers have been used to measure ion temperatures and beam ion thermalization in tokamaks for many years.¹⁻³ Neutral particles emerging from the plasma are typically ionized in a gas stripping cell before they are energy analyzed with magnetic or electrostatic fields. The use of ultrathin foils as stripping agents instead of gas cells in charge-exchange analyzers was first suggested by Gott *et al.*^{4,5} Following their design concepts and taking advantage of the simplicity of solid-target strippers, we have constructed small, compact electrostatic analyzers employing 100 Å-carbon foils for reionizing incoming neutrals. The solid-target analyzers have provided us with a simple, reliable, and comparatively inexpensive diagnostic which requires little space for installation, and can easily be moved from one machine location to another to meet special diagnostic needs. The analyzers are ideally suited for the study of spatially localized phenomena in plasmas with auxiliary heating, and supplement the larger and more complex standard gas-cell charge-exchange analyzers commonly found on present-day tokamaks.

Two solid-target analyzers have recently been used to study the fast-ion losses in high-beta discharges in the Poloidal Divertor Experiment (PDX) tokamak in the Princeton Plasma Physics Laboratory.^{6,7} A third analyzer was added to measure the co-directional charge-exchange flux on the Princeton Beta Experiment (PBX) tokamak during neutral beam heating, and an array of six solid-target analyzers is presently being installed on the Tokamak Fusion Test Reactor (TFTR) tokamak.

In this paper, we discuss the design of the analyzers and their performance during calibration and operation on the PDX tokamak. The calibration covers the energy range between 1 and 70 keV, and thus extends to the regimes of interest for auxiliary-heated fusion plasmas.

I. DESIGN

A schematic of an electrostatic, solid-target analyzer is shown in Fig. 1. The incident particle flux passes first through a carbon foil which establishes charge equilibrium in the emergent particle flux.⁸ The flux is then energy analyzed using two parallel (cylindrical) electrostatic deflection plates, and is detected by a Channeltron detector.

Typical outer dimensions of the analyzers employed on PDX and PBX are 18 cm x 18 cm x 13 cm. The housing was machined of soft iron for magnetic shielding, and was nickel plated to prevent oxidation. The wall thickness is 2.5 cm. The interior of the housing and the deflection plates were painted black to reduce the counting of stray photons. While in operation, the vacuum in the analyzers is maintained directly by their connection to the tokamak vacuum vessel. However, it was necessary to install apertures in the flight tube connecting the analyzer to the tokamak. They served to further reduce the amount of stray light in the analyzer; they also reduced the flow of neutral gas from the tokamak to the analyzer during plasma start-up.

The carbon foils are 100-Å thick and are mounted on a 90%-transmission nickel mesh for mechanical support. The foils cover a 5-mm-diameter hole on a metal disc. Four such discs are mounted in a wheel, to enable the foils to be exchanged easily should any become damaged. One disc carries only a nickel mesh without a foil, which allowed us to alternate between a foil and no-foil configuration during calibration. The no-foil position also enabled us to check the dark count and noise levels during operation on a tokamak.

The theoretical relationship between the energy E of the detected particles of charge Z and the deflection plate voltage V is

$$E = V \cdot Z / \ln(b/a) \quad ,$$

(1)

assuming infinitely tall cylindrical deflection plates and near-circular particle orbits. Here, a and b are the radii of the inner and outer plates, respectively, which are at the potentials $\pm V$. We chose the radii of curvature of our deflection plates to be approximately 9.8 and 11.1 cm, respectively, resulting in a gap of 1.3 cm. Since the width of the plates is 5 cm, fringing fields are minimized. According to Eq. (1), the analyzer can detect 70 keV particles with a plate voltage of approximately 8.7 kV. In other analyzers we chose a slightly smaller radius for the outer deflection plate, in order to detect higher energy ions at lower plate voltages. The plates bend the incoming ions by 90° . This angle was chosen instead of 127° , which provides the optimum focusing of ions of a given energy,^{9,10} to simplify the design. A straight-through hole in the outer deflection plate can be used for optical alignment of the analyzer. It also enables neutral particles to pass through and be detected by a second ("parallel") Channeltron detector. The hole is covered by 90%-transmission nickel mesh to maintain continuity in the electric field.

It was necessary to locate one of the analyzers on the PDX tokamak in the high magnetic field region between two adjacent toroidal field coils.⁶ In this case the analyzer was encased with an additional layer of 1.2-cm-thick soft iron shielding, separated by 1.2 cm from the analyzer's vacuum enclosure. Instead of the four-position foil wheel, which was too bulky to shield effectively, a single foil was mounted inside a 5-cm O.D., 1-cm I.D. soft iron tube. The vacuum inside the analyzer was also maintained via the tokamak's own vacuum system. In this case, however, a bypass arrangement was used, as shown in Fig. 2, in order to protect the foil from being damaged from the air flow while the analyzer was being pumped down. Both analyzers have now been successfully in operation for several years, without necessitating a change in foils.

II. ANALYZER CHARACTERISTICS

A. Energy Calibration

The TFTR ion-beam test stand was used to calibrate the solid-target analyzers for energies from 1 to 70 keV. The test stand can be operated to produce both ion and neutral beams of monoenergetic hydrogen or deuterium.¹¹ At a given beam energy E_0 , an energy spectrum is obtained by scanning the deflection plate voltages in 10 V increments.

Typical energy spectra of beam ions which have passed through the 100 Å-carbon foil and of ions which do not see a foil are shown in Fig. 3 for three beam energies. Each dual peaked spectrum has been obtained in a single scan and a fixed foil setting by using a disc which was only partially covered with foil. A comparison of the foil with the no-foil peak shows that the foil has the effect of shifting the peak of the distribution to a lower deflection plate voltage due to energy loss of the ions in the foil, and of broadening the energy distribution, i.e., worsening the energy resolution.

An energy calibration of the analyzer is obtained by recording the deflection plate voltage V at which the peak ion count rate is obtained for each of the various beam-ion energies E_0 . The results are shown in Fig. 4. In the no-foil case the data can be fitted by the expression

$$E_0(\text{keV}) = 8.65 V_{\text{no-foil}}(\text{kV}) \quad (2)$$

and is found to be the same for hydrogen and deuterium. This agrees with Eq. (1) to within 10%. It should be noted that an experimental calibration is desirable, unless one knows the values of a and b in Eq. (1) very accurately. Since $a \approx b$, a small error in measuring a or b will cause a large error determining $\ln(a/b)$. For example, a 1% error in measuring b will change the value of $\ln(a/b)$ by 9%.

For the case where the beam ions pass through the foil, the deflection plate voltage at which the maximum count rate is attained is generally lower than in the no-foil case. For energies of interest to auxiliary-heated tokamaks ($E_0 \geq 5$ keV), the data in Fig. 4 can be approximated by the equation

$$E_0(\text{keV}) = 8.85 V_{\text{foil}}(\text{kV}) + 1.25 \quad . \quad (3)$$

For energies below 5 keV, the data can be fitted by the expression

$$E_0(\text{keV}) = 10.64 V_{\text{foil}}(\text{kV}) \quad . \quad (4)$$

B. Foil Straggling

The energy loss ΔE that a beam ion experiences while passing through the foil can be determined from the difference in the plate voltages necessary for detection of the peak count rate for the foil and no-foil case, i.e.,

$$\Delta E = 8.65 (V_{\text{no-foil}} - V_{\text{foil}}) \quad . \quad (5)$$

The corresponding data are shown in Fig. 5. The energy loss is found to be similar for the two hydrogenic species. Assuming the incremental energy loss dE per unit thickness dx to be proportional to the particle velocity v ,

$$dE/dx \sim v \quad , \quad (6)$$

then the total energy loss is given by

$$\Delta E \approx 4.4 \cdot 10^{-3} d \sqrt{E_0}(\text{keV}) \quad , \quad (7)$$

where d is the thickness of the foil in Å. The value of the proportionality constant is determined by the solid line in Fig. 5. This result is consistent with the value of 0.32 found by Gott and Motlich in Ref. 5. Figure 5 shows that most data can be described by an expression of the form given by Eq. (7). An exception is the low energy point at 1 keV, for which the measured energy loss is considerably less than the value given by Eq. (7). At the high energies, the data may indicate a leveling off of the energy loss. However, the data exhibit wide scatter, precluding a definite determination of the behavior of ΔE at high E_0 .

C. Energy Resolution

The theoretical energy resolution $\delta E/E$ for the no-foil case can be obtained from Eq. (1). Let δR be a variation of the central particle trajectory $R = (a + b)/2$; then, according to Ref. 12,

$$\delta E/E \approx \delta R/R \quad (8)$$

The variation δR can be controlled by inserting a slit of width ΔR in front of the detector. Experimental results for three different values of ΔR are shown in Fig. 6. The dashed curves represent the theoretical values given by Eq. (8). Good agreement between the data and theory is found for large slit widths and for high energies. With a slit width of 1.3 mm an energy resolution near 1% is obtained. At the lower energies, however, the measured energy resolution is significantly worse than the value predicted by Eq. (8). This may be due to the effect of entrance and exit fringe fields and due to energy straggling of the low-energy particles caused by collisions with the ambient neutral gas in the test stand flight tube. This straggling is

similar to the straggling experienced by the beam particles while traversing the carbon foil, as shown in Fig. 7 and discussed below. The slope of the solid lines in Fig. 6 was chosen to be the same as that of the line in Fig. 7, and the lines indeed approximate the low-energy, no-foil data quite well.

The energy straggling in a solid target depends on the mass M and energy E_0 of the incident particle.¹³ In particular, the energy resolution is predicted to be proportional to

$$\delta E/E \sim M^{-1/2} E_0^{-1/2} \quad (9)$$

In this limit, where the energy resolution is dominated by straggling in the foil, $\delta E/E$ is independent of ΔR . Figure 7 shows the data obtained for two widths ΔR , and indeed no dependence on ΔR can be seen. The proton data can be fitted by the expression

$$\delta E/E = 0.20 E_0^{-0.42} \quad (10)$$

in agreement with Eq. (8). While the energy resolution is much worse than for the no-foil data at low energies, the energy resolution approaches the values of the no-foil data at sufficiently high particle energies, i.e., it approaches the values determined by the analyzer geometry in Eq. (8). The data show that better energy resolution can be achieved with deuterons, which is also in agreement with Eq. (9).

D. Analyzer Efficiency

The analyzer signal f_+ is proportional to the number of ions n_+ which arrive at the perpendicular detector. The quantity of interest, however, is

the total particle flux n_b which emanates from the plasma and enters the analyzer. Hence, it is necessary to obtain a value for the efficiency $\epsilon(E_0)$ of the detector, which allows the relating of n_b to f_+ in the energy range of interest. The ways of achieving this goal are as follows.

In Table 1 we have listed various physical quantities, and the conditions under which they can be measured, for either the parallel or the perpendicular detector. Here n_∞ is the particle flux emerging from the foil, $n_{\infty 0}$ is the neutral component of n_∞ , and n_+^* is the ion flux arriving at the perpendicular detector in the no-foil case. The measured quantities f_b , f_∞ , etc. are proportional to the respective particle fluxes by the detector responses $k_\parallel$ and $k_\perp$ which we assume to be independent of energy.

In order to relate f_+ to n_b we can write

$$n_b = (n_b/n_+) n_+ \quad (11)$$

or

$$n_b \sim f_+/\epsilon, \quad \epsilon \equiv f_+/f_b \quad (12)$$

Hence, we can obtain the desired calibration by measuring the signal on the parallel detector without deflection plate voltage and without foil, and by measuring the signal on the perpendicular detector with plate voltage and with foil. The result is shown in Fig. 8, where the efficiency ϵ has been normalized to unity for $E_0 = 60$ keV.

A second way to relate n_b and f_+ is to make use of the fact that the test stand particle beam consists solely of ions. Hence $n_b \sim n_+$, and the test-beam flux can be measured directly without foil by the perpendicular detector. For this case, we can write

$$n_b \sim (n_+^*/n_+) n_+, \quad \epsilon \equiv f_+/f_+^* \quad (13)$$

This method provides the easiest and most self-consistent way of calibration. Using a disc only partially covered with foil, f_+ and f_+^* can be measured simultaneously under the same disc and voltage settings and with the same detector, as demonstrated in Fig. 2. The method based on Eq. (11), on the other hand, requires the changing of discs and the use of two detectors. The resulting data are shown in Fig. 8. It is seen from the figure that either method produces similar results for the detector efficiency.

Finally, we can write

$$n_b = \left(\frac{n_b}{n_\omega}\right) \left(\frac{n_\omega}{n_{\omega+}}\right) \left(\frac{n_{\omega+}}{n_+}\right) n_+ \quad (14)$$

or

$$n_b \sim \frac{1}{S_f} \frac{1}{n_+} \frac{1}{S_p} f_+ \quad (15)$$

Here $n_{\omega+}$ is the ion component of n_ω . S_f is the fraction of the total flux scattered into the acceptance angle of the parallel detector on passing through the foil

$$S_f \equiv n_\omega/n_b \quad ; \quad (16)$$

S_p is the fraction of unscattered flux on passing through the deflection plates

$$S_p \equiv n_+/n_{\omega+} \quad ; \quad (17)$$

and η_+ is the ion fraction in the flux emerging from the foil, i.e., the foil efficiency

$$\eta_+ \equiv n_{\infty+}/n_{\infty} \quad (18)$$

The foil efficiency cannot be measured directly with our setup. However, using the fact that

$$n_{\infty+} = n_{\infty} - n_{\infty 0} \quad (19)$$

η_+ becomes

$$\eta_+ = 1 - n_{\infty 0}/n_{\infty} \quad (20)$$

Hence η_+ can be measured using the parallel detector. The assumption must be made that losses between the foil and the detector are equal for neutrals and ions. The data are shown in Fig. 9. Phillips has shown that the minimum foil thickness necessary to reach charge-exchange equilibrium is a layer of 6 atoms.⁸ Thus the 100 Å-carbon foil used in the analysis is more than sufficiently thick to obtain an equilibrium flux emerging from the foil. However, we expect that the equilibrium charge distribution is not characteristic of the carbon foil. Instead it is a result of the "dirt" layer (oxygen, water vapor, etc.) on the exit side of the foil. Values measured by Phillips for "dirt" are shown in Fig. 9 (dashed curve) for comparison.

The fraction of the total flux, S_F , which is scattered into the acceptance angle of the parallel detector can be measured using the foil and no-foil setting. This measurement accounts for all scattering losses between the foil and the parallel detector. The results are shown in Fig. 10. No scattering losses are expected for energies in excess of 100 keV.

Assuming $S_p \approx \text{constant}$, we can make an estimate on the detector efficiency based on S_f and η_+ :

$$\epsilon \approx S_f \eta_+ \quad (21)$$

The result of this estimate is included in Fig. 8 and arbitrarily normalized to unity at $E_0 = 60$ keV. The spread in efficiency between 5 and 60 keV is about a factor of three less for the estimate than for the measurements based on the ratios f_+/f_b and f_+/f_+^* .

III. TOKAMAK RESULTS

In Fig. 11 typical beam slowing-down spectra from the pair of solid-target analyzers on the PDX tokamak are shown. The analyzers have near-vertical sightlines viewing the inside and outside plasma edge, respectively. The spectra are compared to results from a bounce-averaged Fokker-Planck code. The code was described in more detail in Ref. 14, where it was used to model slowing-down spectra from the Fast Ion Diagnostic Experiment (FIDE) detector, a gas-target charge-exchange analyzer on PDX.¹ The agreement between the compact analyzer data and simulations in Fig. 11 is comparable to the agreement between the FIDE data and simulations obtained in Ref. 13 under similar plasma conditions.

Although the acceptance angle of the solid-target analyzer is small [limited by the 5-mm-diameter entrance aperture and a 1.3-mm-slit width in front of the detector (0.2 cm^2)], the measured charge-exchange flux is sufficiently intense to resolve fast time fluctuations. This is a result of the high stripping efficiency of solid-target analyzers, as pointed out earlier by Gott and Motlich.⁵ In Fig. 12, the fast time resolution charge-

exchange flux is shown during the fishbone instability¹⁵ at 50 and 70 keV. The charge-exchange signal is modulated at the same frequency (typically 10-20 kHz) as the signal from a Mirnov coil measuring oscillations in the poloidal magnetic field. The frequency response is limited only by the 30- μ sec time resolution of the signal amplifiers.

CONCLUSION

We have successfully employed solid-target charge-exchange analyzers to measure the fast-ion efflux from tokamaks with auxiliary heating. The analyzers have been calibrated for energies up to 70 keV, and the results indicate favorable trends, which suggest improved performance at higher energies. The analyzers are small and compact, and can be adapted for special purposes. Hence, they are ideally suited to supplement more complicated gas-target analyzers by providing additional spatial and temporal information at modest effort and cost. The analyzers were found to be sturdy and highly reliable, with no maintenance required during several years of tokamak operation.

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Table 1

Conditions under which various quantities are measured by
the parallel or perpendicular detector.

Physical Quantity	Measured Quantity	$V = 0$	Foil	Detector
n_b	$f_b = k_{\parallel} n_b$	yes	no	$\parallel$
n_{∞}	$f_{\infty} = k_{\parallel} n_{\infty}$	yes	yes	$\parallel$
n_+	$f_+ = k_{\perp} n_+$	no	yes	$\perp$
$n_{\infty 0}$	$f_{\infty 0} = k_{\parallel} n_{\infty 0}$	no	yes	$\parallel$
n_+^*	$f_+^* = k_{\perp} n_+^*$	no	no	$\perp$

FIGURE CAPTIONS

- Fig. 1. Schematic of a stripping foil charge-exchange analyzer.
- Fig. 2. Schematic of a doubly shielded analyzer with bypass pumping.
- Fig. 3. Energy spectra of detected ions for a 10, 20, and 30 keV proton beam showing the "foil peak" (low energy side) and "no-foil peak" (high energy side).
- Fig. 4. Deflection plate voltage at peak flux versus incident particle energy E_0 . Similar results are obtained for hydrogen and deuterium.
- Fig. 5. Energy loss in 100 Å-carbon foil versus incident proton and deuteron energy. The solid line is based on a theoretical estimate.
- Fig. 6. Energy resolution of the analyzer without carbon foil versus particle energy for three different aperture widths ΔR : (a) $\Delta R = 1.27$ cm; (b) $\Delta R = 0.43$ cm; (c) $\Delta R = 0.13$ cm. The dashed line indicates the energy resolution estimated from Eq. (7).
- Fig. 7. Energy resolution of the analyzer with carbon foil versus particle energy for aperture widths $\Delta R = 0.43$ cm and $\Delta R = 0.13$ cm.
- Fig. 8. Detector efficiency versus proton energy from two methods of direct measurement (solid line) and simple estimate (dashed line). The data are normalized to unity at 60 keV.
- Fig. 9. H^+ equilibrium fraction emerging from the carbon foil versus incident proton energy. The dashed line indicates the H^+ fraction reported in Ref. [8] for "dirt."

- Fig. 10. Fraction of the equilibrium flux emerging from the carbon foil scattered into the acceptance angle of the parallel detector versus incident proton energy.
- Fig. 11. Beam slowing-down spectra for $D^0 + D^+$ injection in a low-mode, diverted discharge; $P_{abs} \approx 2.5$ MW, $I_p \approx 360$ -380 kA, $\bar{n}_e \approx 3.3 \times 10^{13}$ cm $^{-3}$. (a) Inside detector, (b) Outside detector. The solid curves were calculated using a bounce-averaged Fokker-Planck code.
- Fig. 12. Charge-exchange flux at two different detection energies and associated Mirnov-coil signals during a fishbone burst.

Fig. 1

Fig. 2

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Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

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