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**NEUTRAL BEAM SPECIES MEASUREMENTS USING IN SITU
RUTHERFORD BACKSCATTER SPECTROMETRY**

By

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ABSTRACT

This work describes a new in situ method for measuring the neutral particle fractions in high power deuterium neutral beams, used to heat magnetically confined fusion plasmas. Deuterium beams, of variable energies, pulse lengths, and powers up to 47 keV, 100 msec, 1.6 MW, were Rutherford backscattered at 135° from the TiC inner neutral beam armor of the PDX, and detected using an electrostatic analyzer with microchannel plates. Complete energy scans were made every 20 msec and data were obtained simultaneously from five different positions across the beam profile. The neutral particle fractions were measured to be $D^0(E):D^0(E/2):D^0(E/3)=53:32:15$. The corresponding neutral power fractions were $P^0(E):P^0(E/2):P^0(E/3)=72:21:7$, and the associated ionic fractions at the output of the ion source were $D_1^+(E):D_2^+(E):D_3^+(E)=74:20:6$. The measured neutral particle fractions were relatively constant over more than 70% of the beam power distribution. A decrease in the yield of the full energy component in the outer regions of the beam was observed. Other possible experimental configurations and geometries are discussed.

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INTRODUCTION

High power deuterium (D^0) or hydrogen (H^0) neutral beams have been used in many experiments to heat magnetically confined fusion plasmas to high temperatures. The typical deuterium positive-ion based acceleration methods used in these applications, simultaneously produce three ionic species [$D_1^+(E)$, $D_2^+(E)$, $D_3^+(E)$]. Subsequent collisions of these species with gas in the beamline neutralizer cell result in a beam with three neutral components of full, one-half, and one-third energy [$D^0(E)$, $D^0(E/2)$, $D^0(E/3)$], respectively. Although a monoenergetic, full energy beam of $D^0(E)$ would be desirable in fusion heating applications, beam filtering is impractical due to the efficiencies, size, cost, and complexities involved. Consequently, accurate calibration of the neutral deuterium species fractions is important for diagnosing and modeling dense, high temperature plasmas.

There are several well-known methods for measuring the species content of neutral beams.¹⁻⁴ Each of these methods has particular limitations and may be difficult to apply to an installed injection system during heating operations. Optical Doppler shift³ and D-D nuclear reaction⁴ methods for measuring species require relatively high background gas pressures available only in beamline regions far from the target plasma. Consequently, the measurements must be extrapolated to determine the neutral species fractions at the target plasma. Methods involving energy or momentum analysis of the output neutral beam, using electric/magnetic fields, are difficult to use with an installed injection system.¹ Similarly, measurements of the power contained in the residual ionic fractions using momentum analysis are difficult to perform during injection heating operations.¹

In this work, we describe the use of Rutherford backscatter spectroscopy (RBS) to measure the species content of high power neutral beam injection

systems. This in situ species measurement technique yields fast, reproducible results, under actual operating conditions, with relatively simple analysis using well-known parameters. Rutherford backscatter spectroscopy is an established technique for analyzing unknown targets using a known particle beam.⁵ In this work, a known target is used to determine unknown beam properties (i.e., species fractions).

METHOD

Most beam particles in the energy range of interest (10-120 keV), incident on a solid target, are implanted. A small fraction of the incident beam particles will be scattered by target nuclei, and will be reflected from the target. The energy, yield, and angular distribution of the backscattered particles are described by well-known kinematics and the Rutherford elastic cross section. In particular, referring to Fig. 1a, beam particles of energy E_0 are scattered from the top surface layer of the target with an energy KE_0 which is less than E_0 . K is the kinematic recoil parameter given by Eq. (1),

$$K = [m \cos \theta + (M^2 - m^2 \sin^2 \theta)^{1/2}] / [m + M] \quad (1)$$

where m is the incident particle mass, M is the target nucleus mass, and θ is the net angle between the incoming and outgoing particle ($\theta_1 + \theta_2$ in Fig. 1a). The maximum resolution in the backscatter particle energy spectrum is obtained when K approaches 1. K is maximized for a given particle mass (m) by allowing the target mass (M) to be as large as possible, and by detecting the backscatter particle as close to 180° as permitted by the detection geometry. Backscatter yields from near surface single collision scattering are well described by the Rutherford cross section. The scattering yield from depths far from the surface deviates from the near-surface single collision

behavior due, in part, to multiple scattering. Figure 1b shows a schematic backscatter yield spectrum versus backscatter energy for a beam of energy E_0 incident on a surface at angle θ , and containing three species fractions at different energies (e.g., $D^0(E)$, $D^0(E/2)$, $D^0(E/3)$). The knees in the yield curves at E_1 , E_2 , and E_3 represent the yields from the near surface scattering of the respective species components.

The analysis of backscatter spectra is simplified by applying the surface approximation.⁵ Consider a beam particle that undergoes single collision near-surface scattering from a depth δx . The energy loss is given in the surface approximation by Eq. (2).

$$\delta E = \left(\frac{K}{\cos \theta_1} \frac{dE}{dx} \bigg|_{E_0} + \frac{1}{\cos \theta_2} \frac{dE}{dx} \bigg|_{KE_0} \right) \delta x \quad (2)$$

where the angles are defined in Fig. 1a and dE/dx is the rate of energy loss at the indicated energy. An energy loss factor (S) is defined by Eqs. (2) and (3).

$$\delta E = S \delta x \quad (3)$$

The differential Rutherford cross section for single collision elastic scattering is given by Eq. (4).

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{2E \sin^2 \theta} \right)^2 \frac{\{ \cos \theta + [1 - (\frac{m}{M} \sin \theta)^2]^{1/2} \}^2}{[1 + (\frac{m}{M} \sin \theta)^2]^{1/2}} \quad (4)$$

where Z_1 is the beam particle atomic number, Z_2 is the target atomic number, E is the particle energy at the time of collision. The yield (Y) due to scattering from the near-surface layer is

$$Y = [\Delta\Omega f(KE_0) N^0(E_0) \sigma \rho] \frac{\delta E(E_0)}{S} \quad (5)$$

where $N^0(E_0)$ is the number of incident neutral beam particles, $\Delta\Omega$ is the detector solid angle, $f(KE_0)$ is the detection efficiency at energy KE_0 , ρ is the particle density, $\sigma = (d\sigma/d\Omega)\Delta\Omega$ from Eq. (4), and δx is the depth from which scattered particles are detected with energy bandwidth δE . It is seen that the yield is directly proportional to the number of incident particles and several known parameters. If a particle beam has several species components, each with the same mass but with different energies, the respective yields for a beam with species $D^0(E_1)$, $D^0(E_2)$, $D^0(E_3)$ can be obtained as follows from Eq. (5),

$$Y_1 = N^0(E_0) \sigma_1 \Delta\Omega f(E_1) \rho \delta E(E_1)/S_1 \quad (6)$$

$$Y_2 = N^0(E_0/2) \sigma_2 \Delta\Omega f(E_2) \rho \delta E(E_2)/S_2 \quad (7)$$

$$Y_3 = N^0(E_0/3) \sigma_3 \Delta\Omega f(E_3) \rho \delta E(E_3)/S_3 \quad (8)$$

Therefore, since Z_1 , Z_2 , ρ , the detector solid angle $\Delta\Omega$, and the geometry are the same for each detected species yield, the respective species yields are reduced to

$$\frac{D^0(E)}{D^0(E/2)} = \left(\frac{Y_1}{Y_2}\right) \left(\frac{E_1}{E_2}\right) \left(\frac{f(E_2)}{f(E_1)}\right) \left(\frac{S(E_1)}{S(E_2)}\right) \quad (9)$$

$$\frac{D^0(E)}{D^0(E/3)} = \left(\frac{Y_1}{Y_3}\right) \left(\frac{E_1}{E_3}\right) \left(\frac{f(E_3)}{f(E_1)}\right) \left(\frac{S(E_1)}{S(E_3)}\right) \quad (10)$$

where the detector energy bandwidth ratio $\delta E/E$ is taken as a constant. The resulting ratios for the respective species yields are given in terms of the measured surface backscatter yields, the respective backscatter energies, an energy dependent detector efficiency, and the energy loss rate factor from Eqs. (2) and (3). The energy loss rates $[dE/dX \text{ in Eq. (2)}]$ are well tabulated in the literature.⁶ In practice, the surface yield for a particular species (Y_1 , Y_2 , or Y_3) is obtained from the measured backscatter spectrum by first extrapolating the total background yield from higher energy components to lower energy, and then subtracting this background. The effect of small systematic uncertainties in the background subtraction procedure is reduced or canceled by forming the ratio of the measured yields in Eqs. (9) and (10). Thus, the species intensities in the neutral beam are given simply and accurately in terms of directly measured quantities. In the case of a beam having species with the same energy, but differing mass or atomic number, the analysis follows from Eqs. (3)-(5) in a similar manner.

PROCEDURE

A schematic of the experimental geometry is shown in Fig. 2. The Poloidal Divertor Experiment (PDX) NW neutral beam was incident, in the absence of plasma, on a 15- μ thick layer of TiC coated on the 1.27-cm thick graphite neutral beam armor.⁷ Measurements were performed with D⁰ beams of 27-47 keV, 100-msec pulse length, and powers up to 1.6 MW. The ion source accelerator grid was 30 cm in diameter, and the half-width of the beam on target at 1/e of maximum power was 15.5 cm. The yield of the backscattered particles was measured over a range of angles centered at 135°, using a horizontally scanning fast-ion electrostatic analyzer.⁸ It consisted of a neutral stripper gas cell, electrostatic deflection plates for energy

analysis, and a microchannel plate (MCP) detector array at its focal plane. At a given angular position of the analyzer, up to five different detection angles were observed simultaneously by collecting and amplifying signals from five different sections of the MCP array. This allowed the analyzer to detect particles backscattered from five different locations, each approximately 4.2 cm^2 , across the target. A measure of the radial distribution of the species components was thus obtained. This detection method allowed complete backscatter yields to be measured simultaneously at the five selected detection angles as rapidly as every 20 msec. The MCP detector system was operated in the current mode, with a gain corresponding to approximately 1 volt per 6.3×10^4 counts/sec. The analyzer could be pivoted so as to allow a continuous change in viewing angle across the target.

RESULTS

Figure 3 shows a backscatter yield spectrum for a 47 keV, 100-msec long, 1.6 MW, D^0 beam at about 60 msec after accel-voltage turn-on. The data shown in Fig. 3 were acquired in 20 msec. The data were obtained from a region near the center of the beam power density profile. The three prominent knees in the yield spectrum at 13.5, 20.3, 40.5 keV correspond to near-surface scattering from Ti nuclei ($Z=22$) in the TiC surface. The data showed little evidence of backscatter from carbon. Backscatter yields from the carbon nuclei ($Z=6$) at about 9.2, 13.1, and 26.0 keV were at least a factor of 13 less than the Ti yield, due to the Z dependence of the Rutherford cross section. In addition, visual inspection of the inner wall armor indicated the presence of a thin Ti film, of varying thickness, from Ti gettering operations in the PDX vacuum vessel. This Ti film further enhanced the Ti backscatter yield relative to that of the carbon.

Figure 4 shows, for the same beam conditions, a graph of the yield signal (volts) from the full energy backscatter component (Y_1) versus horizontal distance across the beam (cm). The solid curve represents a gaussian least-squares-fitted to thermocouple measurements of the inner wall temperature profile, normalized to the peak yield. This showed that the backscatter yield across the beam profile was consistent with the power density profile measured thermally. The slight drop in the Y_1 yield in the outer regions of the beam is attributed to a relative increase in the lower energy yields as discussed below.

Figure 5 shows the percentage of neutral particles versus horizontal distance across the beam for the same beam conditions given above. The region corresponding to the beam power density profile greater than $1/e$ of full power is indicated by the arrows. The measured fractions are relatively constant over this region, with an average ratio of $D^0(E):D^0(E/2):D^0(E/3)=53:32:15$. This neutral particle ratio gives a neutral power ratio of $P^0(E):P^0(E/2):P^0(E/3) = 72:21:7$. The ionic output ratio from the ion source is estimated to be $D_1^+(E):D_2^+(E):D_3^+(E)=74:20:6$, assuming an equilibrium gas cell and using published charge-exchange data.⁹ This result is in agreement, to within the experimental uncertainties of about 5-10%, with previous measurements made using magnetic analysis of the residual ion fractions, including corrections for possible beamline gas effects.¹ The measured neutral particle ratio was found to be relatively constant over more than 70% of the beam power density distribution. The origin of the apparent decrease in the yield of the full energy component in the outer region of the beam (Fig. 5) is still under investigation. This decrease in the $D^0(E)$ relative yield may be due in part to an increase in the $D^0(E/2)$ and $D^0(E/3)$ yields, resulting from $D_2^+(E)$ and $D_3^+(E)$ molecular scattering. Ion source edge effects are also a possibility.

DISCUSSION

The apparatus and geometry discussed above enhanced the uniqueness and utility of the RBS species measurement method for high power neutral beams. The number of observed "channels" can be increased simply by fabricating more electronics, so as to sample a larger section of the MCP array for giving greater spatial resolution. An alternative approach is to construct several single-channel electrostatic analyzers using channeltron detectors. One such analyzer will be used to perform off-line species ratio measurements for ion sources in a prototype beamline for the Tokamak Fusion Test Reactor (TFTR). Figure 6 shows a schematic diagram of the experimental geometry. The detection system consists of a small electrostatic analyzer mounted on the TFTR neutral beam Test-Stand. A 100 Å carbon foil, mounted on a 90% transmission Ni mesh is used to strip incoming neutrals for energy analysis using electrostatic deflection plates.

Alternatively, the use of solid state surface barrier detectors, to view backscattered particles from high power beams directly, can be restricted by background radiation and increased detector leakage current from light induced at intense beam powers. The use of surface coatings or thin foils to attenuate beam light can also degrade the detection of lower energy components.

This beam species measurement method allows accurate, versatile, prompt, direct, position dependent, in situ species measurements for high power neutral beams incident on targets typically available in fusion heating experiments. In particular, heating efficiency can be a sensitive function of species fractions in fusion reactor plasmas heated by intense neutral beams. This species measurement method thus provides information for diagnosis of plasmas and optimizing neutral beam injection system operation in an efficient and expeditious manner.

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FIGURE CAPTIONS

- Fig. 1a. A schematic diagram of surface scattering geometry.
- Fig. 1b. A schematic backscatter yield spectrum versus energy for a beam containing three species fractions at different energies.
- Fig. 2. A schematic diagram of the experimental geometry.
- Fig. 3. A backscatter yield signal (volts) versus detected particle energy (keV).
- Fig. 4. A graph of the yield signal (volts) from the full energy component (Y_1) versus horizontal distance across the beam (cm) for a 47 keV, 1.6 MW D^0 beam.
- Fig. 5. Percentage of neutral particles versus horizontal distance across the beam (cm) for a 47 keV, 1.6 MW D^0 beam.
- Fig. 6. A schematic of the experimental geometry for off-line backscatter species measurements on TFTR neutral beam injection systems.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

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Fig. 6

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