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ABSTRACT

Local measurements of the fast-ion distribution in auxiliary-heated plasmas are key to understanding the behavior of energetic particles under a variety of conditions, such as beam-ion transport during Alfvén instabilities and the acceleration of beam ions by fast waves. For the first time at DIII–D, line-averaged and local measurements of the energetic-particle density (for E = 5-75 keV) are possible using an array of four compact charge-exchange analyzers.[1] The installation consists of three vertically-viewing analyzers with fixed sightlines, measuring particles with χ = 90° (where χ is the angle between the particle's velocity and the toroidal direction) and one horizontally-viewing analyzer with a variable sightline, measuring particles with 2°Ù χ Ù 60°. All the analyzers can make passive measurements while three detectors, with sightlines that intersect deuterium heating beams, can make active charge-exchange measurements.

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I. INTRODUCTION

Diagnosing the fast-ion population is important in auxiliary-heated plasmas. Ideally, measurements would give details of the fast-ion distribution function f_b in space $\vec{r}$, energy E, and pitch-angle χ. (Here χ is the angle which the particle's velocity $\vec{v}$ makes with respect to the unit vector in the toroidal direction $\hat{e}_\phi$, i.e. $\cos\chi = v_\phi/v$.) At DIII–D, data from diagnostics that measure the 2.5 MeV neutron production rate [1] coupled with the line-averaged electron density yield the total number of beam ions [2], but the diagnostics effectively average over $\vec{r}$, E, and χ. Understanding the local behavior of fast ions is critical for several experiments, such as beam-ion loss during Alfvén instabilities [2] and the acceleration of beam ions by fast-waves [3]. Consequently, local measurements of the distribution function are desirable. Charge-exchange analyzers are able to measure a single point $f_b(\vec{r},E,\chi)$ in the distribution function. The depth into the plasma from which ions can be detected by charge-exchange analyzers is inversely proportional to the line density; given the modest sizes (R ~ 1.67 m, a Ù 67 cm) and densities ($n_e \sim 10^{19}$ m^{-3}) of DIII–D plasmas, these analyzers can detect neutrals coming from the core.

A charge exchange analyzer had been installed on the DIII–D tokamak but could never take data during neutral-beam injection. The "E-parallel-to-B" (E_B) charge-exchange analyzer[4] used a He stripping cell to reionize the neutrals and electric and magnetic fields to deflect the particles onto a microchannel detecting plate [5]. The microchannel plate was far too sensitive to neutrons: even with ~4 cm of lead shielding, the output signal was saturated by a 2.5 MeV neutron flux of ~10^{12} n/s·m^2, roughly the flux at the radial location of the plate produced by the injection of a single deuterium beam into a deuterium target plasma. A charge-exchange analyzer [6,7] using a channel electron multiplier, or "channeltron", to detect reionized particles is a more effective charge-exchange diagnostic for DIII–D. The channeltron is much less sensitive to neutrons than the microchannel plate and operates at fluxes in excess of 10^{14} n/s·m^2 (corresponding to neutron rates of over 10^{16} n/s) with no auxiliary neutron shielding.

This paper describes installation of four compact, energy-resolving analyzers on the DIII–D tokamak. The analyzers [6], originally built and operated at the Princeton Plasma Physics Laboratory, come equipped with channeltrons and are capable of detecting neutrals with energies between 5 and 75 keV. Since nearly all DIII–D discharges are beam-heated D-D plasmas, mass resolution is not a mandatory feature for an analyzer on this tokamak. The array gives four line-averaged and three local measurements of the beam-ion density for a spectrum of energies and pitch-angles.

The horizontal analyzer is described in Section I; the other three have similar characteristics. In Section II, the layout of the array, with a single, horizontally-scanning analyzer at the midplane and three fixed, vertically-viewing analyzers, is discussed. Data from the horizontal analyzer are presented in Section III.

II. DESCRIPTION OF INSTRUMENT

All four analyzers are similar in construction and simple in design (Fig. 1). The incoming particle flux is ionized by a 100 Å-thick carbon foil [8] mounted on a 90% transmission nickel mesh. The mesh is attached to an aluminum disk 1.0 cm in diameter with an aperture of 0.5 cm. Two cylindrically-shaped parallel plates, energized to a potential V_{plate}, deflect the reionized particles 90° to a channeltron detector [5] running in analog (current) mode. A preamplifier acts as a current-to-voltage converter and transmits the signal to a digitizer.

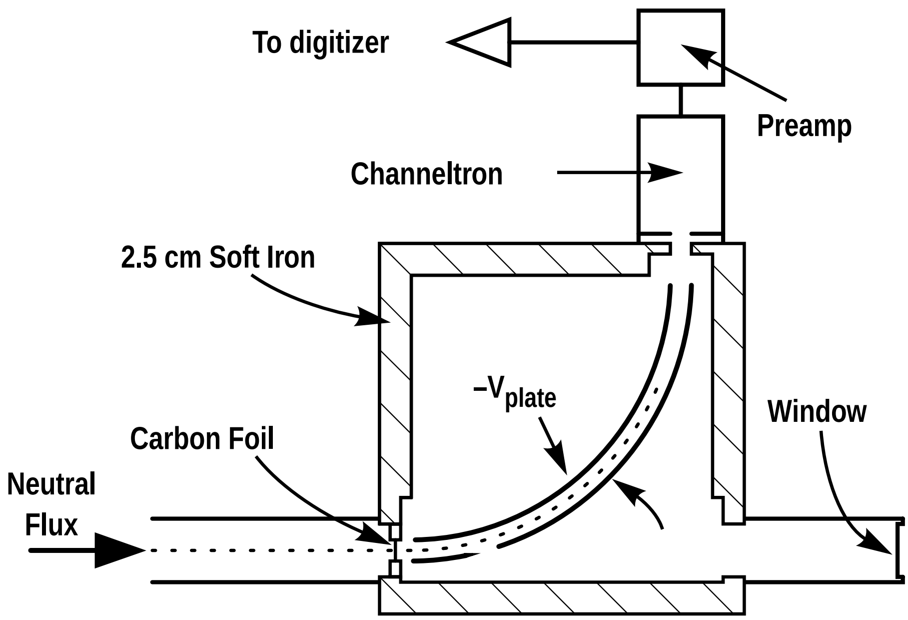

Fig. 1. Schematic of a compact charge-exchange analyzer (not to scale). The analyzer has external dimensions of 18x18x13 cm with an outer housing made of 2.5 cm thick soft iron for magnetic shielding. The upper and lower plates have radii of 9.8 and 11.1 cm respectively. A through-hole is drilled in the bottom plate to allow for sightline alignment of the diagnostic. The mesh and foil are positioned 1.2 cm from the deflection plates by a fabricated stainless piece (not shown) press-fitted into the nipple on the front (machine-side) of the analyzer. The piece is designed so gas flows around the disk, preventing a pressure differential across the foil during pump-down. A window is used to visually inspect the foil while the system is under vacuum.

Two Trek high voltage power supplies [9] provide positive and negative potentials to the lower and upper electrostatic plates respectively. Although the Treks have a maximum output of 10 kV, an operational limit of 8.7 kV is placed on the supplies to prevent arcing. A frequency generator controls the Trek output. The generator supplies either a DC control voltage to deflect particles of a specific energy or a triangle-wave control voltage (τ_{sweep} À 0.1—0.5 s) with a DC offset to deflect particles with a spectrum in energy (E_{max} - E_{min} Ù 75 keV) at the expense of time resolution.

Beiersdorfer *et al.* [6] quantitatively studied the characteristics of this design. The analyzer was tested on a 100 keV ion-beam test stand [10] at the DIII–D facility and the calibration was consistent with their results. For a monoenergetic ion beam, the particle energy E_0 as a function of plate voltage V_{plate} with a foil placed along the beam trajectory was found to vary as (for E_0 Ú 5 keV)

$$E_0\,(\mathrm{keV}) = 8.85 V_{plate}(\mathrm{kV}) + 1.75. \tag{1}$$

This relationship is true for both protons and deuterons. The energy lost by particles passing through a 100 Å-thick foil ΔE_{foil} was measured to be (for E_0 Ú 5 keV)

$$\Delta E_{foil}(\mathrm{keV}) \approx 0.44\sqrt{E_0(\mathrm{keV})}\ . \tag{2}$$

The energy resolution of the analyzers δ⊇E/E is about 0.048[6] since no baffles are placed along the sightline.

During tokamak operations, the channeltron also detects neutrons and gammas generated by d(d,n)^{3}He reactions, but this effect can be subtracted out. The amplitude and time-evolution of the neutron-induced signal is measured by closing the gate valve to the vessel. The resulting signal closely follows the 2.5 MeV neutron production rate as measured by plastic scintillators cross-calibrated to an array of neutron counters [1]. This measurement typically yields a background signal (in volts) of ~ $7\%10^{-17} S_n$, where S_n is the neutron rate in n/s, assuming a normal bias (2.4 kV) is applied to the channeltron. In most cases, this background signal is negligible. (For the discharge shown in Fig. 4, with S_n = $1.8\%10^{14}$ n/s , the neutron-induced signal is ~0.02 V and, for active charge exchange, the signal-to-noise ratio is much greater than unity.) For high performance discharges (S_n Ú 10^{16} n/s), the neutron noise is significant but never saturates the signal.

Plasma light is another potential source of noise. Though studied only qualitatively, the effect of stray light at the horizontal location was found to be negligible. For several shots, the plates were reverse-biased with the gate valve open. This ensures that the diagnostic views the plasma but no reionized neutrals are deflected by the channeltron. The signal correlated well with the 2.5 MeV neutron production rate but had no correlation with the D_α or soft x–ray signals.

III. ARRAY LAYOUT

One analyzer arrived at DIII–D in 1989. The analyzer was mounted directly on the innermost vertically-viewing port on top of the vessel (see Fig. 2) and operated for several months but never collected valid data. The problem was later traced to the stray magnetic field, produced primarily by the Ohmic heating coils, at the analyzer's location (R = 1.46 m, Z = 2.99 m). This field , which can be as large as 2.8 kG, is strong enough to saturate the soft iron shielding and affect the reionized neutral's trajectory inside the shield box. The same analyzer was later installed along the midplane (in place of the E_B analyzer) where the stray fields are an order of magnitude less than at the previous location; here, the analyzer successfully collected valid data.

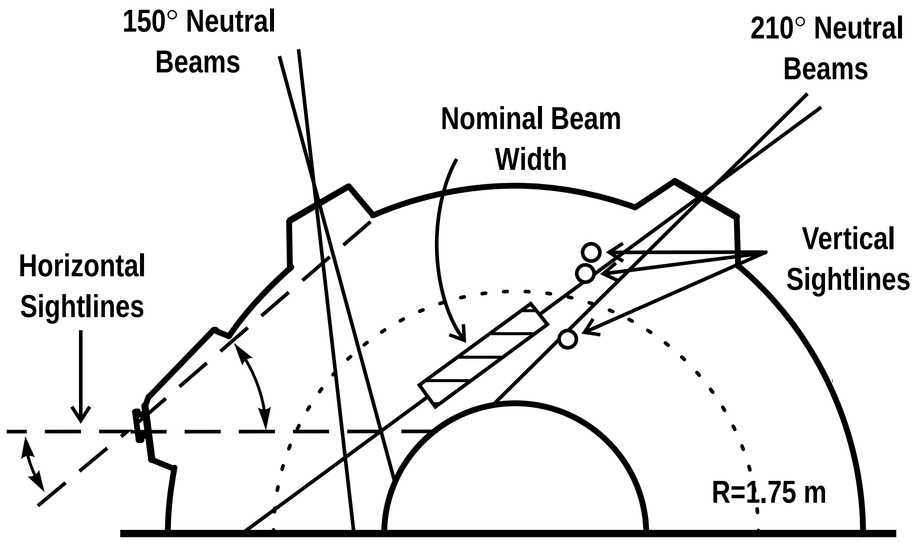

Fig. 2. Plan view of the DIII–D tokamak showing the 150° and 210° degree beam-lines (solid), the horizontal analyzer sightline (dash), and the vertical analyzer sightlines (open circles). For DIII–D, the nominal beam width is 20 cm and is indicated on the figure for the 210° Left beam-line (box with cross-hatches). For clarity, the sightlines for the vertical analyzers have been exaggerated. Also shown (dot) is the magnetic axis of a DIII–D plasma with R = 1.75 m. The horizontal analyzer can scan between the indicated sightlines. Three of the four analyzers can be used for active charge-exchange measurements: the horizontal analyzer with both 150° beams, the innermost vertical analyzer with the 210° Right beam, and the central vertical analyzer with the 210° Left beam.

Four analyzers are currently installed on the DIII–D tokamak: their sightlines, and the centerlines for the 150° and 210° beams, are shown in Fig. 2. Three analyzers are mounted with vertically-viewing sightlines. The one previously installed on the machine retains its horizontal sightline along the midplane.

The strength of stray magnetic fields was a problem at the vertical location so, in the new installation, the vertical analyzers are mounted further away from the vessel at Z = 3.93 m. The stray fields here (1.2, 0.98, and 0.87 kG from R = 1.46, 1.94, and 2.10 m, respectively) are low enough that no additional magnetic shielding is necessary. All three are pumped by a single turbo/backing pump combination.

The horizontally-viewing analyzer, with its own pumping system, rides on a newly-designed cart. The cart is attached to a pivot at the machine end and to a linear bearing mounted on a track at the far end. A welded bellows connects the diagnostic’s vacuum assembly to the vessel port. The cart can pivot from 15° to 60° relative to the line perpendicular to the torus passing through the pivot point; a position transducer [11] measures its position.

At DIII–D, eight neutral beam sources are housed in four beam boxes; for each box, a “Left” and “Right” source inject neutral particles into the torus at tangency radii of R_{tan} = 1.10 and 0.74 m, respectively. For the horizontal analyzer, either source in the 150° beam box can provide a local source of neutrals for active charge-exchange measurements. (Although the horizontal sightline intersects the 210° beam-lines, these sources are ineffective for active measurements since the beam and the escaping neutral particle flux are too strongly attenuated to discern an appreciable signal.) The Left and Right 210° sources can be used as doping beams for the innermost and central vertical analyzers respectively.

Since the horizontal analyzer’s sightline is adjustable, it measures particles with various pitch angles χ. In Fig. 3, χ for detected particles as a function of the major radius R at which the analyzer sightline and the 150° beam-lines intersect is shown. The horizontal analyzer can detect particles with 2°Ù χ Ù 60° while all three vertical analyzers measure particles with χ = 90°. Also shown are the pitch angles of injected neutrals from both 150° beam orientations as a function of the major radius at which they ionize.

Both the neutral density n_0 and the beam-ion distribution function f_b determine the strength of the active charge-exchange signal. The neutral density peaks for large values of R since attenuation of the beam is minimized. On the other hand, for smaller values of R, f_b tends to increase because the detected pitch angle is closer to the pitch angles of the injected beams. A third factor is the beam deposition: this is usually largest near the magnetic axis. For most applications, the horizontal analyzer is set such that the sightline intersects the Left beam at R = 1.84 m since this location is near the magnetic axis.

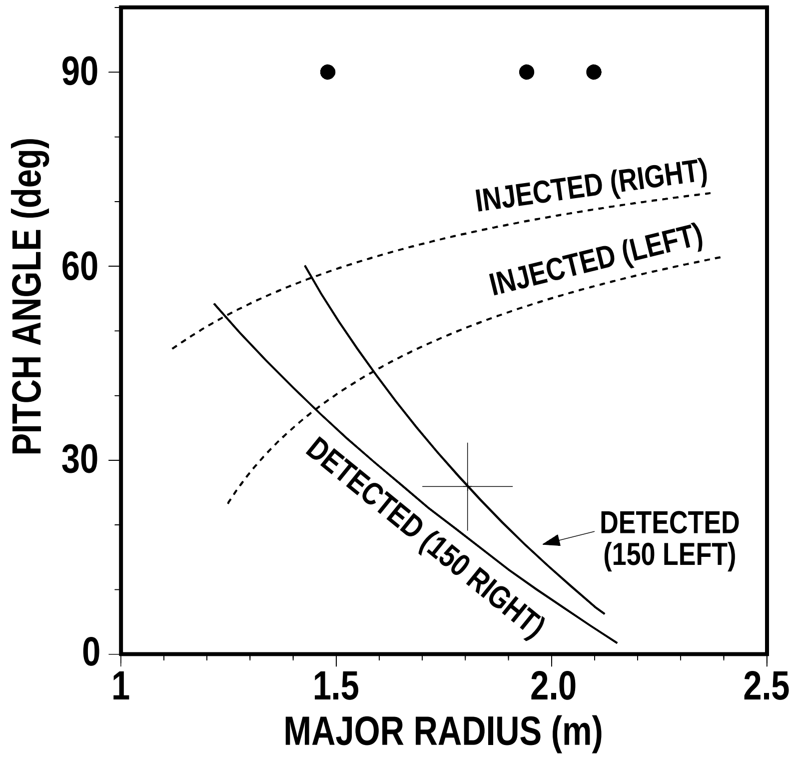

Fig. 3. Pitch angle χ, where $\cos\chi = v_{\phi\supseteq}/v$, versus major radius R. The dashed lines show the pitch angles of ions born near R. The solid lines show the pitch angles accessible to the horizontal analyzer when using the 150° beams for active charge-exchange measurements; the error bar shows the total spread in major radius and pitch angle associated with the beam footprint. (The 1/*e* intensity points are approximately half as large.) The sightlines of the vertical analyzers (circles) are also indicated.

The resolution of the active charge-exchange measurements is determined primarily by the spatial extent of the neutral source provided by the heating beams. For the horizontal measurements, the resolution in major radius is typically ~20 cm (Fig. 3). In contrast, the vertical measurements are well resolved in pitch angle and major radius, but span ~40 cm in the vertical direction.

IV. TOKAMAK RESULTS

Sample data from the horizontal analyzer are shown in Fig. 4(a). Three different sources are employed for this discharge but the beams are programmed so only one source at a time is in use. The analyzer is set to detect ~50 keV particles. The signal more than doubles when neutrals from the 150° neutral beam intersects the analyzer sightline. The background passive signal arises from collisions with edge neutrals. A transition from the L–mode confinement regime to the H–mode occurs at ~1.61 s; this has a larger impact on the passive signal than on the active signal produced by the injected neutrals. To obtain the active signal [Fig. 4(b)], measurements of the beam timing are used to subtract the passive signal from the total signal. As the discharge evolves, the plasma density rises. This reduces the active signal for two reasons: the penetration of the injected 150° neutrals is reduced and reionization losses of escaping neutrals are increased. In order to infer the beam-ion density, it is necessary to correct for each of these effects. Model profiles, atomic cross sections, and the measured line density are used to calculate the corrected data shown in Fig. 4(c). (Work is in progress to develop a computer code that uses the measured density and temperature profiles in a more accurate calculation of attenuation effects.) For this particular orientation of the analyzer, the signals from the Left and Right 150° sources originate from nearly the same position in the plasma; with the attenuation correction, the agreement between the corrected signals from each source is excellent.

This local charge-exchange measurement of beam density is compared with the average beam density inferred from the neutron rate in Fig. 4(c). For the conditions of this discharge, beam-plasma reactions predominate, so the total beam density N_b (averaged over position and fusion cross section) is proportional to the neutron rate S_n divided by the number of target deuterons (which is proportional to the electron density for this DIII–D plasma with a low value of Z_{eff}). In this quiescent discharge, the time evolution of the two signals is similar.

As shown in Fig. 4(c), attenuation effects are modest in low-density DIII–D plasmas ($\overline{n_e}$ Ù 3%10^{19} m^{-3}). However, in high-density plasmas ($\overline{n_e}$ Ú 8%10^{19} m^{-3}), the line density is too large for active-charge exchange measurements. Also, even at moderate values of line density, active charge-exchange measurements from the inside of the torus (Ù1.4 m) are problematic because of the relatively long path lengths.

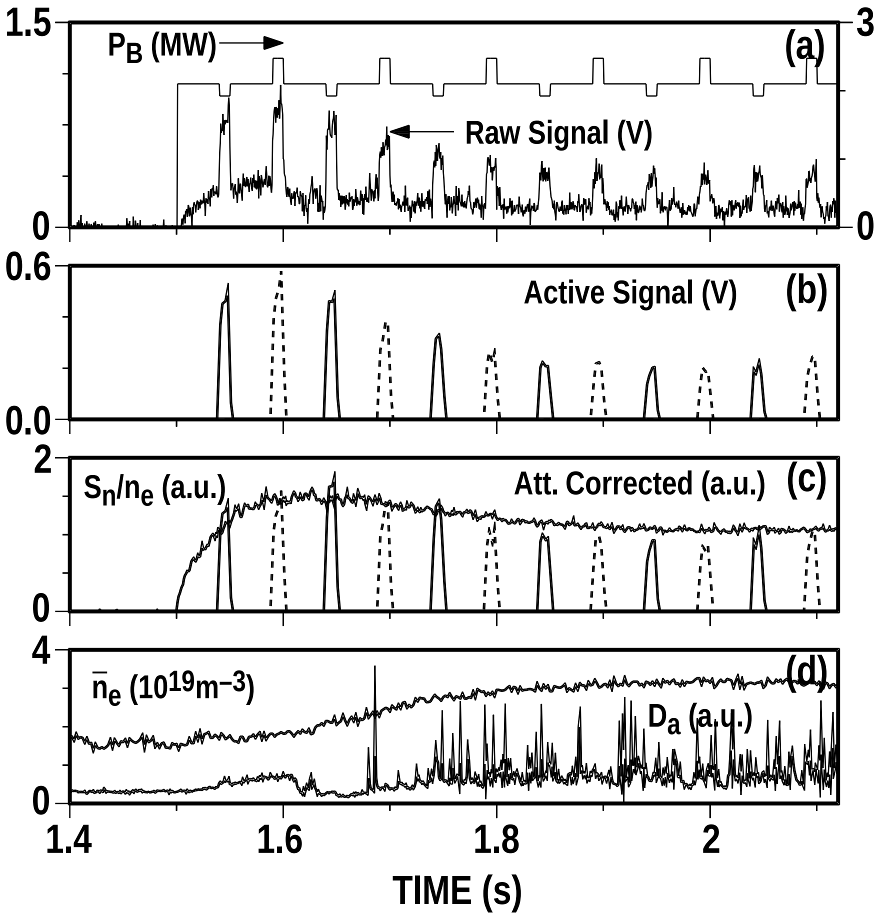

Fig. 4. (a) Time evolution of the injected beam power and the horizontal charge-exchange signal. Although only one neutral beam source injects at a time, three sources are employed: 330° Left (75 kV, 2.1 MW), 150° Left (63 kV, 1.9 MW), and 150° Right (75 kV, 2.5 MW). Neutrals from the 150° Left and Right beams intersect the analyzer sightline at major radii of 2.04 and 2.02 m, respectively. (b) Active charge-exchange signal from the 150° Left (solid) and 150° Right (dash) beams obtained by subtracting the passive signal from the raw signal. (c) Active signals from the 150° Left (solid) and 150° Right (dash) beams including attenuation corrections. The calculations use the experimental values of $\overline{n_e}$ and P_b with model profiles to calculate the attenuation of the neutral beams (modeled as "pencil" beams) and the reionization of the escaping neutrals. Also shown is the neutron rate S_n divided by the line density $\overline{n_e}$, which is an empirical volume-averaged measurement of the beam-ion density. (d) Divertor D_α light and line average electron density from a horizontally-viewing interferometer chord. (Shot #81401: I_p = 0.6 MA; B_T = 2.1 T; double-null divertor configuration.)

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