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Plasma Ion Temperature Measurements via Charge-Exchange Recombination Radiation

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Abstract

Spatially and temporally resolved plasma ion temperatures can be determined by measuring the Doppler-broadened line profiles of transitions excited by charge-exchange recombination reactions between fast hydrogen atoms and fully ionized low-Z ions. Plasma rotation velocity profiles can also be obtained. A sample result from the PDX tokamak using He^+ radiation is presented, and expected line intensities for model cases for PDX and TFTR are calculated.

The measurement of ion temperature is crucial for the understanding of plasma physics experiments. Commonly employed techniques include energy analysis of escaping fast neutral atoms, absolute determination of the thermonuclear neutron production, and measurement of the Doppler broadening of emission lines from partially ionized atoms excited by electron impact.[1,2] Each of these techniques has limitations. For example, the neutron measurements are sensitive primarily to the high energy tail of the ion distribution, and the neutral energy analysis becomes less suitable as plasma density increases. Likewise, the photon measurements rely on the presence of heavy ions of increasingly higher atomic number as the electron temperature increases.

We describe here a technique for measuring ion temperature profiles which overcomes these limitations and is applicable for large, hot, dense plasmas. The approach consists of measuring Doppler-broadened profiles of low-Z impurity spectral lines which are excited by charge transfer collisions between fully ionized low-Z impurity ions and fast hydrogen atoms from a doping neutral beam or a heating neutral beam. The charge transfer collision

$$H^0 + A^{+Z} \rightarrow H^+ + A^{+Z-1}(n,\ell) \qquad (1)$$

produces hydrogen-like ions in excited states (n,ℓ) which decay through photon emission. The cross sections for such processes are large ($> 10^{-16}$ cm^2), with the results that measurable intensities can be obtained with moderate neutral densities. Low-Z impurities are predominantly fully ionized at usual tokamak electron temperatures and thus do not radiate strongly. They are also sufficiently abundant at all radii in the plasma under normal conditions that no artificial contamination of the plasma with the impurity atoms is necessary. Radiation induced by reaction (1) has already been used to measure fully ionized impurity densities by using either a diagnostic neutral beam, as in the T-10[3] and PDX[4] tokamaks, or a heating neutral beam, as in ISX-B.[5]

Good spatial resolution is obtained by viewing across a collimated neutral beam with a collimated spectrometer, and hence no prior knowledge of impurity distributions or use of Abel inversions is necessary. Judicious choice of the beam injection angle and the spectrometer viewing direction also allows spatially resolved measurements of plasma rotation velocity in either the toroidal or poloidal directions. This information is available with the ion temperature measurements simply by determining the shift of the spectral line along with its width. Such measurements of toroidal rotation in the ISX-B tokamak have recently been reported by Isler.[6]

For ions such as He^{+}, C^{5+}, and O^{7+}, the wavelengths of the emissions produced by (1) range from the extreme UV to the visible. Zeeman and Stark effects are usually negligible in the magnetic field and density ranges of interest, and thermal broadening dominates the line profile. For typical tokamak parameters ($T_i > 0.5$ keV), these line widths can be resolved with conventional spectroscopic instrumentation.

A test has been made on the PDX tokamak to demonstrate the determination of temperature via reaction (1). Ohmically heated discharges with a minor radius of 40 cm, $T_e(0) = 700$ eV and $n_e(0) = 1.7 \times 10^{13}$ cm^{-3} were used. The experimental set-up has previously been described in Ref. 4. In brief, a low power (8 kW) diagnostic H° neutral beam (28 kev) injects tangentially into the PDX plasma across the line of sight of a grazing incidence bichromator. The intersection of the highly collimated diagnostic beam and the spectrometer line of sight was at a minor radius of 5 cm. The beam pulse was 20 ms long and modulated by a 500 Hz square wave, which allows discrimination against unmodulated background plasma light.

Measurements of He^+ 304 Å (2-1) radiation were made since He was the lightest impurity in the H^+ discharge and thus had the largest broadening. The spectrometer resolution was low ($\Delta\lambda_I$ = 1Å) and shot-to-shot measurements of the line profile were made in third order of diffraction. A sample raw signal and its cross-correlation with a 10 pulse square wave are shown in Fig. 1. The cross-correlation at zero phase time is proportional to the average intensity induced by the neutral beam. The steady-state background intensity in the raw signal is due to electron impact excitation of HeII at the cool plasma edge.

Spectral scans of the charge-exchange induced signal and the intrinsic 304Å radiation are shown in Fig. 2, and the solid lines show least squares fits of the data to gaussian profiles. A quadratic background is added to the Gaussian for the fit in Fig. (2(b) to account for scattered light in the spectrometer. Since this light is predominantly from the strong edge radiation, it is unmodulated.

Using the fitted Gaussian of Fig. 2(b) as the instrumental function, the near central ion temperature is found to be 550 ± 200 eV. For comparison, the conventional passive charge-exchange ion temperature for this plasma was 450 ± 50 eV.

The noise level in these measurements is due mostly to photon statistics, and the large uncertainty in T_i results from the low light levels reaching the detector. The etendué of the grazing incidence spectrometer is low, and no attempts were made to optimize spectrometer performance for these particular measurements. Employing multichannel detection with a spectrometer with high etendué would produce a significantly lower uncertainty, of course, as would a stronger neutral beam.

To investigate the applicability of this diagnostic to present experiments, expected line intensities have been calculated for two cases of interest in which the technique could be employed as a routine diagnostic: 1) PDX tokamak using the perpendicularly injected heating neutral beams (D°, $\lesssim$ 1.5 W at 50 keV); and 2) TFTR using the steerable diagnostic neutral beam (D°, 0.7 MW at 80 keV).[7] The TFTR diagnostic beam will be modulated while the PDX heating beams are not. The calculations were performed assuming parabolic plasma density profiles, a radial beam injection geometry and a tangential sightline for the spectrometer. Results for several transitions of common low-Z impurities (chosen for ease of observation and maximum brightness) are shown in Fig. 3. In all cases, cascade-corrected cross sections were calculated for the transition of interest using Ref. 8 for cross sections for discrete (n,ℓ) states of C^{5+}, Ref. 9 for O^{7+}, and Ref. 10 for He^{+}. Neutral beam particle densities were calculated via beam attenuation codes.

Although weak, the upper level HeII lines are of interest because of their long wavelengths, where simple optics can be used. Likewise, higher level transitions of C^{5+} and O^{8+} other than those shown in Fig. 3 may allow measurable lines above 1200 Å. However, the ratio of the fine structure splitting to the expected Doppler widths should be considered as the level of excitation increases for a given ion species.

The line intensities and widths calculated for PDX and TFTR are measurable with available spectroscopic techniques, but care must be taken to optimize sensitivity to obtain accurate line profiles. Given both the complexity and limited access of large tokamaks, spectrometer systems with both spectral and spatial imaging capabilities are most desirable for these measurements.

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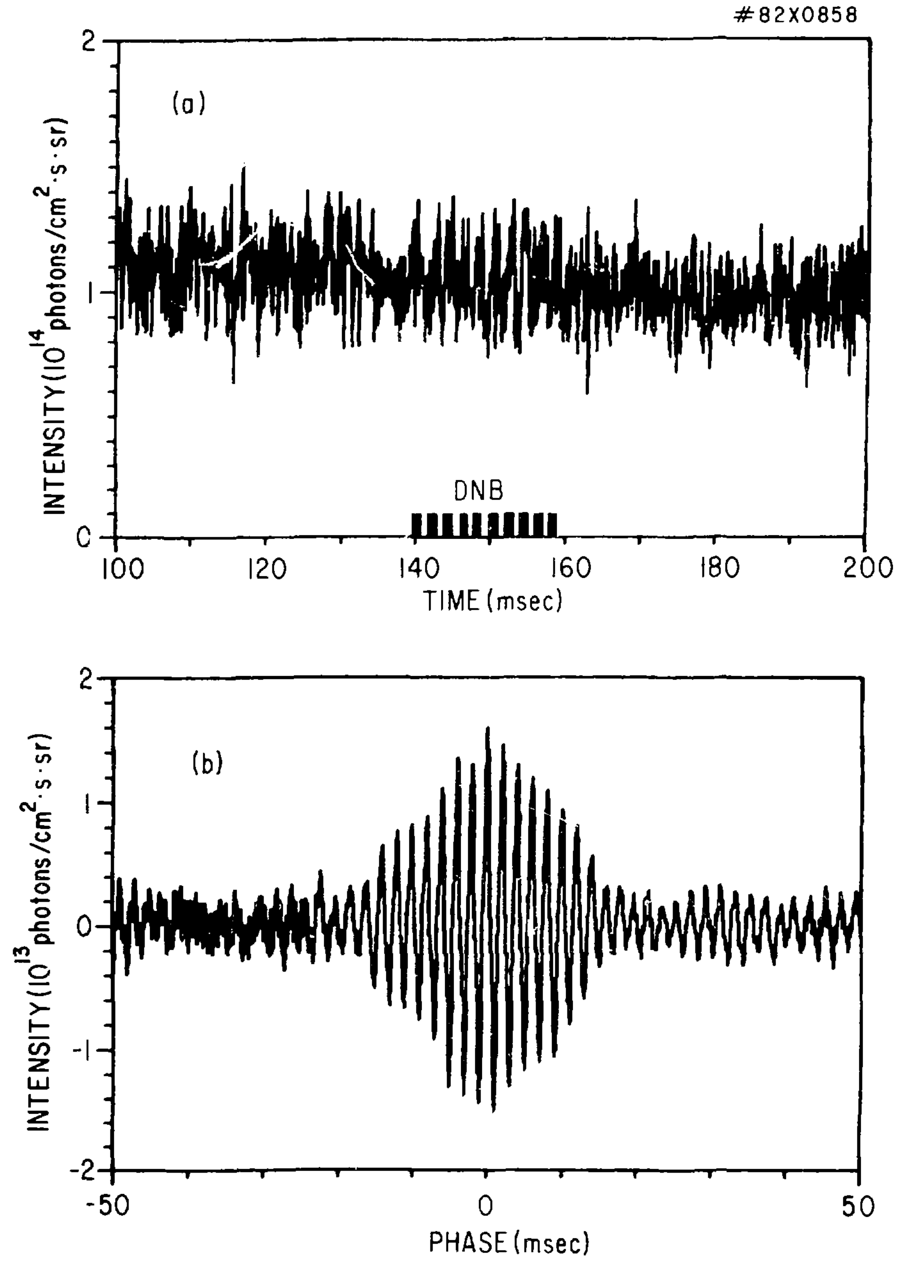
Figure Captions

Fig. 1 Charge-exchange excitation of He^+ 304Å. (a) raw signal with the times of injection of the diagnostic beam. (b) cross-correlation of the data in (a) with a 10-pulse square wave.

Fig. 2 Line profiles of He^+ 304Å in third order of diffraction. (a) charge-exchange induced signal from r = 5 cm. (b) intrinsic background light from the plasma periphery.

Fig. 3 Intensities of charge-exchange induced signals for model cases for PDX and TFTR. The impurity concentrations are assumed constant with $n_Z/n_e = 0.005$. The values plotted are for the spectrometer and beam intersection volume at the plasma center. Key to labels: OVIII: 1 = 3-2 (102Å), 2 = 4-3 (292 Å), 3 = 5-4 (633 Å); CVI: 4 = 3-2 (182 Å), 5 = 4-3 (521 Å); HeII: 6 = 2-1 (304 Å), 7 = 3-2 (1640 Å), 8 = 4-3 (4686 Å).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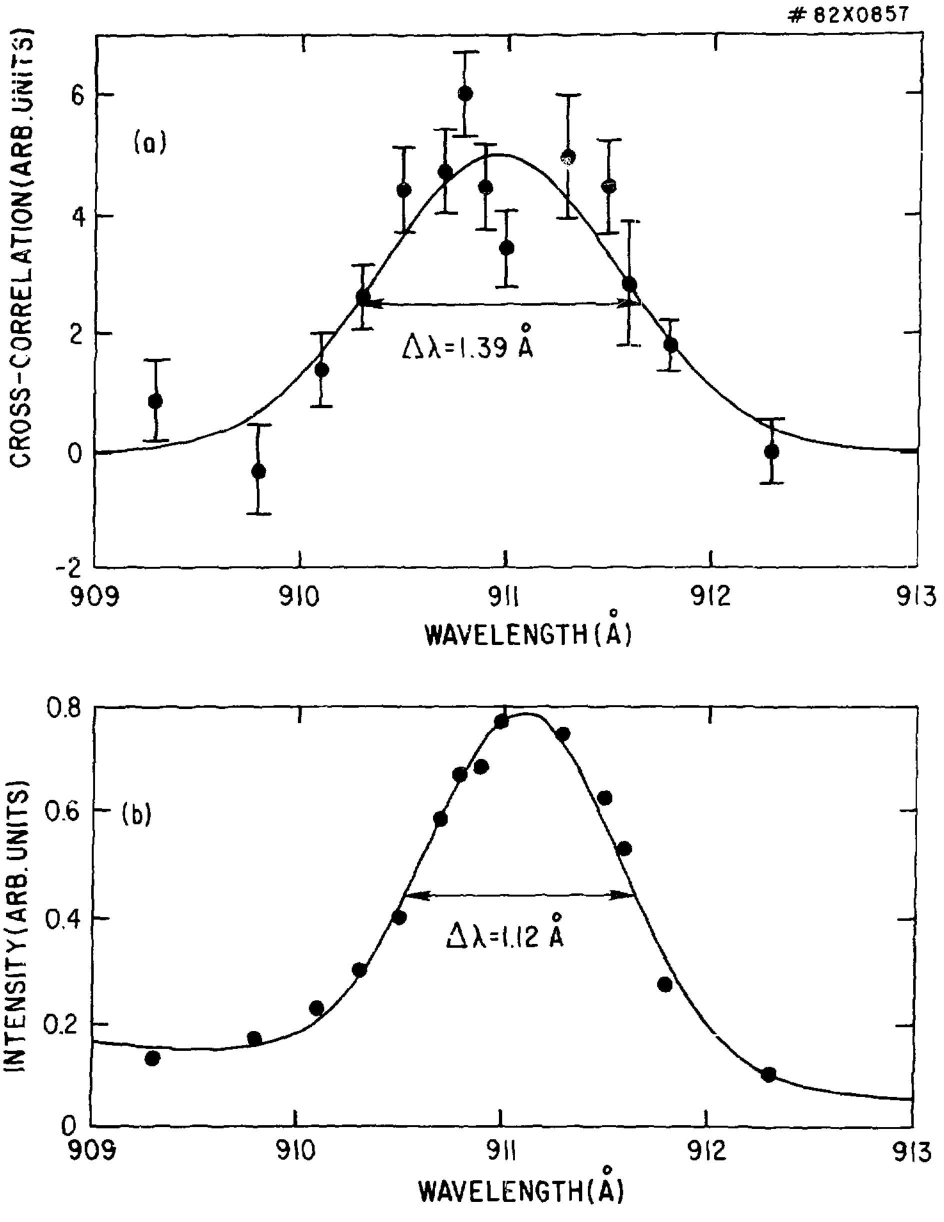
1
0
DNB
100
120
140
160
180
200
TIME (msec)
(b)
INTENSITY(10^{13} photons/cm^2·s·sr)
2
1
0
-1
-2
-50
0
50
PHASE (msec)

Fig. 1



82X0857
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2
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-2
Δλ=1.39 Å
909
910
911
912
913
WAVELENGTH (Å)
(b)
INTENSITY (ARB. UNITS)
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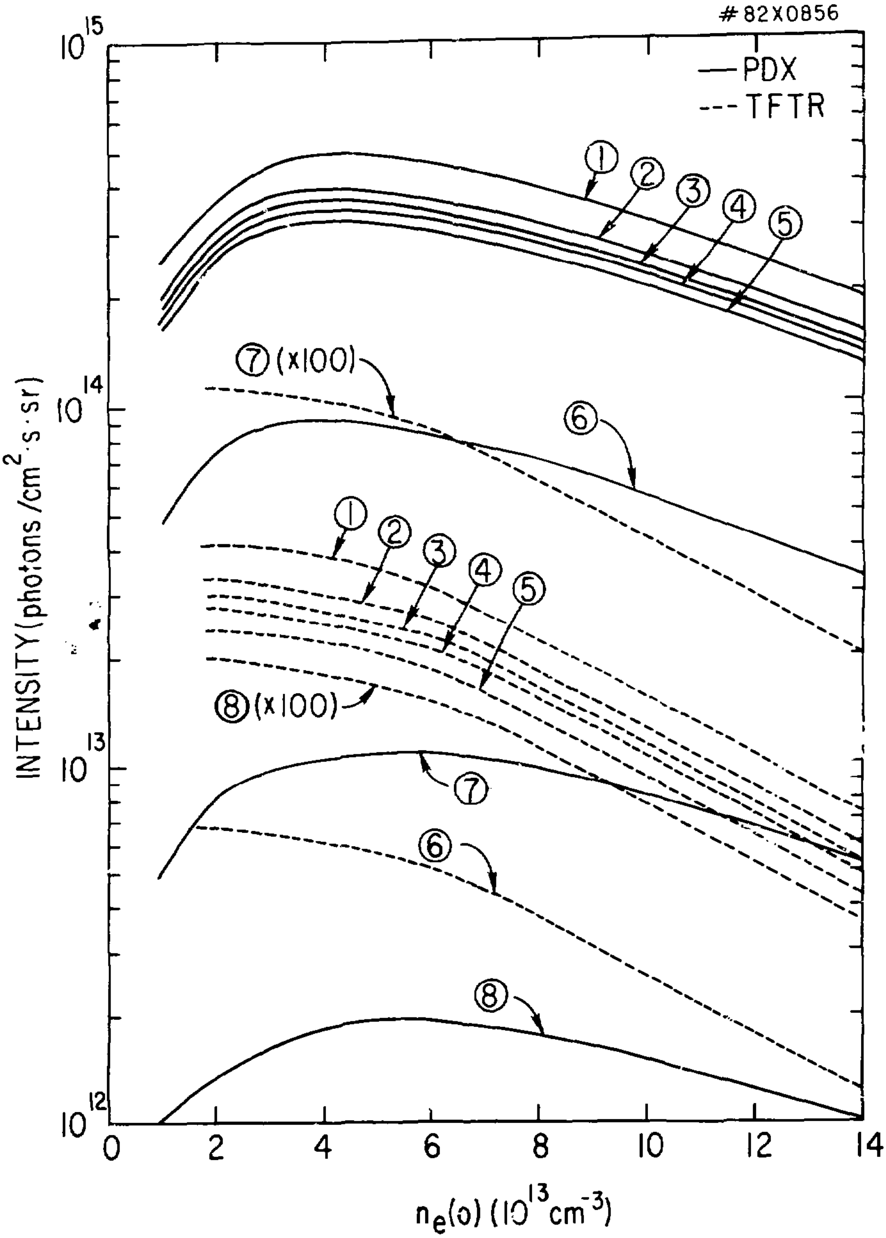
0.4
0.2
0
Δλ=1.12 Å
909
910
911
912
913
WAVELENGTH (Å)

Fig. 2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---TFTR
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10^{14}
10^{13}
10^{12}
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2
4
6
8
10
12
14
$n_e(o)$ (10^{13}cm^{-3})
①
②
③
④
⑤
⑦(x100)
⑥
①
②
③
④
⑤
⑧(x100)
⑦
⑥
⑧

Fig. 3