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Space- and time-resolved measurements of ion temperature with the CVI 5292-Å charge-exchange recombination line after subtracting background radiation

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An ion temperature profile has been obtained with the CVI 5292-Å ($n = 8-7$) charge-exchange recombination (CXR) line using a space- and wavelength-resolving visible spectrometer installed on the JIPP TII-U tokamak. Two sets of 50-channel optical-fiber arrays, one viewing a fast neutral hydrogen beam (CXR channels) and the other viewing off the neutral beamline (background channels), are arranged on the entrance slit of the spectrometer. This spectrometer is coupled to an image intensifier and CCD detector at the focal plane, and provides a temperature profile every 1/60 s. An ion temperature is derived from the Doppler-broadened line profile after subtracting the simultaneously measured cold component (background channels), which is due to electron excitation and/or charge-exchange recombination in the plasma periphery. An alternative approach to obtain the ion temperature profile without CXR is also demonstrated. This method is based on an Abel inversion technique for each wavelength separately.

INTRODUCTION

Space- and time-resolved measurements of ion temperature and electric field inferred from the rotation speed near the plasma edge are crucial for the proper understanding of η_i mode or H-mode transition in a tokamak plasma. Charge-exchange recombination spectroscopy (CXRS) has recently been routinely used for the measurement of ion temperature and toroidal rotation velocity profiles, since it has the advantage of providing multichord data using optical fibers.¹⁻³ Charge-exchange collisions typically between fully ionized ions of a light impurity [e.g., (C^{6+})] and hydrogen or deuterium atoms in a heating or diagnostic fast neutral beam (NB) result in an excited ion with one more electron [e.g., C^{5+} ($n = 8$)]. This process is expressed as

Here n_1 and n_2 are the upper and lower levels of the excited state, respectively. Ion temperature, rotation velocity, and impurity abundance can be inferred from the Doppler broadening, Doppler shift, and line intensity, respectively. The measurement is restricted within the intersection region of the fast neutral beam and the line of sight. A spectral line is also produced by electron excitation and/or charge-exchange recombination of background thermal neutrals in the plasma periphery. These reactions are

and

This background radiation from the cold plasma edge is

called a cold component and is of significant contribution to the radiation from CXR reactions of the fast neutral beam with helium and carbon impurities, while it is negligible for fully ionized oxygen.⁴ The background radiation is not restricted within the intersection of the beamline and the line of sight, and is instead a chord integrated along the line of sight.

Some techniques to avoid contamination by background radiation have been studied on tokamaks, in which the oxygen concentration is too low to measure the charge-exchange recombination line in oxygen lines in the visible region. A nonlinear least-squares fit to two Gaussians was applied to obtain the central ion temperature and rotation velocity from the measured He II 4686-Å line profile in doublet III.³ The narrower of the two Gaussians corresponds to radiation from the cold plasma edge, while the wider and shifted Gaussian corresponds to radiation from the hot central region. Another approach is to chop the diagnostic neutral beam to subtract background as C^{5+} light from the charge-exchange recombination line of fully stripped carbon tried in Poloidal Divertor Experiment (PDX).⁵ In this paper, we present a third approach using two sets of optical-fiber arrays viewing on and off the neutral beam line and a two-dimensional detector to measure multichordal charge-exchange recombination-line profiles [CVI 5292 Å ($n = 8-7$)] and background light simultaneously. The advantage of the two-dimensional detector is that it gives plenty of spatial channels (50 channels in our case), while it is difficult to obtain a large number of channels by using a linear array of photodiodes (eight channels in DIII-D⁶). In their system, the product of spatial channels (eight channels) and spectrum channels (about 80 channels) is limited by the number of pixels of a linear array of photodiodes (1024 pixels).

1. APPARATUS

The current CXRS system for ion temperature profile measurements on JIPP TII-U is shown in Fig. 1. Two small

FIG. 1. Schematic of the experimental setup on JIPP TII-U for charge-exchange recombination spectroscopic measurements of ion temperature profiles. Array (a),(b) is viewing the heating fast neutral beam, while the other array, (c),(d), is viewing off beamline.

aluminum-coated mirrors are set inside the vacuum vessel to obtain midplane tangential view. The view of the optics is limited by these mirrors. Unfortunately, these viewing arrays provide only the information from 95 to 115 cm (outer half of the plasma), although the optical-fiber arrays themselves have wider views. However, this viewing limitation will be eliminated easily in future. These two viewing arrays installed in the tokamak look simultaneously towards the source of the CXR light and away at background light. The objective lenses are made of quartz with a focal length of 10 mm. The effective spot size of the image fibers at the intersection point with the neutral beam is from 4 to 5 mm. Two sets of 50-channel 125- μ m-diam optical fibers (100- μ -core) are led into the entrance slit of a 0.5-m Czerny-Turner spectrograph with a 2400-grooves/mm grating. At the exit plane the light from each fiber gives the spectrum from one spatial position. The light from all of the fibers is focused onto an image-intensifier tube (Hamamatsu V2697U) coupled with a CCD TV camera with 2:1 image reduction. The image of the slit at the exit plane is distorted because of the large slit height (12.5 mm). The distortion is

$$\delta x = m\lambda / (dR \cos \beta) z^2$$

where m and λ are the order and wavelength of interest; d , R , β , and z are the groove spacing of the grating, the focal length, the exit angle of the spectrograph, and the distance from the center of the slit, respectively. This shift δx is 100 μ m at the edge of the slit for our spectrograph, which corresponds to a shift of wavelength of 0.8 $\text{\AA}$. This image distortion is precisely calibrated using our CCD detector and a mercury lamp, and is corrected in software for the actual measurements.

The spatial resolution of the image intensifier is 8 lines/mm for modulation transfer function (MTF) = 50%, and 25

lines/mm for MTF = 5%, while the spatial resolution of the CCD detector is much better (13 μ m). This spatial resolution for MTF = 50% corresponds to 1- $\text{\AA}$ instrumental width (FWHM) and to an exact spacing of optical fibers (0.125 mm) in perpendicular direction on the entrance slit of the spectrograph. These spectrum and perpendicular spatial resolutions are equivalent to 73 eV for CVI 5292 $\text{\AA}$ and to 5–6-mm spatial resolution at the intersection point with neutral beam, respectively. The minimum measurement ion temperature is 50–100 eV, depending on the strength of the detected light. Optical fibers from (a) to (b) in Fig. 1 are viewing the neutral beamline, while fibers from (c) to (d) are viewing off the neutral beamline to subtract the background due to electron impact excitation of C^{5+} and charge-exchange recombination reactions of C^{6+} with thermal background neutrals. This arrangement of the optical fibers enables us to specify the exact nonshifted central wavelength (without toroidal rotation) by taking the average of the measured line centers for the two viewing directions when the neutral beams are not on and assuming toroidal symmetry.

The output of the CCD detector is a standard TV composite video signal, and it is digitized by a Lecroy model 6810 digitizer (12-bit accuracy, 5-MHz sampling, and 512-kword memory). The data is transferred to a micro-VAX II super minicomputer. This computer has 16 MB of memory, three 456-MB magnetic disks, a 2.6-GB optical disk, a cassette streamer, and magnetic tape drive. The TV data consist of 1 MB/shot, and the other JIPP TII-U shot data add up to approximately 1.5 MB/shot. Our TV camera has two scan modes (1/60 s per scan): one is an internal scan and the other is an externally synchronized scan. It takes at most six scans to change the mode from internal to external. Figure 2 shows a diagram of the clock generator circuit which pro-

FIG. 2. Diagram of clock generator for the Lecroy 6810 data-acquisition system for the CCD detector composite video signal.

duces the pretrigger for the CCD camera, and the start trigger and clock bursts for the Lecroy 6810 in order to synchronize the TV frame scan to the plasma discharge. The video signal is clamped to avoid dc offset; then horizontal and vertical synchronization negative pulses are separated. Both vertical and horizontal synchronization pulses produce clock bursts that sample only the positive video signal and skip the negative synchronization pulses. The CCD pretrigger is typically 100 ms (for six frames) before the ADC start trigger ("frame delay" in Fig. 2), since the CCD scan circuit needs at most six frames to switch from an internal to externally synchronized scan. This circuit also enables us to specify the frame window (first and last horizontal line) to be digitized. By not digitizing and saving horizontal lines that correspond to wavelengths outside the region of interest, we are able to save more frames in the available 512-kword of digitizer memory. For example, if the entire picture is digitized, only eight frames (corresponding to 133.3 ms of data) can be saved. But if only one-fourth of the entire wavelength region contains useful information, we can extend the time during which we can take data by a factor of 4 by not saving the part that is not useful. The position of this frame window (i.e., the line numbers of the first and last horizontal lines saved) is read out and stored by the micro-VAX II. By mechanically rotating the CCD camera through 90°, the vertical axis of the video picture can be made to correspond to plasma position instead of wavelength, in which case the frame window is a spatial instead of a wavelength window.

The response of a standard TV camera is intentionally not linear. The so-called γ correction circuit boosts low-level signals and reduces high-level signals to compensate the nonlinearity of TV monitors (monitor output is roughly proportional to input square). This correction circuit masks the intrinsic linearity of the CCD detector. However, we can regain the intrinsic linearity of the CCD response as well as of the image-intensifier tube by removing this γ correction circuit (Fig. 3). The linear response is obtained up to the 80% of the saturation level ($V_{p-p} = 1$ V) of the CCD detector, while the noise level of the output is mainly due to dark

FIG. 3. Linearity of CCD detector coupled with image-intensifier tube. The solid line is a response of the output without the γ correction circuit, while the dashed line is the response with the γ correction.

current of the image-intensifier tube. The absolute calibration of the system from the objective lenses through to the CCD chain has been done by using a standard lamp. We calibrated an output of the CCD camera with γ correction circuit OFF for the standardized spectral radiance at the wavelength of 5292 Å. A neutral density (ND) filter which was calibrated elsewhere was used to reduce the output level to the appropriate level (50%–80% of the saturation level). The space nonuniformity of the system is mostly due to the objective lens and coupling lens between the image-intensifier tube and the CCD camera. We found light losses for the optical fibers near the edge of the objective lens both for the channels viewing the neutral beam injector (NBI) beam path and the other channels viewing the background as shown in Fig. 4 [channels (a), (b), (c), and (d) in figure]. The asymmetry is due to the coupling lens, since (a) and (d) are the edge channels while (b) and (c) are the center channels of this coupling lens.

II. ION TEMPERATURE PROFILE

Figure 5 shows space-resolved spectra for the charge-exchange recombination line CVI (5292 Å, $n = 8-7$) both

FIG. 4. Nonuniformity in space of the CXRS system. Solid line is the relative output for the channels viewing the NBI beamline, while the dashed line is for the channel viewing the background. The viewing point of the edge fibers (a)–(d) is shown in Fig. 1.

FIG. 5. Three-dimensional plot of the charge-exchange recombination line CVI (5292 Å, $n = 8-7$) for the arrays viewing the (a) background and (b) NBI beamline measured in a JIPP TII-U NBI-heated plasma, where $\delta\lambda = 5292 - \lambda$.

for the array viewing the background [Fig. 5(a)] and viewing the NBI beam path [Fig. 5(b)]. The line profile in Fig. 5(b) is much broader than that in Fig. 5(a), since Fig. 5(a) corresponds to the cold component emitted from plasma-edge region and Fig. 5(b) corresponds to the superposition of cold and hot components. The hot component is emitted from the intersection of the fast neutral beam and the line of sight of the optics, in a region of the hot plasma. The resolution of the spectrum channel is 0.4 Å. We subtract the background light from the light emitted from the intersection of the NBI beamline with the line of sight and then perform a Gaussian fit with constant base line taking account of instrumental width. The spatial averaging over two channels is performed to improve the signal-to-noise ratio, and our system has effectively 25 spatial channels for these measurements of ion temperature profile.

The ion temperature profiles obtained with these processes for a 0.7-MW NBI-heated plasma and for a plasma heated by a combination of 0.7-MW NBI and 1.4-MW ion cyclotron range of frequency (ICRF) heating are shown in Fig. 6. The error bars consist of the statistical error from

FIG. 6. Ion temperature profile measured in JIPP TII-U for 0.7-MW NBI-heated plasma and for NBI- (0.7 MW) plus ICRF- (1.4 MW) heated plasma. The solid line is the ion temperature profile corrected by the subtraction of background light, while the dashed line is the ion temperature profile without the correction. The data points are an average of two optical fibers.

fitting the Gaussian profile and the uncertainty in the base line. The plasma current is 220 kA for these discharges, while the central electron density $n_e(0)$ is 0.65 and $1.0 \times 10^{14} \text{ cm}^{-3}$ for NBI and NBI + ICRF-heated plasmas, respectively. The central ion temperature before neutral beam injection is 0.5–0.6 keV, which is measured with a five-channel fast neutral analyzer. Also shown in Fig. 6 is the uncorrected ion temperature profile determined by fitting Gaussian profile to the measured spectrum before the background is subtracted. The difference of the ion temperature with and without the background correction for the NBI + ICRF-heated plasma is significant, while the ion temperature correction for NBI only is relatively small. This is due to the larger ion temperature difference between the hot and cold components, and the relatively higher background level for the NBI + ICRF case. The uncorrected ion temperature profile is broader than that with the correction due to the cold component, in the plasma core region. The value of the central ion temperature for the NBI + ICRF-heated plasma agrees with the value determined from the width of the Ti XXI K_α line ($T_i = 1.8 \pm 0.3 \text{ keV}$) at the plasma core (averaged over $r < 6 \text{ cm}$) measured with an x-ray crystal spectrometer.

The impurity radiation measured without charge-exchange recombination reactions with fast neutral beam atoms is a line integral of the emission along the line of sight, and position information is masked by the integration. An ion temperature profile can be estimated from the integral, and the location of the measurements is calculated using an impurity transport code with measured electron temperature and electron density profiles, and an assumed transport coefficient (usually a diffusion coefficient and convective velocity). The spatial resolution is very poor in this method, since impurities are spread somewhat broadly near the plasma center because of the low electron temperature gradient. Recently, an ion temperature profile was measured using the far-line wings of H_α ; however, the neutral profile should be estimated from results of the neutral deposition code.⁷

FIG. 7. Ion temperature profile measured in JIPP TII-U for NBI- (0.7 MW) plus ICRF- (1.4 MW) heated plasma with only background channels using an Abel inversion technique for each wavelength. The data points are an average of two optical fibers.

We here demonstrate a new technique to obtain the ion temperature profile with better spatial resolution without using CXR reactions with fast neutral beam atoms. This technique enables us to obtain ion temperature profiles for ohmic or ICRF-heated plasmas. The accuracy of an Abel inversion depends on the density of the viewing chords and on the emission profile. The density of our viewing chords is 100–200 per R_a depending on the location, where R_a is the outermost inversion radius. R_a is the minor radius for a poloidal Abel inversion and the major radius for a toroidal Abel inversion. This is much more dense than the usual Abel inversion arrangement (typically 5–10 chord/ R_a). To achieve this density of chords, we use the same arrays of 50 fiber-optic channels as in the CXRS measurement. The spectrum for each location calculated by intensity Abel inversion for each wavelength separately is accurate enough to obtain the local ion temperature, as shown in Fig. 7. The ion temperature profile obtained using this Abel inversion technique from the background channels agrees well with that obtained using CXRS from the channel viewing the NBI beam-line, although the error bars on the ion temperature calculat-

ed from the Abel inversion technique are larger those from CXRS near the plasma center because of the so-called Abel inversion error.

The ion temperature profile measured with CXRS is somewhat smoothed because of the integration within the beamwidth. The actual spatial resolution depends on the angle of the line of sight to the toroidal magnetic field line, since the ion temperature is constant along the magnetic field. This actual spatial resolution is relatively poor near the plasma center, where the gradient of the ion temperature is usually small, and is improved up to 1 cm, especially in the plasma-edge region, which will enable us to study plasma-edge physics.

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