J. Plasma Fusion Res. SERIES, Vol.1 (1998) 370–373

Apparent Wavelength Shifts of H-like Ions Caused by the Spectral Fine Structure Observed in CHS Plasmas

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(Received: 30 September 1997/Accepted 22 October 1997)

Abstract

A new charge exchange spectroscopy (CXS) system viewing the plasma from the upside and the downside simultaneously was installed on the Compact Helical System (CHS) to detect the absolute value of Doppler shift due to poloidal rotation velocity (< 5 km/s). The apparent Doppler shift, not due to plasma rotation, in charge exchange excited spectral lines is observed in the plasma peripheral region ($T_i \sim 100$ eV) and in the after-glow recombining phase ($T_i \sim 30$ eV). The apparent Doppler shift is always red-shift regardless the direction of plasma rotation and is explained as the effect of the spectral fine structure of hydrogen-like ions.

Keywords:

charge exchange spectroscopy, poloidal rotation, fine structure, CHS, Heliotron/Torsatron

1. Introduction

The spectroscopic measurements of plasma rotation are widely used to estimate radial electric fields in magnetically confined plasmas. Radial electric field and rotation velocity should have variation on the magnetic surfaces since the gradient of electrostatic potential and ion pressure are considered to be surface quantities. Especially, the asymmetry of poloidal rotation velocity appearing in the inside and the outside of magnetic axis is important to study the toroidal effect on the plasma rotations. However, the study of this asymmetry has never been done. Moreover, in medium sized Heliotron/Torsatron devices[1,2], typical poloidal rotation velocities are less than 5 km/s, and these values are small compared with the edge poloidal rotation velocity in H-mode plasma in tokamaks[3-6]. To detect the inside/outside asymmetry of the rotation velocity in this range, the precise measurement of Doppler shift is required. There are several problems that come from the offset of wavelength in spectrometers, the interference lines nearby and so on. In order to measure real Doppler shift, the bidirectional viewing fiber arrays for charge exchange spectroscopy (CXS)[7] have been installed in the Compact Helical System (CHS).

In this paper, the calibration and analysis technique to measure the absolute value of poloidal rotation velocity in the order of 1 km/s are described. Especially, the apparent Doppler shift due to the spectral fine structure of hydrogen-like ions, which are used in CXS, observed in CHS plasmas is presented.

2. Experimental Setup

Figure 1 shows the schematic arrangement of the charge exchange spectroscopy. CHS is a Heliotron/Torsatron type helical torus with the major radius of $R=1$ m, the averaged minor radius of $a=0.2$ m and the magnetic field strength of < 2 T. It has two tangential neutral beams for heating. The accelerating voltage and the injected power of each beams are < 40 kV and < 1 MW respectively. Charge exchange spectral lines from one of these beam lines (NBI#1) are used for

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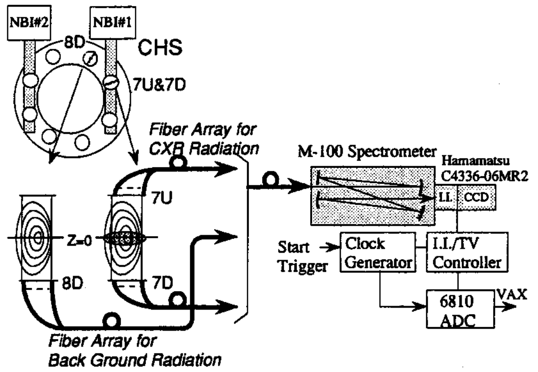

Fig. 1 The schematic of the optical system and the experimental arrangement. This system uses two fiber arrays viewing the beam from port 7D and 7U simultaneously, and one more fiber array to measure the background radiation at port 8D.

spectroscopic measurements of ion temperature and poloidal rotation. To measure the real Doppler shift canceling the wavelength offset of the spectrometer, this measurement system has two fiber arrays viewing the plasma from upper and lower port simultaneously at the vertically elongated section (port 7D and 7U), and the average of the wavelength measured from both sides gives the wavelength without Doppler shifts ($\Delta\lambda=0$). And it uses one more fiber array to measure the background radiation[8] at another vertically elongated section (port 8D). All of these fibers (90 ch) are connected to the entrance slit of a spectrometer and the diffraction pattern is detected by a CCD camera with an image intensifier.

The spectrometer itself has intrinsic apparent wavelength shift depending on fiber channels arranged in the vertical direction. Figure 2 shows this dependence calibrated with Hg line ($\lambda=366$ nm, 435 nm, 546 nm). The local structure of this dependence comes from fiber position error in horizontal direction because the diameter of fibers in this system is smaller than the slit width. And the global structure of this dependence comes from the distortion of diffraction patterns which depends on wavelength. This shift is corrected in the derivation of the spectral profiles from the CCD image.

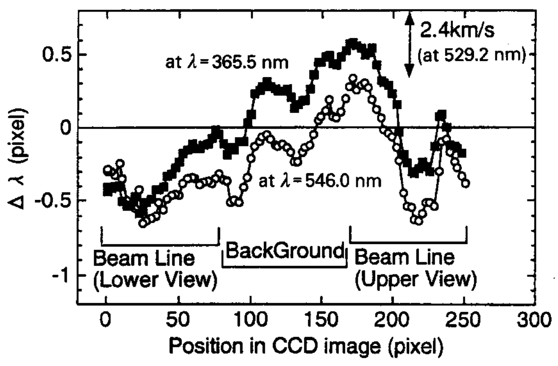

Fig. 2 The dependence of wavelength shifts $\Delta\lambda$ on the position in vertical direction of the diffraction pattern (CCD image). Marks ○ and ■ indicate fiber channels.

3. Result and Discussions

The wavelength shifts measured from the upper and lower viewing array should have the same magnitude of Doppler shifts in the opposite direction (*i.e.* one is the blue shift and the other is the red shift) at each observation chords. The measurement result of a charge exchange spectral line (CVI; $\Delta n=8-7$, $\lambda_{vacuum}=529.2$ nm) given by single Gaussian least square fitting, however, doesn't have this up/down symmetry of wavelength shifts. Figure 3 shows the spatial distribution of this wavelength shifts. In the outside of plasma center, the upper viewed spectral line shows red-side shift while the lower viewed one shows blue-side shift. Although this direction is consistent with the expected plasma rotation, the magnitude of the shifts measured from up and down sides differs from each other nearly by factor 2 in the peripheral low ion temperature ($T_i\sim 100$ eV) region. These shifts include the apparent shift to red-side of the CVI line itself not due to plasma rotation.

One more example of apparent shifts given by single Gaussian least square fitting was observed in a CVI line ($\Delta n=7-6$, $\lambda_{vacuum}=343.5$ nm) in after-glow recombining phase with the ion temperature of 30 eV as shown in Figure 4. The wavelength shifts measured from the up and down sides show the real Doppler shift

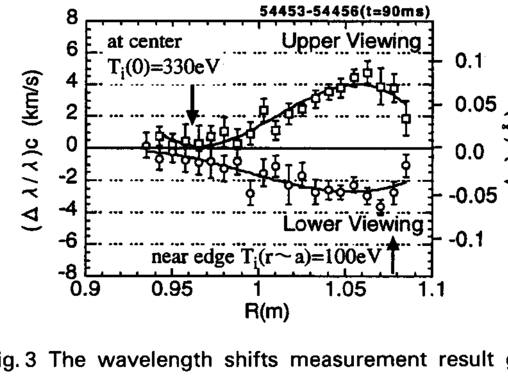

Fig. 3 The wavelength shifts measurement result given by single Gaussian fitting at the upper and lower viewing chords (CVI; Δn=8-7, λ=529.2 nm).

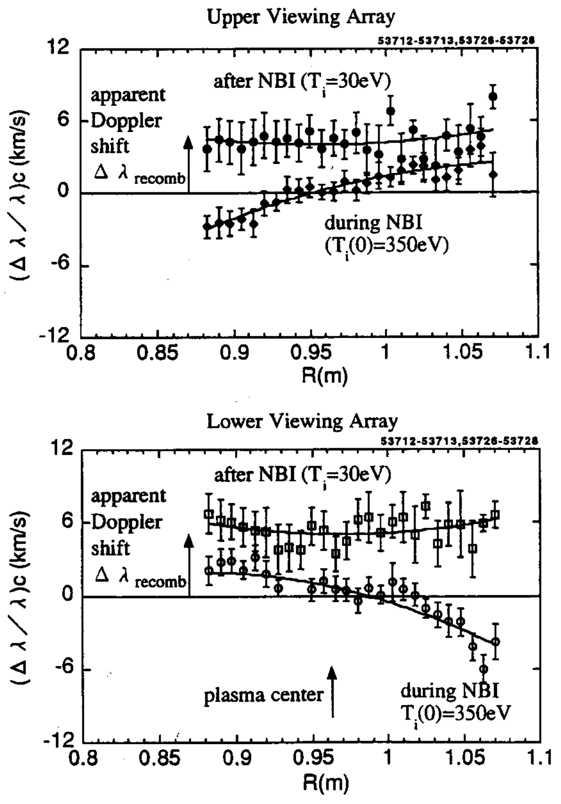

Fig. 4 The wave length shifts in the NBI heated phase and the after-glow recombining phase (CVI; Δn=7-6, λ=343.5 nm).

due to the poloidal rotation during NBI heated phase. After NBI, however, the both of them shift to red-side. This is not a real Doppler shift but the apparent shift.

These apparent Doppler shifts can be explained by the discrepancy between the measured spectral profiles and the fitted single Gaussian profiles since the measured profiles have red-side/blue-side asymmetry due to the spectral fine structure of hydrogen-like ions. Hydrogen-like ions have the splitting of energy levels due to a relativistic effect expressed in the formula

$$E(n,j) = -\frac{Z^2 R_y}{n^2}\left[1+\frac{(\alpha Z)^2}{n}\left(\frac{1}{j+1/2}-\frac{3}{4n}\right)\right].$$

where, n is principal quantum number, j is total angular momentum, Z is nuclear charge, R_y is Rydberg constant and α is fine structure constant (= 1/137). The over-estimation of ion temperature caused by this splitting has been pointed out by Fonck[7]. Although the difference between 'real' and 'apparent' ion temperature can not be directly measured in CXS, 'real' and 'apparent' Doppler shift can be distinguished by the observation along opposite viewing directions.

The intensity ratio of fine structure components depends on the sub-level population. The charge exchange excitation rates[7] are estimated applying the Pengelly and Seaton's theory of collisional transition between degenerate energy levels in the recombining plasmas[9]. From this study, the n=7,8 states in C^{5+} ion, which can cause the transition with visible range lines, are in the 'collisional l-mixed' state in the plasma parameter regime of CHS plasmas. In 'l-mixed' state, the sub-level populations are proportional to statistical weights $2(2l+1)$.

Figure 5 shows the example of observed spectral profile of the CVI line ($\Delta n = 7-6$, $\lambda_{vacuum} = 343.5$ nm) and the fine structure pattern calculated with this assumption. Observed spectral profile has red-side/blue-side asymmetry, and thus fitting with the spectral profile made by superposition of fine structural component with Doppler broadening shows better agreement with the measured spectrum than the least square fitting with single Gaussian. The apparent Doppler shifts shown in Figs. 3 and 4 are derived with this single Gaussian fitting and shift to red-side when the red-side/blue-side asymmetry becomes strong due to the narrow Doppler width. Figure 6 shows the center wavelength for the half-maximum of these calculated spectra. It shifts to red side with decreasing ion temperature (*i.e.*

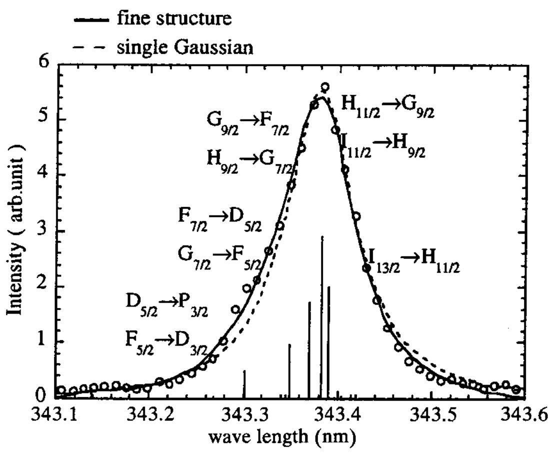

Fig. 5 Spectral profile obtained at the plasma edge with the ion temperature of <200 eV (denoted by ○), and the intensity ratio of spectral fine structure components (transitions with Δj=13/2-11/2, 11/2-9/2, 9/2-7/2 and so on) calculated using statistical weighted sub-level population. The solid curve denotes the Doppler broadened profiles of this pattern. It gives a better fit to the measured profile than single Gaussian profile (CVI; Δn=7-6, λ=343.5 nm).

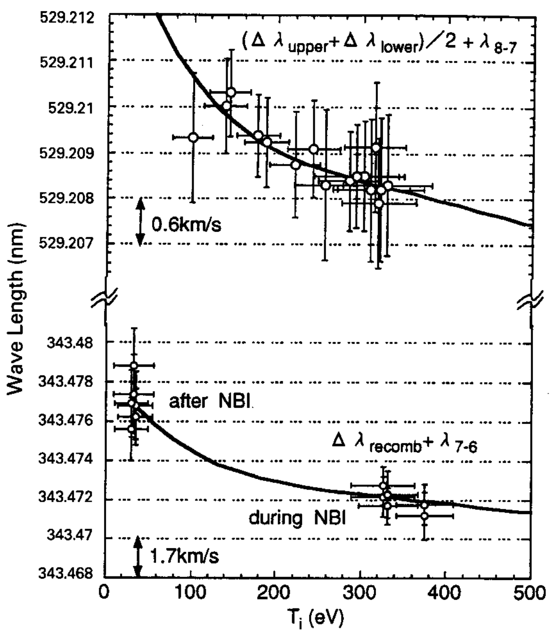

Fig. 6 The dependence of the apparent wavelength on ion temperature calculated for the CVI lines in visible range (solid curves). And the measured 'apparent' wavelength without 'real' Doppler shifts $(\Delta\lambda_{upper} + \Delta\lambda_{lower})/2 + \lambda_{8\text{-}7}$ from Fig. 3 and the measured 'apparent' wavelength $\Delta\lambda_{recomb} + \lambda_{7\text{-}6}$ in the after-glow recombining phase, where $\lambda_{8\text{-}7}$ and $\lambda_{7\text{-}6}$ are taken to be 529.2082 nm and 343.472 nm respectively.

Doppler broadening) and total shift in the ion temperature range of hundreds eV corresponds to the velocity error of a few km/s. The measured apparent wavelength without real Doppler shifts $(\Delta\lambda_{upper} + \Delta\lambda_{lower})/2+\lambda_{8\text{-}7}$ in the plasma shown in Fig. 3 and the measured apparent wavelength $\Delta\lambda_{recomb} + \lambda_{7\text{-}6}$ in the after-glow recombining phase shown in Fig. 4, where $\lambda_{8\text{-}7}$ and $\lambda_{7\text{-}6}$ are taken to be 529.2082 nm and 343.472 nm respectively for the best fit of the data to the calculated curve, are also shown for the comparison of the dependence on ion temperature. The dependence of these wavelength on ion temperature is consistent with the prediction from the fine structure calculation.

4. Concluding Remarks

The apparent Doppler shifts due to the spectral fine structure of CVI lines in visible range are observed using the bidirectional viewing CXS system. The dependence of shifts derived with the least square single Gaussian fitting on ion temperature is consistent with the prediction from the fine structure calculation based on collisional l-mixing model assuming the statistical weighted sub-level population. This effect causes the velocity error of a few km/s in the peripheral region with the low ion temperature of < 200 eV. It should be corrected in the precise charge exchange spectroscopy to detect the spatial variation and/or the time evolution of the plasma velocity of a few km/s.

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