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Kinetic Energy Measurement of Hydrogen in LHD Peripheral Plasma with a Multi-wavelength-range Fine-resolution Spectrometer

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Abstract

We have simultaneously measured high resolution emission spectra of the hydrogen atomic Balmer-α, -β, -γ lines and molecular Fulcher-α band for a LHD peripheral plasma generated under a central magnetic field strength of 0.4 T. It is found that the velocity distributions of excited atoms calculated from the Balmer-α, -β, and -γ line shapes show similar profiles to each other. The translational kinetic energy corresponding to the average velocity is about 13 eV, which is about 300 times larger than the rotational energy of hydrogen molecules estimated from the line intensities in the Fulcher-α band. The velocity distributions differ from Maxwellian and have a high velocity tail over 1 x 10^5 m/s. A correlation between the high velocity tail and the electron temperature and density is seen and suggesting the excited atoms having such high velocities to be generated by the charge exchange collisions from high velocity protons in the peripheral region.

Keywords: charge exchange; velocity distribution; line shape.

1. Introduction

In magnetically confined plasmas, the behavior of hydrogen molecules and dissociated atoms in the peripheral region has a significant influence on the plasma confinement [1, 2]. Plasma emission spectroscopy is one of powerful tools for investigating their dynamics. For molecular hydrogen, Shikama *et al.* estimated the vibrational and rotational temperatures from the Fulcher-α band spectra measured for the TRIAM-1M plasma [3]. Regarding the atomic hydrogen, the Balmer-α spectra have been observed and analyzed by several groups (TEXTOR [4], LHD [5], TRIAM-1M [6]). It was found that the velocity distribution of the excited atoms derived from the Doppler profile is far from thermal equilibrium and the excited atoms have much larger translational energy than the rotational energy of the molecules. A simultaneous measurement of these emission spectra together with the Balmer-β and -γ spectra for the same plasma with the same line of sight may give us more information about the heating situation of the atomic hydrogen.

We recently developed a multi-wavelength-range fine-resolution (MF) spectrometer, with which the high resolution spectra of the Balmer-α, -β, -γ lines and the Fulcher-α band (*v' = v''* = 2) vibronic transition band can be measured simultaneously from a single or multiple optical fibers input, where *v'* and *v''* are the vibrational quantum numbers of the upper and lower states, respectively [7]. In this work, we applied this spectrometer to the observation of the hydrogen emissions from a LHD plasma.

2. Experiment

Figure 1(a) shows the LHD poloidal cross section and the line of sight we used. Plasma emission is introduced to the MF spectrometer through an optical fiber. In the MF spectrometer, the light passes through a stigmator (indicated with the gray shadow in Fig.1(b)) and is collimated by a concave mirror (focal length: f = 1143 mm). The collimated light is incident on a diffraction grating (2400 grooves/mm). The diffracted light beams are focused by 4 concave mirrors (f = 1143 mm) which are at the location corresponding to the wavelength of the Balmer-α (wavelength: λ = 656 nm), -β (λ = 486 nm), and -γ (λ = 434 nm) lines and the Fulcher-α (*v' = v''* = 2) *Q*-branch (λ = 622 nm) on different regions of a CCD detector (Andor, DV435-BV). The instrumental widths (FWHM) for these emission lines are 0.019, 0.023, 0.030, and 0.022 nm, respectively.

The spectra were measured for the neutral beam injection (NBI) discharge with a central magnetic field strength of 0.4 T. The time development of the electron temperature measured by Thomson scattering and the line averaged electron density measured by laser interferometer are shown in Fig. 2, in which the exposure time of the CCD detector are shown by the dotted squares.

3. Result and Discussions

Figure 3 shows the spectra of the Balmer-α, -β, -γ lines and Fulcher-α band observed at t = 1940 - 2030 ms. The observed atomic spectra show broadening and have tails while such broadening and tail are not detected for the molecular Fulcher-α band (*v' = v''* = 2) *Q*1 line. The Zeeman splitting of the Balmer-α, -β, and -γ lines are estimated to be 0.015, 0.008 and 0.007 nm, respectively, at a magnetic field strength of 0.4 T which is the strongest magnetic field strength along the line of sight. These splitting are enough small in comparison with the instrumental widths. The Stark effect on these atomic lines may also be small and neglected [8]. The facts that the spectral tail shows negative dependence on the electron density in our experiment, as explained below, support our assumption of the neglect of the Stark effect. The broadening is considered to be due to the Doppler effect of the upper state atoms of the emission transitions.

Figure 4 shows the velocity distributions along the line of sight of n = 3, 4, and 5 atomic hydrogen derived from the Balmer-α, -β, and -γ line shapes, respectively. Here, n is the principal quantum number. It is noted that the velocity distributions near v = 0 are affected by the instrumental widths, the corresponding velocity widths of which are 0.9 x 10^4, 1.4 x 10^4, and 2.1 x 10^4 m/s for n = 3, 4, and 5 atoms, respectively. Here, v is the velocity of excited atoms. Some overlapped regions by other emissions or continuum are omitted in the velocity distributions.

The velocity distributions of the excited hydrogen atoms in the n = 3, 4, and 5 states show similar profiles to each other. It is clear that they are different from Maxwellian distribution. The average velocity is derived to be about 5.0 x 10^4 m/s and the corresponding translational kinetic energy of 13 eV is about 300 times larger than the rotational energy of hydrogen molecules of 0.03 – 0.04 eV estimated from the measured molecular emission intensities of Fulcher-α band (*v' = v''* = 2) *Q*1, *Q*2, *Q*3, and *Q*4 lines shown in Fig. 3 (e). It is noted here the velocity corresponding to the molecular rotational energy is within the instrument width. It is found that there are significant amount of atoms having much higher velocity $|v| > 1$ x 10^5 m/s (corresponding translational kinetic energy is 54 eV).

As the heating processes of the atomic hydrogen, molecular dissociation and charge exchange collisions with protons are frequently proposed [4, 9, 10]. The temperature of the excited atoms generated by molecular dissociation is predicted to be typically under 10 eV [9, 10], and to be different among the excited states [10]. In our measurement, however, the differences among the velocity distributions of the n = 3, 4, and 5 excited atoms were not detected within the experimental accuracy.

Figure 5 shows the velocity distributions of the excited hydrogen atoms in the n = 3 state measured at t = 1490 - 1580, 1940 – 2030, and 2390 - 2480 ms. It is found that the time-dependence of the velocity distribution for $|v| < 1 \times 10^5$ m/s is very small while that for $|v| > 1 \times 10^5$ m/s is prominent. The high velocity tail decreases as the discharge time passes, where the central electron temperature increases and the line averaged electron density decreases as shown in Fig. 2. Since such high velocity excited atoms are not generated through molecular dissociation [9, 10], they are thought to be generated by charge exchange collisions with high velocity protons in the peripheral region, and whose velocity may depend on the core plasma parameters.

4. Conclusion

The velocity distributions of the excited hydrogen atoms in the n = 3, 4, and 5 states in the LHD plasma were derived from the Balmer-α, -β and -γ emission spectra simultaneously measured by the MF spectrometer. The distributions show similar profiles to each other and the translational energy is found to be much larger than the rotational one of the molecular hydrogen. The velocity distribution has a high velocity tail which may come from charge exchange collisions of hydrogen atoms with high velocity protons in the peripheral region.

Fig. 1 (a) Poloidal cross section of LHD and the line of sight. Some magnetic surfaces are shown by the gray lines. (b) Schematic top view of the MF spectrometer.

Fig. 2 (a) The central electron temperature and (b) the line averaged electron density. The exposure time of the CCD detector are shown by the dotted squares in (b).

Fig.3 The observed spectra of the Balmer- (a) α, (b) β, (c) γ lines, and (d) the Fulcher-α band ($v' = v'' = 2$) $Q1$ line at t = 1940 – 2030 ms. The $Q1$, $Q2$, $Q3$ and $Q4$ spectra of the Fulcher-α band are shown in (e).

Fig. 4 Velocity distributions along the line of sight of the excited hydrogen atoms in the $n = 3$ (red curve), 4 (blue curve) and 5 (purple curve) states derived from their emission spectra observed at $t = 1940 - 2030$ ms. The areas are normalized to unity and the scale of the vertical axis is logarithmic. The instrumental width for each wavelength is indicated by the distance between the vertical dotted bars in the legend.

Fig.5 Velocity distribution along the line of sight of the excited hydrogen atoms in the n = 3 state at t = 1490 - 1580 (red curve), 1940 – 2030 (blue curve), and 2390 - 2480 (black curve) ms.

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