Fast and high-resolution spectroscopy of a Balmer-α line profile for an LHD plasma

K. Fujii[1], T. Shikama[1], M. Goto[2], S. Morita[2], M. Hasuo[1]

[1] *Department of Mechanical Engineering and Science, Graduate School of Engineering,*
Kyoto University, Kyoto 606-8501, Japan

[2] *National Institute for Fusion Science, Toki 509-5292, Japan*

Introduction

Balmer-α intensity is known to be nearly proportional to particle flux ionizing in magnetically confined plasmas [1]. The flux has been also known to relate to charged particle outflux from the plasma [2]. The fast changes of the Balmer-α intensity observed in L-H transition and in the edge-localized-mode are well-known examples. From the early study of fusion plasmas, the temporal development of the Balmer-α intensity has been monitored at a measurement frequency over several tens of kHz [3].

On the other hand, Balmer-α line profiles have been observed and analyzed for a decade in order to investigate neutral particle transport in the edge region [4, 5]. From the Zeeman splitting appeared in the profile, it has been revealed that most hydrogen atoms are ionized outside of the confined region with light emission [6, 7]. It has been also found that the profile has substantial wings which cannot be expressed by a single Maxwellian velocity distribution [4-7]. Recently, we reported that the wing reflects the existence of high velocity neutral atoms and depends on the plasma parameter in the confined region [8]. The high velocity neutral atoms are attributed to those penetrating into the confined region and being heated through charge exchange collisions with high temperature protons there. Recently, Goto *et al.* estimated the penetrating neutral atom density from the Balmer-α line profile [9].

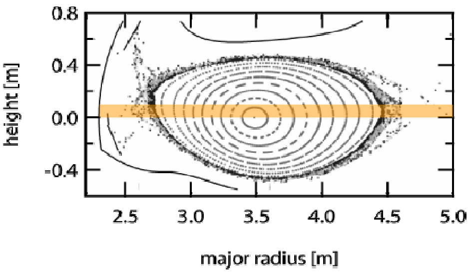

Fig 1. LHD poloidal cross section and the line of sight. Inner surfaces of the vacuum chamber, open magnetic field lines, and closed magnetic flux surfaces are shown by the black line, gray dots, and gray dashed lines, respectively.

In this work, we report a time-resolved measurement of the Balmer-α line profile for an Large Helical Device (LHD, National Institute for Fusion Science, Toki, Japan) plasma for the

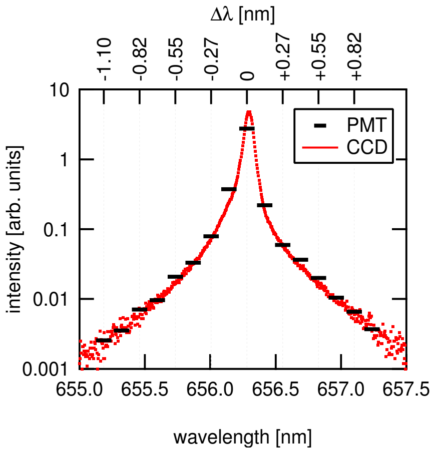

Fig 2. A typical Balpmer-α line profile measured by the fast spectroscopic system (black bars) and a conventional spectrometer with a CCD (red dots).

purpose of separating the temporal behaviour of the peak and wing components of the Balmer-α line.

Experiment

Figure 1 shows a poloidal cross section of LHD. We observe emission from the plasma with a horizontal line of sight with a height of 0.05 m. The field of view is roughly 150 mm height and 100 mm width. The emission is introduced by optical fibers into a high dispersion spectrometer (THR1000, Jobin Yvon, focal length: 1 m, grating: 2400 grooves/mm). The spectrum focused on the exit of the spectrometer is refocused on the photo cathodes of a multi-anode photo-multiplier-tube (PMT, R-5900U-20-L16, Hamamatsu) by an achromatic lens (diameter: 30 mm, focal length: 100 mm) with twice enlargement. The PMT equips 16 channels along the dispersion direction with a pitch of 1 mm. The output signal is digitized by a 16-channels AD converter (National Instruments, USB-6251). The sampling rate is 70 kHz and the cut-off frequency of all the channels is set to be 40 kHz. The linear wavelength dispersion at the photo cathodes of the PMT is 0.14 nm/ch and the wavelength bandwidth is 2.1 nm. Figure 2 shows a typical Balmer-α spectrum measured by this fast spectroscopic system together with that measured by a CCD camera (Andor, DV-435) with a high-dispersion spectrometer (McPherson, Model 209).

A hydrogen discharge in LHD is generated under a confining magnetic field strength of 1.5 T. Figure 3 (a) shows temporal changes of the electron temperature and density at the plasma center measured by a Thomson scattering method [10]. The discharge is ignited by the neutral beam injection (NBI), whose power is shown in figure 3(b). The electron temperature decreases and the density increases at t = 4.40 and 5.40 s when hydrogen gas are puffed. At t = 5.85 s, small hydrogen solid pellet is injected. Figure 3(c) shows the temporal development of the Balmer-α intensities at the wavelength components of $\Delta\lambda$ = 0.0 nm (line center), ±0.27 nm, ±0.55 nm, ±0.82 nm, -1.10 nm. The intensity at the line center quickly increases with the gas puffs and pellet injection. In the LHD discharge, the NBI input power is modulated with a frequency of 10 Hz for the purpose of the charge exchange spectroscopic diagnostics. All the

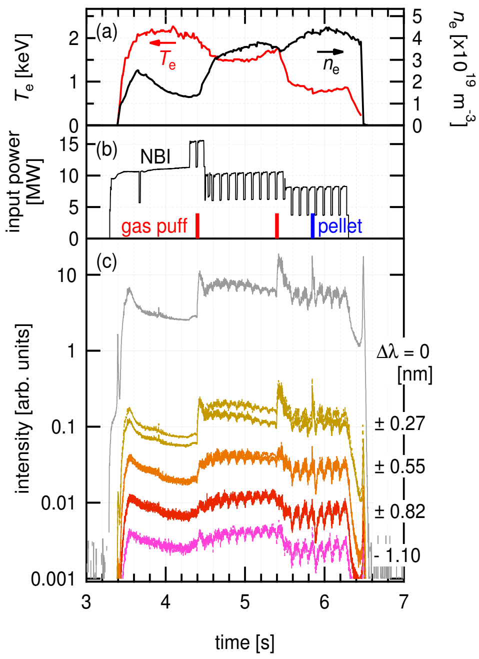

Fig 3 Temporal developments of (a) the electron temperature (red line) and density (black line) at the plasma center, (b) the NBI input power and (c) several components of the Balmer-α profile. The wavelengths shifted from the line center are indicated as $\Delta\lambda$. The gas puffs and pellet injection in the discharge are shown with the vertical bars in (b).

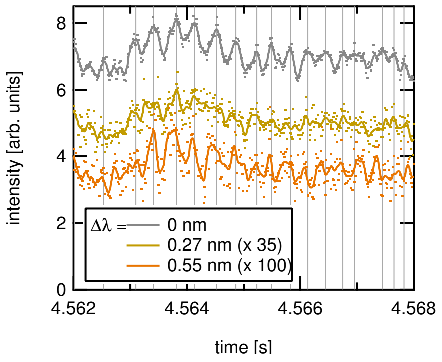

Fig 4. Enlarged temporal development of several components of the Balmer-α profile. The solid lines are moving averaged over 10 points. The vertical lines indicate the local maxima for the line center ($\Delta\lambda = 0$ nm).

wavelength components of Balmer-α profile are found to synchronize to the NBI input power modulation. This phenomenon suggests the charged particle flux to the divertor plates changes according to the NBI input power.

Figure 4 shows the temporal developments of the Balmer-α profile components at $\Delta\lambda = 0$ nm, 0.28 nm, 0.55 nm at $t = 4.562 \sim 4.568$ s. It is found that all the components oscillates at a frequency of about 3 kHz. In the figure, the local maxima of the line center are indicated with the vertical lines. The magnetic field oscillation at the same frequency is also observed by magnetic probes. The oscillation is attributed to be a pressure driven MHD instability with the toroidal-poloidal mode number of $m/n = 2/3$, whose rational surface is located just inside the last closed flux suface of LHD. In figure 4, it is also found that the oscillation of the intensity at $\Delta\lambda = 0.55$ nm leads to that of the line center. We derive the relative phase differences of other 15 components to the line center. The results are shown in figure 5. The oscillation of the components at $|\Delta\lambda| > 0.55$ nm leads to that of the line center about $\pi/4$.

Discussion

Since the intensity of Balmer-α was reported to be nearly proportional to the particle flux into the confined region [1], the intensity oscillation observed in the line center is thought to be due to fluctuation of neutral influx to the plasma. Since the source of the neutral particle is considered to be neutralization or desorption at the

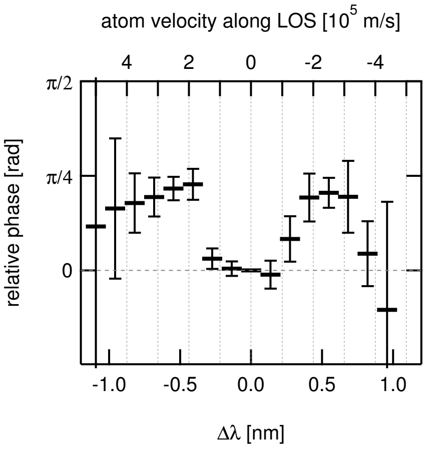

Fig 5. The relative phase against the line center at *t* = 4.555 ~ 4.579 s. The top axis indicates the velocity of hydrogen atoms along the line of sight.

divertor region, the intensity oscillation reflects the charged particle flux oscillation syncronized to the plasma turbulence.

On the other hand, the intensity at the wing component is affected not only by the neutral influx but also by the plasma density and temperature in the confined region [8, 9]. At the top axis in figure 6, we show the velocity component of excited hydrogen atoms along the line of sight. The intensity oscillation of the emission from atoms having the velocity over 2 x 10^5 m/s leads to that from atoms with 0 m/s. The kinetic energy corresponding to the velocity of 2 x 10^5 m/s is about 0.2 keV. We may interprete that the phase difference corresponds to the time difference (50 μs) between the plasma turbulences at the location of 0.2 keV proton temperature and the neutral influx.

On the other hand, the electron temperature at the rational surface of *m*/*n* = 2/3 instability is measured to be 0.25 keV by a Thomson scattering method [10]. The value is consistent with the proton temperature, where the plasma turbulence is detected by our fast Balmer-α profile measurement.

Reference

1. K. Sawada and T. Fujimoto, *J. Appl. Phys.*, **78** (1995) 2913

2. F Wagner and U Stroth, *Plasma Phys. Control. Fusion*, **35** (1993) 1321

3. L.A. Artsimovich, *Nucl. Fusion*, **12** (1972) 215

4. J. D. Hey, M. Korten, Y. T. Lie *et al.*, *Contrib. Plasma Phys*, **36** (1996) 583

5. J. L. Weaver, B. L. Welch, H. R. Griem *et al*, *Rev. Sci. Instrum.*, **71** (2000) 1664

6. A. Iwamae, A. Sakaue, N. Neshi, *et al*, *Plasma and Fusion Research*, **5** (2010) 032

7. T. Shikama, S. Kado, H. Zushi, *et al*, *Phys. Plasmas*, **11** (2004) 4701

8. K. Fujii, K. Mizushiri, T. Nishioka, *et al*, *Nucl. Instrum. Methods Phys. Res., Sect. A*, **623** (2010) 690

9. M. Goto, K. Sawada, K. Fujii, *et al*, *Nucl. Fusion*, **51** (2011) 023005

10. K. Narihara, I. Yamada, H. Hayashi, *et al.*, *Rev. Sci. Instrum.*, **72** (2001) 1122