Fast and high-resolution spectroscopy of a Balmer-\(\alpha\) line profile for an LHD plasma

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Introduction

Balmer-\(\alpha\) 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-\(\alpha\) 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-\(\alpha\) intensity has been monitored at a measurement frequency over several tens of kHz [3].

On the other hand, Balmer-\(\alpha\) 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-\(\alpha\) line profile [9].

In this work, we report a time-resolved measurement of the Balmer-\(\alpha\) line profile for an Large Helical Device (LHD, National Institute for Fusion Science, Toki, Japan) plasma for the
Fig 2. A typical Balmer-α line profile measured by the fast spectroscopic system (black bars) and a conventional spectrometer with a CCD (red dots).

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
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 surface 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
divertor region, the intensity oscillation reflects the charged particle flux oscillation synchronized 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 $2 \times 10^5 \text{ m/s}$ leads to that from atoms with 0 m/s. The kinetic energy corresponding to the velocity of $2 \times 10^5 \text{ m/s}$ is about 0.2 keV. We may interpret 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 $\frac{m}{n} = 2/3$ 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

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