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Self-reversal in Lyman- α line profile for diagnosis of fusion plasma

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Abstract. We have observed Lyman- α line profile which exhibits the so-called “self reversal” at the line center. A one-dimensional radiation transport equation is numerically solved for simulating the Lyman- α line profile, where the emission and absorption coefficient distributions over the line-of-sight are evaluated based on the Laplace inversion analysis of the Balmer- α line measured simultaneously with the Lyman- α line. While the synthetic profile of the Lyman- α line shows a good agreement with the measured data in the line profile tail, the central part shows a significant discrepancy between the synthetic and measured profiles. It has been known that the neutral density profile in the plasma boundary region derived from the Balmer- α line profile analysis has a relatively large error and the present results shows that the Lyman- α line measurement would play a complementary role to determine an entire neutral density profile from the core to the edge.

1. Introduction

The neutral atom density in the plasma is an important parameter for evaluating the plasma confinement characteristics because the ionization of neutral atoms is essential in the particle source, and neutral atoms in the plasma cause particle and energy loss through the charge exchange process.

Many efforts have been made to determine the hydrogen atom density or the ionization rate in the plasma, most of which are based on spatial inversion of chord-integrated intensities of an emission line such as the Balmer- α line [1] or the Lyman- α line [2]. Nevertheless, this kind of measurement has an essential problem because observed line emissions of neutral atoms are mainly located at the outermost boundary of the plasma and weak line emissions in the core region, if any, are difficult to be detected by a line-integrated measurement with a line-of-sight which passes through both the edge and core regions.

In our previous study, we focused on the tail component of observed Balmer- α line profiles and established a method to deduce a spatial distribution of the hydrogen atom density [3]. This method has a such advantage that the line radiation in the high-temperature core region, which is responsible for the tail component of the line profile, is directly detected without being veiled behind the strong radiation in the low-temperature edge region, which mainly forms the central part of the line profile.



Meanwhile, this method has also a disadvantage in determining the neutral density in the plasma edge region because the central part of the line profile suffers from the Zeeman effect. Moreover, the condition assumed in the analysis that the atom temperature is approximately equal to the proton temperature would be inappropriate in the plasma edge region because atoms should mainly be created by the dissociation processes of molecules and not by the charge exchange process with protons.

On the other hand, we have noticed that the Lyman- α line profile shows a dent near the line center, which is called “self-reversal” and is considered to be due to strong reabsorption effect [4, 5]. Since the large reabsorption effect means the large line-integrated neutral density along the line-of-sight, the degree of the self-reversal should have information on the atom density in the edge region. In this paper, we examine the consistency between the neutral atom density profile derived from the Balmer- α analysis and the Lyman- α line profile.

2. Experiment

For the Lyman- α line observation, a normal incidence VUV spectrometer is used [6]. The spectrometer has a focal length of 3 m and is equipped with a 1200 grooves/mm grating. The Lyman- α line is measured with its second order diffracted light for having a better wavelength resolution. The spectrometer is placed at an outboard side port such that its optical axis overlaps the major radius of the plasma at the toroidal position where the plasma is horizontally elongated. In the present measurement, the field-of-view of the spectrometer is limited to ± 10 mm in the toroidal direction by a vertical aperture placed between the plasma and the spectrometer. The vertical width of the field-of-view is also limited to 20 mm by a horizontal aperture placed between the entrance slit and the grating in the spectrometer.

The measurement was performed for a discharge with $R_{\text{ax}} = 3.6$ m and $B_{\text{ax}} = 2.75$ T, where R_{ax} and B_{ax} are the major radius of the magnetic axis and the magnetic field strength at the magnetic axis, respectively. The temporal development of the discharge is shown in Fig. 1. The

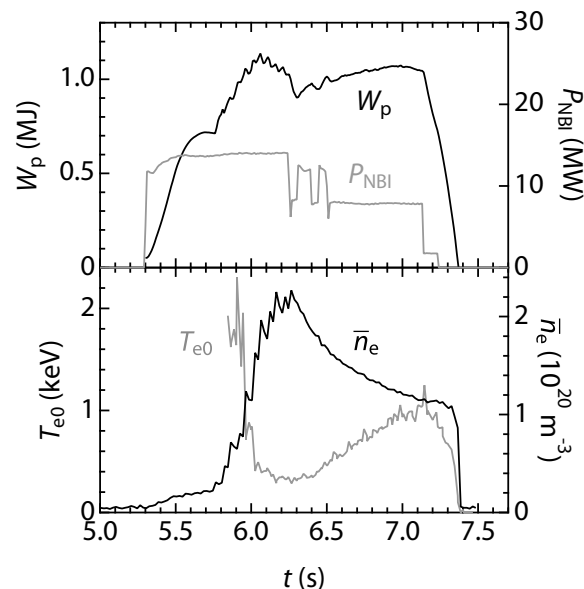


Figure 1. Temporal development of the discharge for the present measurement. The black and gray lines in the upper panel are the stored energy W_p and the neutral beam power P_{NBI} , respectively. The black and gray lines in the lower panel show the line-averaged electron density \bar{n}_e and the central electron temperature T_{e0} , respectively.

line-averaged electron density \bar{n}_e is increased by repetitive injection of hydrogen pellets between $t = 5.7$ s and $t = 6.3$ s and gradually decays after termination of the pellet injection. Conversely, the central electron temperature T_{e0} drops by the pellet injection and recovers after $t = 6.3$ s. The spectrum is recorded every 54 ms with an exposure time of 32 ms.

Figure 2 shows the measured profile of the Lyman- α line at around $t = 6.5$ s as indicated by the dotted line in Fig. 1. A salient feature of the spectrum is the dent at the line center, which

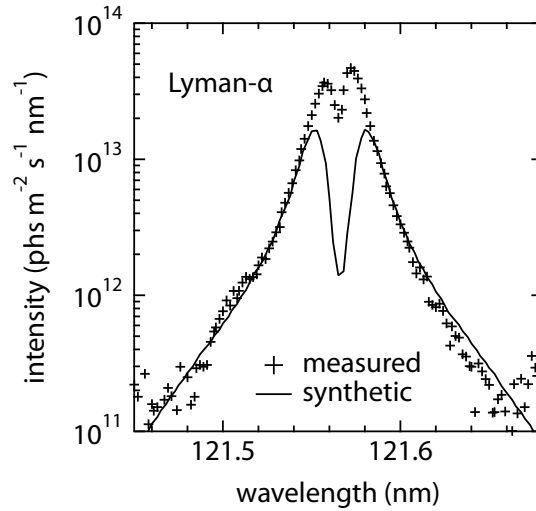


Figure 2. Measured (crosses) and synthetic (solid line) Lyman- α line profiles.

is thought to be due to a strong reabsorption effect by low temperature atoms existing in the plasma boundary region.

3. Results and discussion

For a quantitative evaluation of the line profile with the self-reversal, an equation of radiation transport is solved. We here consider a one-dimensional model which is expressed as

$$\frac{d}{dx}I(\lambda, x) = -\kappa(\lambda, x)I(\lambda, x) + \eta(\lambda, x), \quad (1)$$

where the coordinate x is taken along the line-of-sight. The parameters $\eta(\lambda, x)$ and $\kappa(\lambda, x)$ are respectively the emission and absorption coefficients at wavelength λ and at x . They are explicitly expressed as

$$\eta(\lambda, x) = \frac{hc}{4\pi\lambda_0}n_2(x)A_{21}P(\lambda, x), \quad (2)$$

$$\kappa(\lambda, x) = \frac{hc}{4\pi\lambda_0}n_1(x)B_{12}P(\lambda, x), \quad (3)$$

where h and c are the Planck's constant and the speed of light, respectively, λ_0 is the center wavelength, A_{21} and B_{12} are Einstein's coefficients for the spontaneous emission and the absorption, respectively.

The line profile at x , $P(\lambda, x)$, is here assumed to be determined by the Doppler broadening, where the atom temperature is approximated by the proton temperature at the same location because neutral atoms in the confined region are mainly created by the charge exchange process.

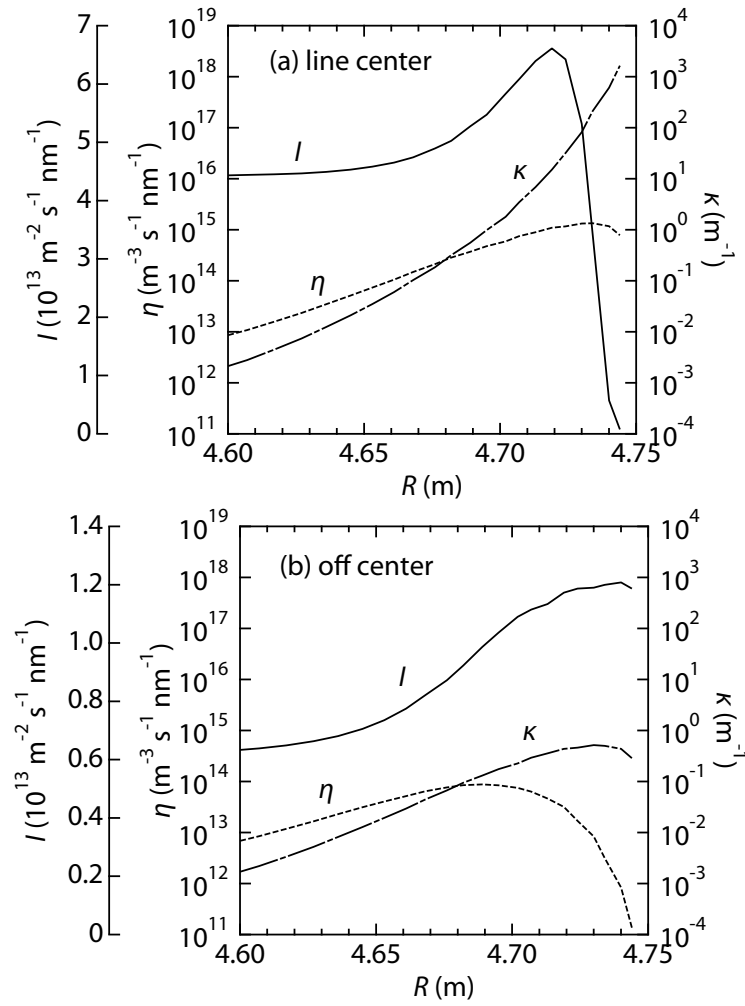


Figure 3. Radial profiles of the emission coefficient η (dashed line), absorption coefficient κ (dot-dashed line), and the resulting intensity (solid line) of the Lyman- α at the line center (a) and at 0.02 nm off the center (b) evaluated from the Balmer- α line profile analysis.

Moreover, the proton temperature is expected to be in equilibrium with the electron temperature T_e because the electron density n_e is high. Therefore, we employ the T_e profile measured by the Thomson scattering system for the atom temperature profile.

The spatial profiles of the ground state density $n_1(x)$ and the $p = 2$ level density $n_2(x)$, where p is the principal quantum number, are derived from the detailed analysis of the Balmer- α line [3] measured simultaneously with the Lyman- α . In this analysis, the Balmer- α line profile is regarded as a superposition of various temperature components and a distribution function against the temperature is derived by the Laplace inversion technique after replacement of variables. The obtained distribution function against the temperature is assigned to actual radial positions in the plasma and thus the entire radial profile of the Balmer- α line emissivity is obtained with the T_e profile measured by the Thomson scattering system, where the atom temperature profile is assumed to be identical to that of T_e as mentioned above. The quantities $n_1(x)$ and $n_2(x)$ are finally derived from the Balmer- α line emissivity, and T_e and n_e values with a help of the collisional-radiative model calculation.

Figure 3 shows the dependence of $\eta(\lambda, x)$ and $\kappa(\lambda, x)$ on the radial position at the line center

(a) and at 0.02 nm off the center (b). It is noted that the coordinate x is here translated into the major radius R . The parameters at the line center and at the off center show larger discrepancy as the position moves outward. This is due to a fact that the line profile in the edge region is narrower than that in the core region. The same figure also shows $I(\lambda, x)$ as a solution of Eq. (1). It is readily noticed that $I(\lambda, x)$ shows a rapid decrease in the edge region only at the line center. This is understandable because $\kappa(\lambda, x)$ at the line center increases rapidly in the edge region.

The complete synthetic line profile is shown in Fig. 2 with the solid line. The absolute intensity of the measured data is normalized to the synthetic profile in the wavelength region $|\lambda - \lambda_0| > 0.04$ nm where an optically thin condition is expected. It is found that the agreement in the tail components of the both profiles is good, which supports our understanding of the penetration of neutral atoms in the plasma core region. However, a significant discrepancy is observed in the central wavelength region of the profile, which indicates the accuracy of the parameters derived in the analysis of the Balmer- α line profile is insufficient especially in the outermost region.

This is understandable because the central region of the Balmer- α line profile suffers from the Zeeman effect and because the assumption of equivalent temperature between atoms and protons would be inappropriate. In other words, the Lyman- α line can be used as a complementary method to the Balmer- α line analysis in determining the neutral density profile.

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