Evaluation of particle source rate and its influence on particle transport in fusion plasma

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Abstract. We have carried out numerical inversion of the Laplace transform for the observed line profile, and have derived the intensity distribution function against the atom temperature. The temperature dependence is interpreted to the spatial dependence, where other diagnostic results are used, so that the radial profile of photon emission rate is derived. The photon emission rate is then interpreted to the ionization rate with the help of collisional-radiative model calculation. From the ionization rate derived we have evaluated the particle confinement time \( \tau_p \) as a function of the average minor radius, \( r_{\text{eff}} \), for two discharges characterized by the different magnetic field strength. In the strong field case, a turning point is clearly seen in the \( \tau_p \) profile at around \( r_{\text{eff}} = 0.6 \), which corresponds to the last closed magnetic flux surface. In the weak field case, the absolute confinement time is approximately one-order smaller than that in the strong field case.

1. Introduction

The ionization rate of neutral hydrogen or, in other words, the particle source term in the continuity equation is indispensable information for the study of particle transport in the fusion plasma experiment. The conventional method of experimental determination of hydrogen atom density in the plasma has been based on spatial inversion of chord-integrated intensities of an emission line such as the Balmer-\( \alpha \) line [1] or the Lyman-\( \alpha \) line [2]. However, the atom density deep inside the core region tends to have a large uncertainty because the line intensity from those atoms is generally obtained after dominant fractions originated in the plasma edge region are subtracted from the measured signal.

It has been noticed that Balmer-\( \alpha \) line profiles observed contain a considerably broad component which is thought to originate from hot atoms created by the charge exchange process [3–6]. Since hydrogen atoms are thought to have a relatively large penetration depth due to the charge exchange process [7], if that is the case, the broad line profile component may have information on the atoms or protons in the central region of the plasma. However, the analysis to date has been rather superficial and no practical interpretation of the broad component has been proposed.

Under such circumstances, it has been demonstrated that the line emissivity distribution along the line-of-sight can be derived through numerical inversion of the observed Balmer-\( \alpha \) line.
profile in the Large Helical Device (LHD) [8]. Furthermore, the results have been utilized to evaluate radial profiles of the ionization rate, inward neutral flux, and neutral atom density with the help of collisional-radiative model calculation.

In this paper we attempt to derive the particle confinement time as an application of the line emissivity distribution obtained with the method of line profile inversion and consider the validity of the present analysis through comparison of the results for two different discharges.

2. Experiment

The central region of a poloidal plasma cross section which is horizontally elongated is viewed with a single line-of-sight as shown in Fig. 1. The optics consists of an optical fiber with the core diameter of 100 µm and a collimator lens. The spatial resolution is approximately 30 mm. The collected light is introduced into the astigmatism-corrected UV-visible spectrometer [9] which has the focal length of 1.33 m and is equipped with a 1800 grooves/mm grating (McPherson Model 209). The reciprocal linear dispersion is 0.312 nm/mm at the wavelength of the Balmer-α line (656.280 nm). A CCD (charge coupled device) having 1024 pixels in the direction of wavelength dispersion and with 13 µm squares pixel size (Andor DV-435) is used as the detector. The absolute sensitivity of the entire system has been calibrated with a standard light source which consists of a halogen lamp and an integrated sphere (Labsphere USS-600C).

We have made analysis for two different types of discharges. One is a discharge with $R_{ax} = 3.6$ m and $B_{ax} = 2.75$ T, where $R_{ax}$ and $B_{ax}$ are the major magnetic axis radius and the magnetic field strength at the magnetic axis, respectively. The aim of the experiment is getting high stored energy with gas puff. The other is with $R_{ax} = 3.59$ m and $B_{ax} = 0.41$ T which aims at obtaining the highest $\beta$, the plasma pressure normalized to the magnetic pressure. The apparent difference between the two discharges is the magnetic field strength.

Figure 2 shows the Balmer-α line profiles obtained for the two discharges. It is clearly seen that the strong field case has a larger broad component than the weak field case. This is understandable because that broad component is thought to correspond to line emissions in the plasma core region and the temperature is higher in the strong field case.
Figure 2. Balmer-α line profiles measured for the two discharges.

3. Laplace inversion of line profile
The observed line profile $I(\lambda)$ [photons m$^{-2}$ s$^{-1}$ nm$^{-1}$], where $\lambda$ is the wavelength, is understood as a line-integral along the line-of-sight and can be expressed as

$$I(\lambda) = \int_{R_{\text{min}}}^{R_{\text{max}}} \eta(R) G(R, \lambda) \, dR, \quad (1)$$

where $R$ stands for the major radius, and $R_{\text{min}}$ and $R_{\text{max}}$ indicate the inboard-side and outboard-side edge radii of the line-integral, respectively. The quantities $\eta(R)$ [photons m$^{-3}$ s$^{-1}$] and $G(R, \lambda)$ [nm$^{-1}$] are respectively the power density of line radiation at location $R$ and the local line profile function at $R$ that is normalized. When $G(R, \lambda)$ is the Gaussian function of $\lambda$, it is represented by the line width instead of $R$ so that Eq. (1) can be rewritten as

$$I(\lambda) = \int_{0}^{\infty} f(w) \frac{1}{\sqrt{\pi w}} \exp \left[ - \left( \frac{\lambda - \lambda_0}{w} \right)^2 \right] \, dw, \quad (2)$$

where $\lambda_0$ is the wavelength at the line center, $w$ is the Gaussian half width having the relation $w_{1/2} = 2\sqrt{\ln 2} w$, where $w_{1/2}$ is the full width at half maximum, and $f(w)$ is the contribution fraction of a Gaussian component having the width of $w$ to the entire line profile. After replacement of variables as

$$s = (\lambda - \lambda_0)^2, \quad (3)$$
$$t = \frac{1}{w^2}, \quad (4)$$

Eq. (2) can be rewritten in the form of Laplace transform as

$$\mathcal{F}(s) = \int_{0}^{\infty} F(t) \exp(-st) \, dt, \quad (5)$$

where

$$F(t) = \frac{f(t^{-1/2})}{2\sqrt{\pi t}}. \quad (6)$$
Figure 3. Profiles of the ionization rate $S$ (a) and the electron density (b) as a function of $r_{\text{eff}}$ for the two discharges.

4. Results and discussion

As mentioned above we assume that $T_a$ is equivalent to the proton temperature $T_p$ at the same location. In addition to that, since the electron density $n_e$ is rather high in the present discharges, $T_p$ and the electron temperature $T_e$ are expected to be in equilibrium, namely, $T_p = T_e$ would be established. Under such circumstances, the $T_a$ dependence in Eq. (7) is interpreted to the spatial dependence with the help of $T_e$ profiles by the Thomson scattering measurement so that the radial profile of photon emission rate is derived. The photon emission rate then yields the ionization rate with the help of collisional-radiative model calculation [8]. Figure 3 (a) shows the ionization rate profiles derived, where the horizontal axis indicates the average minor radius $r_{\text{eff}}$. The decay of $S$ as going deep into the core region is much faster in the strong field case.
Figure 4. Particle confinement time $\tau_p$ as a function of $r_{eff}$ for the two discharges.

than in the weak field case. This may be due to the higher electron density in the strong field case as seen in Fig. 3 (b).

The ionization rate or the particle production rate in the confined region is an important parameter to evaluate the particle confinement time, which is a measure of the performance of plasma confinement. The particle confinement time for electrons or protons inside a magnetic surface at $r_{eff}$, $\tau_p(r_{eff})$, is defined as

$$\tau_p(r_{eff}) = \frac{\int_{r_{eff}} n_e(r) \, dV}{\int_{r_{eff}} \nabla \cdot \Gamma(r) \, dV}$$

(9)

where $n_e(r)$ and $\Gamma(r)$ are the electron density and the outward flux of electrons at position $r$, respectively, $\int_{r_{eff}} \nabla \cdot \Gamma(r) \, dV$ means the volume integral inside the surface at $r_{eff}$, and $\int_{r_{eff}} \nabla \cdot \Gamma(r) \, dV$ is the surface integral of $\Gamma$ over the same surface. With the help of continuity equation, i.e.,

$$\frac{\partial n_e(r)}{\partial t} + \nabla \cdot \Gamma(r) = S(r),$$

(10)

where $S(r)$ is the ionization rate of hydrogen atom, Eq. (9) is rewritten as

$$\tau_p(r_{eff}) = \frac{\int_{r_{eff}} n_e(r) \, dV}{\int_{r_{eff}} S(r) \, dV - \int_{r_{eff}} \frac{\partial n_e(r)}{\partial t} \, dV}.$$  

(11)

From the ionization rate $S$ in Fig. 3 (a) and $n_e$ profile by the Thomson scattering measurement, we have evaluated the three integrals in Eq. (11) and have derived $\tau_p(r_{eff})$. The results are shown in Fig. 4. In the strong field case, $\tau_p$ decreases as going outward and the decay speed is suddenly increased at around $r_{eff} = 0.6$ m. This is understandable because that location approximately corresponds to the position of the last closed magnetic flux surface. In the weak field case, the absolute confinement time is about one order smaller and its decay speed as going outward is larger than those in the strong field case. These results qualitatively agree with general understanding of the dependence on the magnetic field strength of the particle confinement time.
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