19pB-1

Evaluation of hydrogen atom density distribution in LHD core plasmas based on high dynamic range Balmer-α spectroscopy

高ダイナミックレンジバルマーα分光による
LHDコアプラズマ中水素原子密度分布の計測

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Balmer-α emission of hydrogen atoms in the edge and core regions of a magnetic confinement fusion plasma are mainly observed in the central and wing parts of the Doppler-broadened spectral profile, respectively. Based on a decomposition of the spectral profile into several temperature components, we present in this work an evaluation method of the radial distribution of the hydrogen atom density from the areas of these components. The evaluated radial distribution from the observation of the Large Helical Device (LHD) plasma was consistent with the simulated one by a Monte-Carlo method.

1. Introduction

In fusion plasmas, most of neutral hydrogen atoms are ionized in the edge region. Nevertheless, a small amount of atoms penetrate into the core region through several repetitions of charge exchange collisions with hydrogen ions [1,2,3]. Such atom transport is an important issue because their ionization acts as the particle source and they neutralize fast ions by the charge exchange collisions.

Recently, we have found that Balmer-α emission from the high-temperature atoms generated by the charge exchange collisions are dominantly observed as the far wings of the Doppler-broadened spectral profile, the intensity of which is smaller than the peak intensity by a factor of > 10^4 [2,3]. We have developed a spectroscopic system with 10^6 dynamic range for the quantitative observation of the emission intensity from the line peak to the far wings [4].

In this paper, we report an evaluation of n_H from the edge to core regions of the LHD plasma from the high dynamic range Balmer-α spectral profile and the radial distribution of the ion temperature.

2. Evaluation of $n_\mathrm{H}(r_\mathrm{eff})$

The carbon ion temperature T_i measured by the charge exchange spectroscopy [5], and T_e and n_e measured by the Thomson scattering [6] are shown in Fig.1 as a function of the effective minor radius r_eff. The last closed flux surface (LCFS) is located at $r_\mathrm{eff} \sim 0.63$ m.

The observed Balmer-α spectrum is shown in Fig.2 as a function of the wavelength shift $\Delta\lambda$ from the line center, λ_0 = 656.28 nm. The wing profile due to the Doppler broadened emission of the high temperature atoms can be seen. For example, emissions appearing at $|\Delta\lambda|$ = 1.0 nm are radiated by atoms with the velocity along the line of sight of 4×10^5 m/s. This speed corresponds to a kinetic energy of 1 keV.

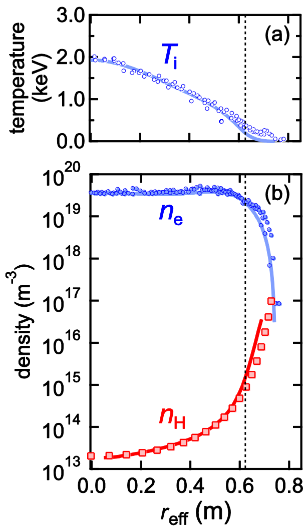

Fig.1 Radial distributions of (a) T_i and (b) n_e. The n_H distribution evaluated in this work is also shown in (b) by squares. The bold red curve in (b) is the simulated result of n_H by the Monte-Carlo method.

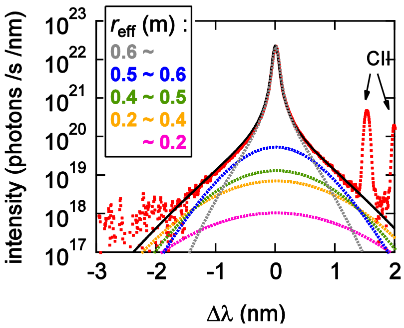

Fig.2 Dots: The observed Balmer-α spectrum. A black solid curve: The fit result. Colored curves: spectral components which are emitted from atom groups generated by charge exchange collisions in the r_{eff} ranges indicated in the figure.

Here, we consider a relation between the spectral profile and the distributions of T_{H}^{+} and the hydrogen ion density n_{H}^{+} in the plasma. The charge exchange collision rate, $\Delta\Phi(r_j)$ [s^{-1}], in a volume $\Delta V(r_j)$ [m^3] with an effective minor radius of $r_j \sim r_j + \Delta r_j$ is proportional to $n_{\mathrm{H}}(r_j)$ [m^{-3}] and $n_{\mathrm{H}}^{+}(r_j)$ as

$$\Delta\Phi(r_j) = R_{\mathrm{CX}}\, n_{\mathrm{H}}^{+}(r_j)\, n_{\mathrm{H}}(r_j)\, \Delta V(r_j). \qquad (1)$$

where R_{CX} [$\mathrm{m}^3\mathrm{s}^{-1}$] is the rate coefficient of the charge exchange collision. We assume $T_{\mathrm{H}}^{+} = T_{\mathrm{i}}$ and $n_{\mathrm{H}}^{+} = n_{\mathrm{e}}$.

The charge exchange collision is approximately a backward collision and impact velocity dependence of its cross section is small [7]. Therefore, if the velocity distribution of the ions at a position r_j is a Maxwell distribution at $T_{\mathrm{H}}^{+}(r_j)$, the atoms generated at r_j by the collisions have the same temperature as $T_{\mathrm{H}}^{+}(r_j)$. The observed spectral profile $I(\lambda)$ is the sum of the emissions from these atoms generated from the core ($r_1 \sim 0$ m) to the edge ($r_N \sim 0.68$ m) regions;

$$I(\lambda) = \sum_{j=1}^{N} \Delta\Phi(r_j) P_\alpha \frac{1}{\sqrt{\pi}\, w(r_j)} \exp\left[-\left(\frac{\Delta\lambda}{w(r_j)}\right)^2\right] \qquad (2)$$

with

$$w(r) = \lambda_0 \sqrt{\frac{2kT_{\mathrm{H}^+}(r)}{Mc^2}} \qquad (3)$$

where $r_1 < \ldots < r_j < \ldots < r_N$ m are the discretized effective minor radii. We set $N = 30$. k, M, and c are the Boltzmann constant, hydrogen atom mass, and light speed, respectively. P_α is the probability that an atom emit a Balmer-α photon between successive charge exchange collisions. P_α is nearly constant at 0.02 photons/atom [4].

We evaluate $n_{\mathrm{H}}(r_j)$ by fitting the observed spectral profile with this equation using a regularization method called as "uniform penalty" [8] which minimizes the chi-squares as well as the quadratic sum of the second derivatives of n_{H}.

3. Results

The fit result with Eq.(2) is shown by a black curve in Fig.2. The observed line profile is well fitted. The spectral components according to the several r_{eff} ranges are shown by colored curves in the figure. The wings with $|\Delta\lambda| > 0.7$ nm is mainly due to the emission of the atoms generated inside the LCFS. The evaluated $n_{\mathrm{H}}(r_j)$ is shown in Fig.1(b) by squares. n_{H} values at $r_{\mathrm{eff}} = 0$ and 0.63 m are evaluated to be 2 x 10^{13} and 1 x 10^{15} m^{-3}, respectively.

For the purpose of cross-checking the result, we carry out a numerical simulation. In this simulation, the trajectories of hydrogen atoms in the three-dimensional space are traced from the outermost region of the plasma to the ionization point repeatedly until a statistical convergence is obtained. T_{i}, T_{e}, and n_{e} at every position are given from the measured radial distributions shown in Fig.1.

The simulated result of n_{H} is shown in Fig.1(b) by a red solid curve. We note that the result is scaled to fit the experimental one in $r_{\mathrm{eff}} < 0.4$ m because the simulation outputs the relative values but not the absolute ones. A good agreement is seen between the n_{H} distributions evaluated by the two independent approaches, i.e., the experimental method based on the spectral decomposition and the numerical simulation, both of which use the same T_{i}, T_{e}, and n_{e} distributions.

References

[1] S. Tamor, *J. Comput. Phys*. **40**, 104 (1981).
[2] K. Fujii, T. Shikama, M. Goto et al., *Phys. Plasmas* **20**, 012514 (2013).
[3] M. Goto, K. Sawada, K. Fujii, M. Hasuo et al., *Nucl. Fusion* **51,** 023005 (2011).
[4] K. Fujii, S. Atsumi, S. Watanabe et al., *Rev. Sci. Instrum*., **85**, 023502 (2014).
[5] K. Ida, S. Kado, and Y. Liang, Rev. Sci. Instrum., **71**, 2360 (2000).
[6] K. Narihara, I. Yamada, H. Hayashi, and K. Yamauchi, *Rev. Sci. Instrum.*,**72**, 1122 (2001).
[7] P. S. Krstic and D. R. Schultz, *J. Phys. B,* **36**, 385 (2003).
[8] P. Charbonnier, L. Blanc-Feraud, G. Aubert and M. Barlaud, *IEEE Trans. Image Process.* **6**, 298 (1997).