Study of Intensity Ratios of He I Lines (668 nm, 706 nm and 728 nm) for Measurement of Electron Temperature and Density in the JT-60U Divertor Plasma

KUBO Hirotaka, GOTO Motoshi¹⁾, TAKENAGA Hidenobu, KUMAGAI Akira²⁾, SUGIE Tatsuo, SAKURAI Shinji, ASAKURA Nobuyuki, HIGASHIJIMA Satoru and SAKASAI Akira

Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Ibaraki 311-0193, Japan

¹⁾National Institute for Fusion Science, Toki 509-5202, Japan

²⁾Plasma Research Center, University of Tsukuba, Tsukuba 305-0006, Japan

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Abstract

Emission of He I lines (668 nm, 706 nm and 728 nm) has been simultaneously observed in the JT-60U divertor plasma. From calculations using a collisional-radiative model, intensity ratios of these He I lines are considered to be useful to measure electron temperature and density. In order to evaluate the feasibility of the intensity ratio method for temperature and density measurements, the measured intensity ratios are compared with those calculated from the temperature and density measured with Langmuir probes. As a result, the measured intensity ratios are well reproduced by the calculations. The discrepancies in the ratios $I(728 \text{ nm}) / I(706 \text{ nm})$ and $I(668 \text{ nm}) / I(728 \text{ nm})$ between the measurements and calculations are about 12%.

Keywords:

electron temperature, electron density, line intensity ratio, He I, diagnostics, tokamak, divertor, spectroscopy, collisional radiative model, JT-60U

1. Introduction

Measurement of electron temperature and density in divertor plasmas is crucial for understanding of divertor physics [1]. Langmuir probes are useful for measuring the temperature and density [2]. Recently, Thomson scattering has been applied to measure divertor plasmas in DIII-D [3]. However, the Langmuir probe suffers damage by heat flux, and installation of the Thomson scattering system is limited due to poor accessibility in the divertor region. In TEXTOR, He I lines (668 nm, 706 nm, and 728 nm) from an injected He-atom beam have been used to measure the peripheral region of the limiter plasmas [4,5]. In JET, the same technique has been applied for divertor plasma

measurements [6]. Using emission from helium particles is favorable, because helium injection has little effect on fusion plasma performance. Helium atoms are intrinsically produced by nuclear reactions in fusion reactors. Although using emission from recycling helium atoms in divertor plasmas is favorable with respect to accessibility, it has not been reported in detail. It is important to evaluate the feasibility of using line emission from the recycling helium atoms for determination of the temperature and density. Study of emission from the recycling helium atoms is also significant to diagnose helium particle behavior in divertor plasmas.

In JT-60U, helium gas was injected and the He I

corresponding author's e-mail: kubo@naka.jaeri.go.jp

lines (668 nm, 706 nm and 728 nm) emitted from the recycling helium atoms in the divertor plasmas have been simultaneously observed. The temperature and density derived from the intensity ratios using a collisional-radiative model are compared with those measured with Langmuir probes at the divertor plates. The intensity ratios are also calculated from the temperature and density measured with the Langmuir probes. By comparison of the measured intensity ratios with the calculated ones, the feasibility of the intensity ratio method to measure temperature and density is discussed.

2. Experiment

JT-60U is a tokamak with a major radius of 3.4 m and a minor radius of 1.1 m. Confinement improvement and steady-state operation have been studied with a W-shaped divertor in the bottom [7,8]. A cross-sectional view of the divertor is shown in Fig. 1. The W-shaped divertor is composed of divertor plates, dome and baffle plates. Neutral particles are exhausted through the gap between the inner divertor plates and the dome.

Diagnostics for the present study are also shown in Fig. 1. A 60-channel fiber optic array measures the spatial distribution of visible light radiated from the divertor region with a spatial resolution of about 1 cm. The intensity distributions of four visible lines including the He I lines (668 nm, 706 nm and 728 nm) are simultaneously measured using an interference filter optics with four interference filters and four image-intensified photo-diode arrays [9]. Langmuir probes are installed at the divertor plates with a separation of about 2.5 cm to measure the electron temperature and density.

Fig. 1. Cross-sectional view of the JT-60U divertor and diagnostics for the present study.

The investigation was performed in L-mode discharges [10]; the plasma current was 1.2 MA, the toroidal magnetic field was 3.5 T, and the power of the neutral beam injection was 4 MW. The working gas was hydrogen, and helium gas was injected for 0.2 s before the neutral beam injection. The helium density measured by the charge exchange recombination spectroscopy was about 6% of the electron density in the main plasma. The signal of the He I line emission was integrated for 1 s in a steady state period during the neutral beam heating in order to reduce the statistical error. Attached and partially detached plasmas in the outer divertor have been studied.

3. Collisional-Radiative Model

Intensities of the He I lines are calculated using a collisional-radiative model [11]. Under the assumption that the quasi-steady-state approximation is valid for the populations of the all excited levels, the population $n(p)$ of the level p is expressed by

$$n(p) = [R_0(p) n(\text{He}^+) + R_1(p) n(\text{He})] n_e, \quad (1)$$

where $R_0(p)$ and $R_1(p)$ are the reduced population coefficients for the level p ; $n(\text{He}^+)$ and $n(\text{He})$ are helium ion and atom densities, respectively; and n_e is the electron density. The population which is proportional to the helium ion density is the recombination component, and that proportional to the helium atom density is the ionization component. Under ionizing conditions, $n(\text{He}^+)$ in eq. (1) can be neglected, and the intensity $I_{p'p}$ for a transition from level p to level p' can be expressed by

$$\begin{aligned} I_{p'p} &= A_{p'p} n(p) \\ &= A_{p'p} R_1(p) n(\text{He}) n_e \\ &= \epsilon_{p'p} n(\text{He}) n_e \end{aligned} \quad (2)$$

where $A_{p'p}$ is the transition probability from the level p to the level p' , and $\epsilon_{p'p}$ is an emission rate coefficient which depends on temperature and density. Ionizing conditions are satisfied for the He I lines in JT-60U divertor plasmas. The emission rate coefficients are calculated considering radiative decay, collisional excitation and deexcitation, and ionization. It is assumed that the plasma is optically thin. Proton collisions are also considered for transitions between different orbital-angular-momentum (l) levels. The excited levels with principal quantum number $n \leq 20$ are included in the calculation. The excited states with $n \leq 7$ are treated as

individual levels, except for the levels with $l \geq 3$. The latter levels are grouped together for each individual principal quantum number. The excited levels with $n = 8 - 10$ are grouped according to principal quantum number and total spin number. The excited levels with $n = 11 - 20$ are also grouped according to principal quantum number. Details of the calculation and the atomic data are described in ref. 12.

Emission rate coefficients for the He I lines are shown as functions of electron temperature and density in Fig. 2. The emission rate coefficients decrease rapidly with decreasing temperature in the temperature range below 20 eV, because the excitation energy from the ground level to the excited levels is about 23 eV.

The intensity ratios of the He I lines: $I(728 \text{ nm}) / I(706 \text{ nm})$ and $I(668 \text{ nm}) / I(728 \text{ nm})$, are shown in Fig. 3. The intensity ratio $I(728 \text{ nm}) / I(706 \text{ nm})$ depends strongly on the temperature and weakly on the density. The temperature dependence is ascribed to different energy dependence between the excitation cross sections from the ground level to the singlet level ($3s^1S$) and that to the triplet level ($3s^3S$). The intensity ratio is suitable for temperature measurements. On the other hand, as shown in Fig. 3 (b), the intensity ratio $I(668 \text{ nm}) / I(728 \text{ nm})$ depends strongly on the density and weakly on the temperature. It is suitable for density measurements. The density dependence is ascribed to l -changing processes which make the population ratios of the $3s^1S$ and $3d^1D$ levels close to the statistical weight ratio of the levels with increasing density. Therefore, the temperature and density satisfying simultaneously the relations in Fig. 3. can be derived from the two intensity ratios. Limitations in the measurement technique are discussed in ref. 13.

4. Results and Discussion

Figure 4 shows an intensity distribution of the He I line (668 nm) measured with the 60-ch fiber optic array. The two peaks correspond to the inner and outer divertor plates. In the present paper, emission from in front of the outer divertor plates, that is measured using viewing chord 53, is discussed. The viewing chord is indicated in Fig. 1.

The electron temperature and density measured with the Langmuir probes at the divertor plates are shown in Fig. 5. In the discharge with a line-averaged electron density in the main plasma of $1.2 \times 10^{19} \text{ m}^{-3}$, the divertor plasma is attached. In the discharges with the density in the main plasma of $2.7 \times 10^{19} \text{ m}^{-3}$, the divertor plasma is detached in a narrow region near the

Fig. 2. Emission rate coefficients for the He I lines ((a) He I $2p^1P-3d^1D$, 668 nm; (b) He I $2p^3P-3s^3S$, 706 nm; and (c) He I $2p^1P-3s^1S$, 728 nm). Thick solid lines: electron density is $1 \times 10^{18} \text{ m}^{-3}$, thick broken lines: $1 \times 10^{19} \text{ m}^{-3}$, and thin lines: $1 \times 10^{20} \text{ m}^{-3}$.

separatrix (partial detachment) [14,15]. The detachment is not clearly seen in the probe measurement, since the width of the detached region is less than 1 cm and the divertor plasma is attached outside of the narrow detached region. However, the detachment is detected from the spatial distribution of $D\alpha$ emission from the divertor region [16]. Profiles of the temperature and density are fitted using exponential functions:

$$T_e(x) = T_e^{\text{sep}} \exp(-x/\lambda_T) \quad (3)$$

$$n_e(x) = n_e^{\text{sep}} \exp(-x/\lambda_n) \quad (4)$$

Fig. 3. Intensity ratios of the He I lines. (a) $I(728 \text{ nm}) / I(706 \text{ nm})$ and (b) $I(668 \text{ nm}) / I(728 \text{ nm})$.

where x is the distance from the separatrix field line along the outer divertor plates, T_e^{sep} and n_e^{sep} are the electron temperature and density at the separatrix, and λ_T and λ_n are e-folding distances for the temperature and density. The fitted profiles of the temperature and density are also shown in Fig. 5 as lines. For the partially detached plasma, the Langmuir probe data for $x < 1 \text{ cm}$ are neglected for the fit, because the data seem to be affected by the detachment.

The temperature and density derived from the fits to the Langmuir probe data are shown in Fig. 6 for a number of discharges. The temperature and density at the separatrix are plotted for the attached plasmas, and those at the distance from the separatrix of 1 cm are plotted for the partially detached plasmas. The temperature decreases from 53 to 6 eV as the electron density in the main plasma increases. On the other hand, the density increases from 0.3×10^{19} to $3.6 \times 10^{19} \text{ m}^{-3}$ as the main plasma density increases. The e-folding distances for the temperature and density are shown in Fig. 6 (c). The e-folding distance for the density is about 10 cm and does not change with the density in the main plasma. On the other hand, the e-folding distance for the temperature is as large as that for the density in the low-density range, and it increases with the density in the main plasma. As shown in Fig. 5 (a), the temperature profile is flat in the partially detached divertor plasma.

The temperature and density derived from the ratios of the He I line intensities measured with the fiber optic array using the relations presented in Fig. 3 are also

Fig. 4. Intensity distribution of the He I line (668 nm) measured with the 60-ch fiber optic array. The line-averaged electron density in the main plasma is $1.2 \times 10^{19} \text{ m}^{-3}$.

shown in Fig. 6. The temperature and density vary qualitatively similar to the values derived from the Langmuir probe measurement. Thus, the intensity ratio method is useful for obtaining information about the temperature and density. However, the temperature and density derived from the intensity ratios are generally lower than those derived from the Langmuir probe measurements.

In the collisional-radiative model calculation, the quasi-steady-state approximation is assumed for the populations of the all excited levels and the plasma is assumed to be optically thin. Here, we will briefly discuss validity of these assumptions for the present experiment. To apply the quasi-steady-state

approximation, the length that the atoms move in the longest relaxation time of the excited levels must be shorter than the length for change of the plasma. In the present case, the longest relaxation time is determined by the ionization rate of the $2s\ ^3S$ level [13] and it is estimated to be shorter than 2×10^{-6} s. Then, the length that the atoms move in the time is estimated to be

Fig. 5. (a) Electron temperature and (b) electron density at the outer divertor plates as functions of the distance from the separatrix on the outer divertor plates. Closed circles: the line-averaged electron density in the main plasma is $1.2 \times 10^{19} \text{ m}^{-3}$; open circles: $2.7 \times 10^{19} \text{ m}^{-3}$. The lines indicate fitted profiles of the temperature and density.

Fig. 6. (a) Electron temperature, (b) electron density, and (c) reciprocal e-folding distances for the temperature (solid circles) and density (crosses) as functions of the line-averaged electron density in the main plasma. In figures (a) and (b), the solid circles are the temperature and density derived from the Langmuir probe measurements and crosses are those derived from the He I line intensities measured using the viewing chord passing in front of the outer divertor plates.

shorter than 3 mm and it is much shorter than the length for change of the plasma. Therefore, the assumption of the quasi-steady-state is valid. The most considerable effect of radiation trapping is for the $1s^2\ ^1S-1s2p\ ^1P$ and $1s^2\ ^1S-1s3p\ ^1P$ lines. The escaping factors for these two lines are estimated to be larger than 0.75 and 0.9 using a simple calculation [11]. Then, the change in the intensity ratios due to the radiation trapping is estimated to be less than 3%. Therefore, the effect of optical thickness is not important in the present study.

The discrepancy could be ascribed to chord integration effects for the He I line intensity measurement. The intensity $I_{p'p}$ in front of the divertor plates is expressed as

$$I_{p'p}(x) = [\Gamma_{He}(x) / V_{He}] n_e(x) \epsilon_{p'p} [T_e(x), n_e(x)], \quad (5)$$

where Γ_{He} and V_{He} are the flux density and flow velocity of the helium atoms recycled at the divertor plates, respectively. Since most of the helium atoms are desorbed from the divertor plates, it is assumed that the flow velocity does not change with the distance x [10]. We assume that the helium atom flux density is proportional to the hydrogen ion flux density Γ_{H^+} to the surface of the divertor plates, which can be expressed by

$$\Gamma_{H^+}(x) = n_e(x) c_s(x) \sin [\theta(x)], \quad (6)$$

where c_s is the acoustic speed and θ is the angle between the magnetic field line and the surface of the divertor plates. Since the acoustic speed is proportional to the square root of the temperature, using eqs. (5) and (6), the chord-integrated intensity $\int I_{p'p}(x) dx$ to be measured using the viewing chord passing in front of the outer divertor plates is expressed as

$$\int I_{p'p}(x) dx \propto \int n_e^2(x) T_e^{1/2}(x) \sin \theta(x) \epsilon_{p'p} [T_e(x), n_e(x)] dx. \quad (7)$$

Using eqs. (3), (4) and (7), we can calculate the intensity from the data presented in Figs. 2 and 6. In the case of the partial detachment, we exclude the range with $x < 1$ cm from the integration range, since the ion flux density and electron density are negligibly small in the detached region [14,15].

The measured intensity ratios $I(728) / I(706)$ and $I(668) / I(728)$ are compared with the calculated ones in Fig. 7. The calculations reproduce the measurements

well. The root-mean-square discrepancies in the ratios between the calculations and measurements are about 12%. The discrepancies can be probably ascribed to the error in the Langmuir probe measurement and collisional-radiative model calculation.

As a result, the emission rate coefficients for the He I lines are reliable for measuring the temperature and density. Two-dimensional distribution measurement of the He I line emission is expected to be useful for determination of the exact distribution of the temperature and density in the divertor plasma.

Fig. 7. Relation between the measured and calculated intensity ratios. (a) $I(728) / I(706)$ and (b) $I(668) / I(728)$.

5. Summary

The three He I lines emitted from recycling helium atoms in the divertor plasma were observed simultaneously. Information about the electron temperature and density could be qualitatively obtained from the He I line intensities. The measured intensity ratios were compared with those calculated from the temperature and density measured with Langmuir probes, and it was found that the emission rate coefficients for the He I lines are reliable for measurement of the temperature and density. Two-dimensional distribution measurement of the He I line emission is expected to be useful for determination of the exact distribution of the temperature and density in the divertor plasma.

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