Impact of Nonuniform Spatial Distribution of Ground-State Atoms on He I Line Intensity Ratio Analysis

Shogo OTSUKA[1)]*, Hiroyuki TAKAHASHI[1)], Keigo YOSHIMURA[2)], Ryota NISHIMURA[1)], Shigetaka KAGAYA[1)], Muto TAKAHASHI[1)], Ryota INOUE[1)], Daichi KARAHASHI[1)], Hiroki MINAMI[1)], Tetsutarou OISHI[1)]

[1)] *Department of Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan*
[2)] *National Institutes for Quantum Science and Technology, Rokkasho, Aomori 039-3212, Japan*

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This study developed a model to calculate the optical escape factor in consideration of the spatial distribution of ground-state (1^1S) helium atoms. Based on the improved model, the impact of spatially nonuniform distribution on the helium line intensity ratio (LIR) method was investigated. The LIR method reproduced the input n_e and T_e values with good agreement when the spatial distribution was considered appropriately, whereas n_e and T_e evaluated without considering the distribution exhibited considerable deviations. These results suggest that the spatial distribution of the 1^1S atoms can be a significant source of uncertainty in the helium LIR method.

Keywords: helium line intensity ratio method, radiation trapping, escape factor, spatial distribution of ground-state atoms, CR model

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The He I line intensity ratio (LIR) method is widely used to diagnose electron density (n_e) and electron temperature (T_e). However, in the LIR method, radiation trapping becomes a significant source of uncertainties under optically thick plasma conditions. A convenient way to compensate for radiation trapping is by introducing the optical escape factor (OEF) for 1^1S-n^1P resonant transitions, where n denotes the principal quantum number. The effect of radiation trapping is more pronounced for resonant levels (n^1P); thus, several OEF calculation models have been proposed [1, 2] for various spatial distributions of the upper level. In most cases, these models assume that the spatial distribution of the helium atoms in the ground state (1^1S) is uniform. However, in realistic plasmas, this distribution can be nonuniform, primarily due to neutral pumping [3], which is caused by ion drag and gas heating. Discrepancies between the assumed and actual spatial distributions lead to increased uncertainties in the LIR method; however, their impact has remained unclear. Thus, in this study, we developed the OEF calculation model proposed by Iida [2] to account for the spatial distribution of the 1^1S atoms.

OEF (Λ) at a certain normalized position (R_N) in cylindrical coordinates is calculated based on Eqs. (1) and (2). Here, q and p denote the upper and lower levels, specifically corresponding to the n^1P and 1^1S levels, respectively. L_q denotes the characteristic length of the spatial profile of the population density of the upper level (n_q). Note that atoms excited in n^1P levels are strongly coupled with those in the ground state; thus, the same value can be utilized for temperatures T_q and T_p [4]. In this study, 300 K was assumed. The definitions of other parameters are the same as reported in the literature [2]. k'_{pq0} is the absorption coefficient at the spectral center. The effect of spatially nonuniform 1^1S atoms was incorporated by spatially integrating the term in square brackets in Eq. (1) and considering the spatial profiles of $n_p(R_N)$ in Eq. (2). In this study, the OEF was calculated up to $n = 7$.

$$\Lambda_{qp}(R_N) = 1 - \frac{2}{\pi\sqrt{\pi}}\frac{k'_{pq0}(R_N)L_q}{n_q(R_N)}\int_0^{+\infty}dx\int_0^{\pi}d\varphi\int_0^{\frac{\pi}{2}}d\theta$$
$$\exp\left[-\left(1+\frac{T_q}{T_p}\right)x^2\right]\times\int_0^{r_{Nj}}dr_N \tag{1}$$
$$\times\left\{n_q(R_N'(r_N))\exp\left[-\int_0^{r_N}\frac{k'_{pq0}(r_N')}{\sin\theta}\exp\left(-\frac{T_q}{T_p}x^2\right)dr_N'\right]\right\},$$

$$k'_{pq0}(R_N) = \frac{e^2}{4m_e c\varepsilon_0}f_{pq}\lambda_{qp}\sqrt{\frac{m_{He}}{2\pi\kappa_B T_p}}\,n_p(R_N). \tag{2}$$

The impact of the spatially nonuniform 1^1S atoms on the helium LIR method was investigated as follows based on the developed OEF model. (1) First, the population densities excited into the 3^1S, 3^1D, and 3^3S levels were calculated using a collisional-radiative model for the He atom [5], assuming the spatial distributions of n_e, T_e, and 1^1S atoms. Simultaneously, the OEFs for 1^1S-n^1P transitions were calculated. (2) The LIRs of 2^1P-3^1D/2^1P-3^1S (667.8/728.1 nm) and 2^1P-3^1S/2^3P-3^3S (728.1/706.5 nm) were obtained based on the calculated population densities. This combination is suitable for investigating the impact of the 1^1S atom distribution because

*Corresponding author's e-mail: otsuka.shogo.r5@dc.tohoku.ac.jp

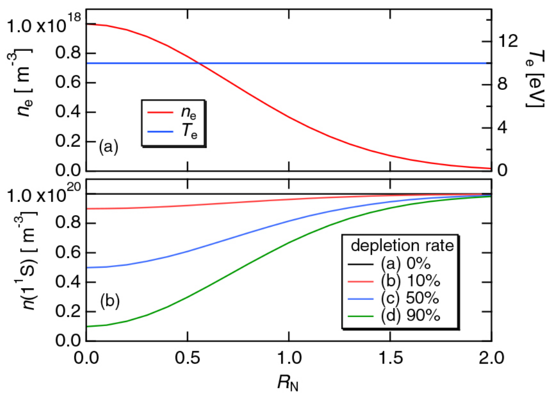

Fig. 1. Assumed spatial distributions of (a) n_e and T_e, and (b) 1^1S atoms.

it is the simplest one in LIR analysis for helium plasma. (3) The above ratios were calculated again for various combinations of n_e and T_e using the OEFs calculated assuming spatially uniform and nonuniform 1^1S atoms. (4) Finally, n_e and T_e were obtained by minimizing the difference between the line ratios obtained in Steps (2) and (3).

As shown in Fig. 1(a), we assumed a center-peaked distribution for n_e and a spatially uniform distribution for T_e because such distributions are commonly observed in laboratory plasmas. Here, the horizontal axis is the plasma radius normalized by L_q (the e-folding length of n_e). In this study, L_q was set to 0.01 m. At the plasma core, neutral atoms in a cylindrical plasma are sometimes depleted by neutral pumping [6]. To consider this effect, four spatial distributions with different depletion rates were employed in this study (Fig. 1(b)). In contrast, although the temperature profile of the 1^1S atoms can also be nonuniform, a spatially uniform profile was employed to investigate the effect of the density profile.

Prior to investigating the impact of the spatial distribution of the 1^1S atoms, we confirmed that the assumed n_e and T_e could be appropriately reproduced when the assumed distributions of the 1^1S atoms were utilized in Step (3). The results are summarized in Fig. 2. As can be seen, both n_e and T_e were reproduced with good agreement regardless of the assumed depletion rates. Note that n_e and T_e at $R_N \geq 1.2$ are not plotted because negative OEFs were obtained at this region, making effective interpretation of the results difficult [2].

In contrast, as shown in Fig. 3, when the 1^1S population was assumed to be spatially uniform in Step (3), the LIR method yielded different n_e and T_e values depending on the depletion rates. For example, at depletion rates of 0% and 10%, the LIR method obtained values that were consistent with the inputs. However, with a large depletion rate (90%), the reproducibility deteriorated considerably at $R_N \leq 0.5$ and $R_N \geq 1.0$. At $R_N \leq 0.4$, n_e and T_e are not plotted due to negative OEF values. At $R_N \geq 1.0$, the OEFs were positive; however, n_e and

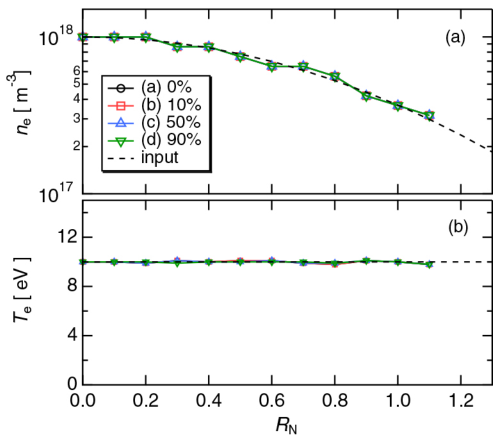

Fig. 2. (a) n_e and (b) T_e obtained by LIR analysis using spatially varying 1^1S atom distribution in Step (3).

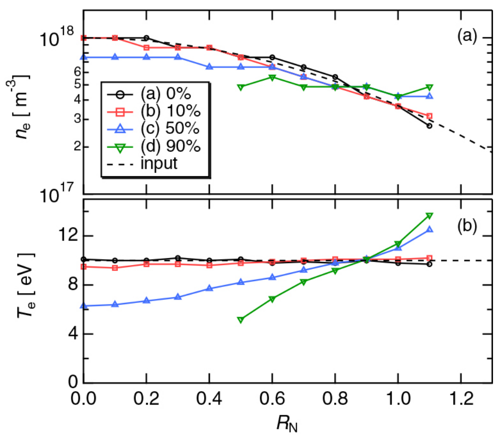

Fig. 3. (a) n_e and (b) T_e obtained by LIR analysis using spatially uniform 1^1S atom distribution in Step (3).

T_e were overestimated compared with the input values. These results suggest that the spatial distribution of 1^1S atoms can be a significant source of uncertainty in helium LIR analysis.

Using the improved OEF model, we have demonstrated that performing helium LIR analysis without considering appropriate spatial distribution of the 1^1S atoms leads to uncertainties in the evaluation of n_e and T_e.

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