Radiation Reabsorption Using Plasma Spectroscopic Diagnostics of High Density He Arc Plasmas

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ABSTRACT

It is possible to determine the plasma parameters such as electron temperature/density and the external field by observing the light emission spectroscopically from the plasmas. The so-called plasma spectroscopy is used as one of the non-invasive plasma diagnostic methods which investigates the plasma dynamics. However, if we simply treat the effect of radiation reabsorption, which is neglected in the usual analytic model, the observed plasma may impair the understanding of this observation. It deals with the effects of radiation reabsorption on plasma spectroscopic diagnosis. The efforts will be made for linear divertor simulators and plasma spectrometers for high-density LHD plasmas where the optical thickness cannot be ignored. Thus, we discuss the influence of radiation reabsorption in the observations using He arc plasmas.

Keywords: radiation reabsorption, plasma spectroscopy, collisional radiative model, optical thickness, plasma spectroscopic diagnostics, helium arc plasmas, nuclear fusion.

INTRODUCTION

Plasma spectroscopic diagnostics in which plasma parameters such as electron temperature, density and dynamics of the emitting particles are investigated by the spectroscopic observation of the plasma emission. It is one of the invasive plasma diagnostic methods. The effect of radiation reabsorption neglected in conventional analytical model. The optical thickness cannot be neglected in a simulated linear divertor and high density LHD plasmas. In this paper, the radiation reabsorption of the plasma spectroscopy discussed using Helium (He) arc plasmas.

The plasma emission lines observed, and their intensity ratios are analyzed using a collisional radiative (CR) model. Electron temperature and density are evaluated by their intensity ratios of emission lines using CR model. The method has been used as one of the non-invasive methods [1]. The measurement of the high-resolution spectral shapes has enabled the determination of the magnetic field of the luminous atoms at the emission position in LHDs and other plasmas [2,3]. The basic analytical models of plasma spectroscopic diagnostics assume that the observed emission is the direct emission from the atoms/ions to be observed. However, the assumption is not always valid. The optical thickness of the plasma itself or around the atomic gas is not negligible, then emission is also assumed to be same as that from the observed region. Also, if the origin of the emission from the observed region may be re-emitted after absorbing the emission from the other regions of the plasma, the effect of such radiation reabsorption [4] is expected to increase as the plasma density increases. The effect of radiation reabsorption cannot be overlooked as plasma density increases and plasma spectroscopic diagnostics become more accurate [5-7].

The He atom presented in this article. Because the He atom not only always appears in fusion plasmas, but its radiance is of the interest as typical application of collisional radiative (CR) model. It is mainly used for plasma spectroscopic diagnostics. The emission lines from the upper level, which is in the ^1P state, is known to be susceptible to radiation reabsorption because it is connected to a large number of ground state atoms in the surrounding plasma by resonance transitions. In this study, we show the plasma spectroscopic diagnostics using He arc plasmas and introduce the effects of the radiation reabsorption to raise the awareness of the importance of this issue in nuclear fusion.

COLLISIONAL RADIATION IN LINEAR DIVERTOR SIMULATOR MODEL AND RADIATION REABSORPTION

In a fusion reactor, He is produced by the fusion reaction of deuterium and tritium. Therefore, the fusion plasma is originally Hydrogen-He mixed plasma and the intensity of the emission lines from the He is of great importance. The intensity ratio (or occupied density ratio) of the emission lines from the He is calculated using CR model that describes the occupied density of the excited levels. The electron temperature and density are determined by comparing the intensity ratio of the emission lines from the He with the CR model [8]. This method describes the occupancy density of the excited level has proposed [9]. In the case of boundary layer and divertor plasmas with low electron temperature and high neutral atom density due to the gas puffing and recycling, photo absorption process (radiation reabsorption or radiation capture) can be observed which have been ignored in the conventional CR models. The photon absorption process affects the distribution of the excitation levels and has the effect of decreasing the emission process. And thus, the spontaneous emission coefficient (Einstein A coefficient) has been introduced in the calculation. The optical escape factor (hereafter referred to as the escape factor) can be incorporated into the CR model by multiplying the natural emission coefficient (Einstein A coefficient) by the optical escape factor. However, there are many assumptions involved in the deviation process. The discussion of the findings is necessary when applying the CR model to plasmas with high neutral atom density.

CR MODEL WITH RADIATION REABSORPTION

The CR model is a steady state rate equation for the excitation and deexcitation isogenic processes with respect to the occupancy density (population) of the excited levels. In order to use the He I CR model [8] for plasma diagnostics, it is important to select the emission line pairs. The intensity ratio method is also called the “line intensity ratio method” uses the sensitivity of the intensity ratio (occupancy density ratio). The simplest method is to use a plot of the intensity ratio to the selected emission line pairs. Since a straight line parallel to the electron temperature (T_e) axis is independent of the change in the value of the other axis, i.e., the occupancy density ratio. It corresponds directly to the value of the other axis such as the value of emission line pair which can be used for the measurement. Similarly, if there is a pair of emission lines with occupied density ratio where lines parallel to the axis and in this case the parallelism of the two axes will give the error of the estimated value. However, if the plot height changes in the parameter region of interest must be sufficiently steep compared to the range of the accuracy of intensity measurement. If there are no parallel lines, but there are lines with opposite trends (intersections) as in the binary linear equation, the intersections of the two pairs of occupancy density ratio lines are simultaneously determined. In the absence of clear independence, the convergence properties of the least-squares fitting to the evaluation function of multiple measured occupancy density ratios are investigated. The evaluation function should minimize the sum of squares of the difference between the measured occupancy density ratio and the value calculated by the CR model. In some cases, depending on the weights, a method such as using the ratio of the occupancy density divided by the degeneracy or using the logarithm of the ratio is employed.

The energy dependence of the excitation cross section is above the threshold value with a gradual decay in the singlet and a slightly steeper decay in the triplet. The ratio of the singlet to the triplet is therefore sensitive to the electron energy distribution function, resulting in emission line pairs that are dependent on the electron temperature. Conversely, singlet to singlet, triplet to triplet and triplet to singlet, the frequency of excitation depends on the number of collisions, and thus the electron density has a large effect on the excitation frequency. The “optically thick” condition, in which radiation reabsorption is an important elementary process. In this paper, we discuss the spontaneous emission coefficients for the resonance transitions that are optically coupled to the ground level (satisfying the selection rule). The spontaneous emission coefficient is replaced by ΛA and multiplied by the escape factor (Λ) which is due to the radiation reabsorption (n=2 to 7, but in practice there is no significant difference to the extent that the measurement is made). The escape factor can be expressed as a function of the physical quantity τ, the “optical thickness”, that is a measure of the contribution of the radiation reabsorption. If $\tau << 1$, $\Lambda = 1$, i.e., optically thin, and if $\tau > 1$, ΛA is smaller than $\Lambda << 1$, i.e., optically thick. The functional form of the escape factor depends on the model used and conditions assumed.

FUNCTIONAL FORM OF ESCAPE FACTOR

This section introduces the functional form of the escape factor of the plasma center, which is often used in cylindrical plasmas. The two approaches to derive the escape factor: direct integration and eigen mode expansion method. When spatial distribution of the upper level is known, a considerable amount of effort is required to calculate the escape factor at an arbitrary position. Therefore, various assumptions have been made historically to simplify the model and make it relatively easy to perform the calculations. If the spectral shape is Gaussian (determined by the doppler broadening), spatially uniform, i.e., the temperature is uniform in space, and induced emission is negligible (the upper-level density is small), the optical thickness τ is given by Eq. (1) with the mass number 4 for He,

$$\tau(= \tau_{pq\,0}) = 1.16546 \times 10^{-8} f_{pq} \lambda_{qp} \sqrt{\frac{A_M}{T_p}}\, n_p L_q \qquad (1)$$

Therefore, the parameters describing the escape factor are the temperature [K] of the lower level, the density [m^{-3}], and length [m] to the modal boundary with respect to the upper level (called the radiation capture radius) f_{pq} is the oscillator strength of the p → q transition. And in the case of He I (1^1S-2^1P), f_{pq} is 0.27625 (strong emission lines are generally on the order of 0.1-1). Then, assuming f_{pq}~1, T_p=400 K, and λ=58.4 nm, the value is about τ~ 10-17 n_p L_q. Therefore, a gas pressure of about ~1.5 pa is sufficient to enter the optically thick ($\tau > 1$) region. The optical thickness of the material is about 1 for 400 K and 58.4 nm.

Below is the functional form of the concrete escape factor. For example, to solve specifically using the eigenmode expansion method assume a plasma shape as a boundary condition. In the case of a cylindrical plasma the lowest order eigenfunctions are bell-shaped and can be written using Bessel functions. The numerical solution of the eigenvalues, i.e., the escape factor, was presented by Phelps [10] and an easy-to-use approximation has been developed by Fujimoto [1].

$$\Lambda(\tau) = \frac{1.92 - 1.3(1+\tau^{1.2})^{-1}}{(\tau+0.62)(\pi \ln(1.357+\tau))^{0.5}} \qquad (2)$$

The above equation was proposed by Phelps-Fujimoto. The derivation of this equation is an escape factor that can be used when the radial distribution of the upper levels is bell-shaped. The spatial distribution of the upper levels is consistent with the used eigenfunction, the escape factor is an eigen value which is spatially uniform. However, in reality, the escape factor is not completely uniform due to the errors near boundaries [12].

On the other hand, Otsuka [13] used a direct integration method. If the ratio of the upper and lower levels is constant, i.e., if the lower level is uniform, the upper level also has a uniform rectangular distribution up to the model boundary and a Gaussian spectral shape is obtained. Iida [14] proposed a similar approximation using the functional form of Phelps-Fujimoto approximation.

$$\Lambda(\tau) = \min\left(1, \frac{3.811 - 3.284(1+(a\tau)^{b})^{-1}}{(a\tau+0.429)(\pi \ln(b+a\tau))^{0.675}}\right) \qquad (3)$$

The corresponding equation in reference [14] is erroneous. In the case of the direct integration method, the escape factor is obtained as the eigenvalue corresponding to the upper-level spatial distribution (eigenfunction). The question is which formula to use, or whether our system satisfies the conditions for the application of this formula.

CR MODEL WITH ESCAPE FACTOR

In the visible spectra of He I, the lower level is n=2 (^1S, ^1P, ^3S, ^3P) and the upper level is n>=3, but the emission is limited to n=2 and the allowed transitions are S, P and D terms. So, once the upper level is determined, the lower-level n=2 and the corresponding wavelengths are uniquely determined. The upper-level term is often used as the label to distinguish the emission lines. The escape factor for visible light is almost 1, which means that it is optically thin. The effect of radiation reabsorption occurs at the optically allowed transition between 1^1S and n^1P levels in the vacuum ultraviolet region. The ^1P level occupancy density is distributed to each level by collision. Therefore, the effect on the electron temperature T_e measurement using the singlet-triplet occupancy density ratio is remarkable. Let’s look at the change of the occupied density ratio by assuming a divertor plasma with the electron temperature T_e=1-20 eV and electron density $n_e=10^{11-14}$ cm^{-3}. The escape factor is the Otsuka-Iida Eq. (3) with pressure ~1.3 Pa, atomic temperature 400 K based on the Hydrogen molecular rotation temperature [15],

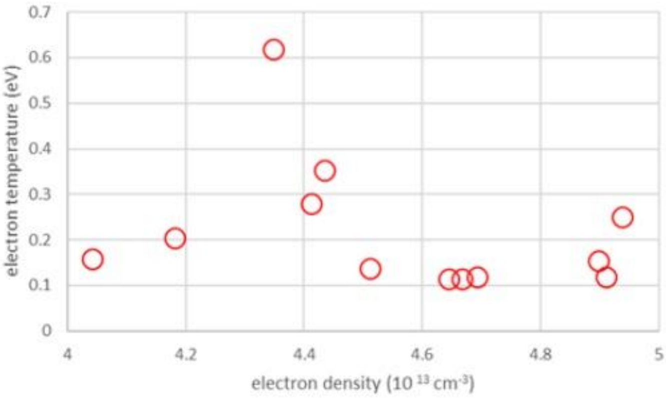

Figure 1: The effect of radiation reabsorption on the occupied density, which is widely used as a parameter for He-containing plasmas from visible emission spectrum.

As shown in Fig. 1, the electron density [16,17] against the electron temperature [18] for the measurement where it is optically thin in the low temperature region. The electron temperature is as high as ~0.7 eV for the electron density of 4.3×10^{13} cm^{-3}. The emission lines are deformed by radiation reabsorption for high temperature region. The emission lines are limited to $4\text{-}5\times10^{13}$ cm^{-3}. The sensitivity may deteriorate in the high electron density region.

Sasaki et. al. proposed the use of n=4 emission lines in low temperature plasmas such as divertor simulator and found that the effect of radiation reabsorption on the occupied density, showed that the effect of radiation reabsorption appeared [19]. In general, the triplet stage is not susceptible to radiation reabsorption, but it is essential to evaluate the sensitivity, i.e., whether the change in the occupied density is sufficient for a change in the plasma parameters.

ESCAPE FACTOR AND T SIMILARITY

For a line integral measurement, the density ratio reflects the value of the central bright region, so using the escape factor of the center was not a poor approximation. However, based on the derivation process, the Phelps-Fujimoto equation (Eq. 2) cannot be used when the radial distribution of the upper levels is not bell-shaped, and the Otsuka-Iida equation (Eq. 3) cannot be used when the distribution is not uniform.

The relationship between the escape factor for the Gaussian upper-level distribution is shown in Fig. 2 (a) as a function of τ where τ used for Gaussian upper-level distribution as written as optical thickness. Optical thickness increases when the optical escape factor decreases for the high-density region. Figure 2 (b) shows the distribution of plasma giving the escape factor against the electron density. Plasma radius increases when the electron density increases due to the effect of the radiation reabsorption. The radiation reabsorption process is prominent for the lower escape factor sections.

Dependence of Escape factor on the optical thickness according to Molish approx. [4]

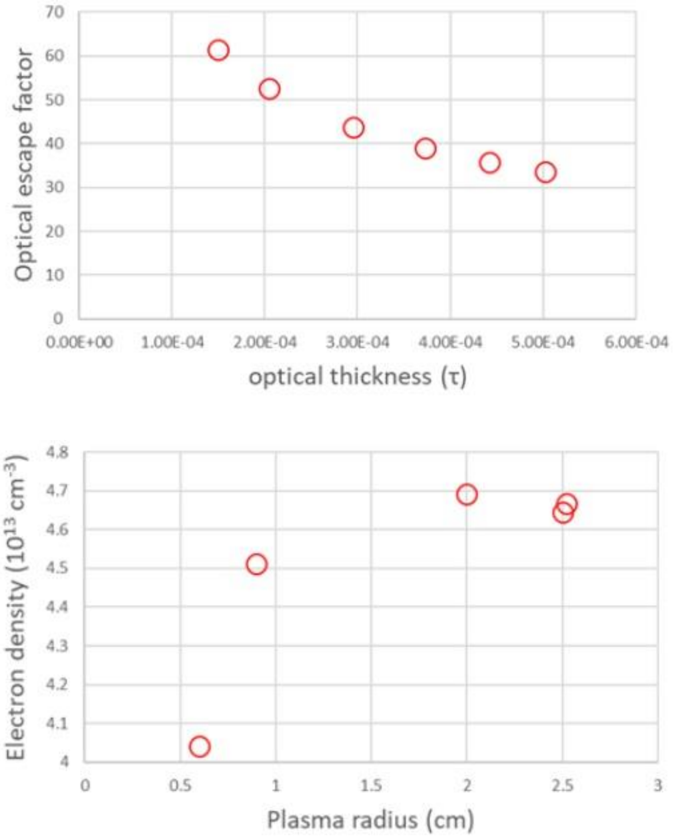

Figure 2: (a) Dependence of Escape factor on the optical thickness according to Molish approx. [4] (b) Distribution of plasma giving the Escape factor.

SUMMARY

The population of the levels on each emission lines of heated He plasmas are evaluated by plasma spectroscopy. The contribution of radiation reabsorption to the population is quantified by the CR model. The influence of radiation reabsorption is quantified by an analysis using the radiation transport equation. And Monte Carlo treatment of radiation reabsorption will be necessary to quantify the contribution of radiation reabsorption to population. However, this is a very difficult problem to analyze the effect quantitatively.

Heated helium plasma spectroscopy is pivotal for numerous applications, spanning from controlled fusion research to astrophysical investigations. Analyzing emission line population levels offers valuable insights into plasma temperature, density, and composition, crucial for enhancing plasma-based technologies and unraveling natural phenomena. Precise assessment of population levels is instrumental in refining plasma-based processes, including the development of diagnostic systems for fusion reactors operating in high-density plasma environments. Here, meticulous control over plasma parameters is imperative to attain optimal performance.

Quantifying the impact of radiation reabsorption on population dynamics, employing the CR model and radiation transport equation, entails intricate mathematical and computational processes. Complexity escalates notably with the incorporation of Monte Carlo treatment to ensure precise evaluation. These complexities pose challenges in terms of computational demands, requisite expertise, and time-intensive analyses. Furthermore, the theoretical models utilized for quantification necessitate validation through experimental data, which is particularly challenging to obtain in the high-temperature, high-density environments characteristic of plasma studies, introducing uncertainties in the analysis. Surmounting obstacles in quantifying radiation reabsorption holds the potential to drive advancements in plasma-based technologies, facilitating enhanced energy generation in fusion reactors, refining plasma processing methodologies for material synthesis, and pioneering innovations in space propulsion systems. Moreover, the methodologies and techniques devised for analyzing plasma populations and radiation reabsorption offer broader applications beyond plasma physics. Their adaptation and utilization in fields such as astrophysics and nuclear engineering, where radiation transport and population dynamics are significant, hold promise for transformative developments.

In brief, undertaking the complexities of analyzing radiation reabsorption in heated He plasmas offers valuable opportunities for advancements in real-world applications. Overcoming these challenges can provide valuable insights, benefiting various fields from improved plasma technologies to interdisciplinary scientific pursuits.

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