# Spectroscopic Diagnostics of Radiation Reabsorption in Dense He Arc Plasmas

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## ABSTRACT

Observing the light emission from plasmas spectroscopically allows for the determination of key plasma parameters like electron temperature, density and external field. This method, known as plasma spectroscopy, serves as a non-intrusive diagnostic tool to study plasma dynamics. However, overlooking the impact of radiation reabsorption in the typical analytic model may compromise the accuracy of observed plasma behavior. This study addresses the influence of radiation reabsorption on plasma spectroscopic diagnosis, focusing on linear divertor simulators and plasma spectrometers designed for high-density Large Helical Device (LHD) plasmas, where optical thickness cannot be disregarded. The discussion delves into understanding the effects of radiation reabsorption in these observations.

**Keywords:** nuclear fusion, helium arc plasmas, radiation reabsorption, plasma spectroscopic diagnostics, optical thickness plasma spectroscopy, collisional radiative model, dense plasmas, He plasmas, LHD plasmas, electron temperature, electron density.

## INTRODUCTION

Plasma spectroscopic diagnostics involve exploring plasma parameters, including electron temperature, density, and the dynamics of emitting particles, through spectroscopic observation of plasma emissions. This diagnostic method is considered intrusive. Conventional analytical models often overlook the effect of radiation reabsorption. In simulated linear divertor and high-density LHD plasmas, the optical thickness becomes a significant factor that cannot be ignored. This paper focuses on discussing the radiation reabsorption in plasma spectroscopy, utilizing Helium (He) arc plasmas as a study.

The analysis of plasma emission lines and their intensity ratios employs a collisional radiative (CR) model. The evaluation of electron temperature and density relies on the intensity ratios of emission lines using the CR model, a non-intrusive method [1]. High-resolution spectral shape measurements have facilitated the determination of magnetic fields and luminous atoms at emission positions in devices like LHDs [2] and other plasmas [3]. While basic analytical models in plasma spectroscopic diagnostics assume direct emission from the observed atoms or ions, this assumption isn't universally valid. The optical thickness of the plasma itself or the surrounding atomic gas becomes non-negligible, leading to the assumption that emission is equivalent to that from the observed region. Additionally, if emission from the observed region is re-emitted after absorbing emissions from other plasma regions, the impact of radiation reabsorption is expected to amplify with increasing plasma density [4]. The influence of radiation reabsorption becomes crucial as plasma density rises [5], enhancing the accuracy of plasma spectroscopic diagnostics [6,7].

This article focuses on the presence of He atoms. The significance of He atoms lies not only in their consistent occurrence in fusion plasmas but also in their radiance, making them a noteworthy application for the CR model. Primarily utilized in plasma spectroscopic diagnostics, He atoms, specifically those in the $^1P$ state, exhibit emission lines that are susceptible to radiation reabsorption. This susceptibility arises from their connection to a substantial number of ground state atoms in the surrounding plasma through resonance

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transitions. The study herein demonstrates plasma spectroscopic diagnostics using He arc plasmas and underscores the impact of radiation reabsorption, emphasizing its importance in the context of nuclear fusion.

**Experiment setup:**

To explore radiation reabsorption in a high density arc plasmas [8], we utilize the He cascade arc discharge source [9] with a channel diameter of 8 mm. The arc plasma, generated between the anode and cathode, expands through the anode exit into a large vacuum chamber. Emission spectroscopy in VUV wavelengths is employed for characterizing the high-density He plasmas. Figure 1 illustrates a schematic diagram of the experimental setup for the cascade arc plasma source and a schematic drawing of the VUV and visible emission spectroscopic systems within the vacuum chamber. The cascade arc apparatus comprises water-cooled floating intermediate electrodes (molybdenum Mo) positioned between a cathode and an anode (Mo). The cathode, constructed of lanthanum hexaboride ($LaB_6$), and consists of hollow cylinders [8], is heated to over 1600 °C by a carbon composite heater to facilitate the arc discharge. Molybdenum, which has excellent mechanical and chemical properties, i.e., high melting point and a low coefficient of thermal expansion, is often used as the cathode material. But it has a work function, which indicates the ease of emitting thermions, is relatively high at 4.2 eV. Therefore, $LaB_6$ on a hollow shape cylinder with a low work function of 2.7 eV is employed as a thermionic source. Since the cathode part has a hollow structure, spectroscopic measurement of the plasma discharge part is possible from here.

The VUV spectrometer captures plasma emission at a 45° angle with respect to the plasma jet axis. A tube connects the vacuum chamber, and the VUV spectrometer is exiled by turbomolecular pumps to maintain a high vacuum. Introducing He gas into the expansion chamber allows control over the recombination process of the He arc jet. To determine the electron density at the anode through Stark broadening, visible emission is also measured. Small visible spectrometers observe the cathode and anode electrodes, and a precise discharge current monitor is installed to confirm any fluctuation in the discharge plasma during the experiment. He I spectra around series limit (24.6 eV) are measured with the VUV spectrometer to evaluate the electron temperature from the radiative continuum emission [10]. The VUV spectrometer with a focal length of 1.0 m has a diffraction grating and a back illuminated CCD camera. The plasma expanded as sonic jet into the vacuum chamber. The He gas in the chamber is exhausted to a calculated value, as low as possible, during the plasma operation by large vacuum pump. Besides, He gas is fed through pipe at the center of hollow shape cathode to the tapered and cylindrical channels at different flow rates, which is controlled by a mass flow controller. Solenoid coils create a magnetic field at the intermediate electrodes. The weekly ionized He arc plasma is defined as a viscous gas, because of a low value of the Knudsen number.

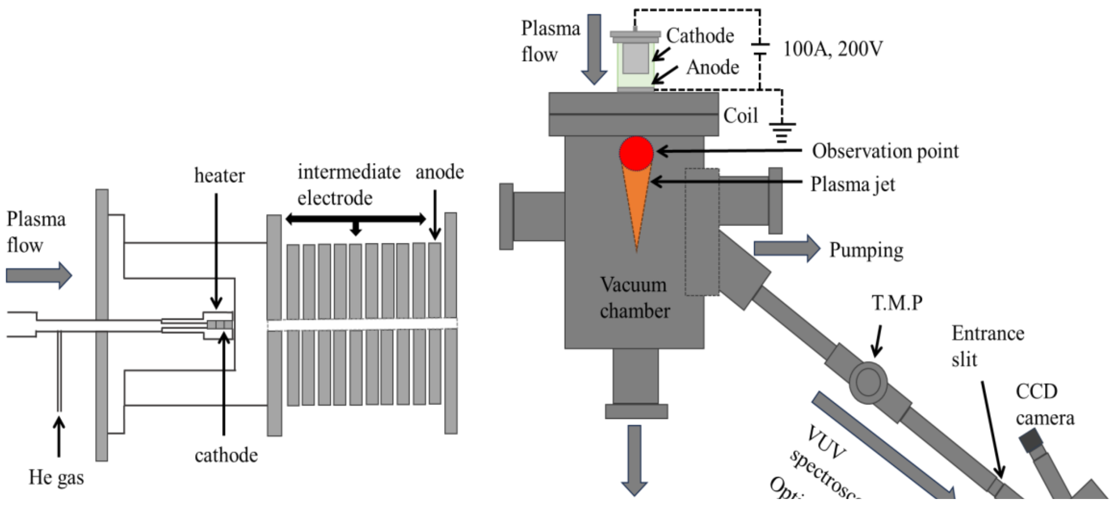


Figure 1: Schematic of He discharge device and Diagram of experiment setup.

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**Collisional Radiation and Radiation Reabsorption in Linear Divertor Simulator Models:**

In a fusion reactor, He is generated through the fusion reaction of deuterium and tritium. Consequently, the fusion plasma initially comprises a Hydrogen-Helium mixed plasma, with the emission lines from He being of significant importance. The intensity ratio, or occupied density ratio, of these He emission lines is computed using the CR model, which characterizes the occupied density of the excited levels. The electron temperature and density are determined by comparing the intensity ratio of the He emission lines with the CR model [11]. This approach has been introduced, proposing the description of the occupancy density of the excited level [12].

In scenarios involving boundary layer and divertor plasmas with low electron temperature and high neutral atom density resulting from gas puffing and recycling, the photo absorption process, known as radiation reabsorption or radiation capture, becomes observable. This process, previously overlooked in conventional CR models, impacts the distribution of excitation levels, leading to a reduction in the emission process. Consequently, a spontaneous emission coefficient (Einstein A coefficient) is 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, i.e. Einstein A coefficient, by this optical escape factor. However, it's crucial to acknowledge the various assumptions inherent in this deviation process. Discussion of these findings becomes essential when applying the CR model to plasmas characterized by high neutral atom density.

**Radiation reabsorption in CR model:**

The CR model represents a steady-state rate equation governing excitation and deexcitation processes in terms of the population (occupancy density) of excited levels. To apply the He I CR model in plasma diagnostics [11], careful selection of emission line pairs is crucial. The intensity ratio method, also known as the "line intensity ratio method," relies on the sensitivity of the intensity ratio, which corresponds to the ratio of occupancy densities.

The excitation cross section's energy dependency is notable above the threshold, exhibiting a gradual decrease in the singlet and a slightly steeper decline in the triplet. Consequently, the ratio of singlet to triplet is highly sensitive to the electron energy distribution, leading to emission line pairs reliant on electron temperature. We also address the significance of the "optically thick" condition, where radiation reabsorption plays a vital role. This paper delves into spontaneous emission coefficients for resonance transitions optically linked to the ground level, adhering to selection rules. These coefficients, denoted as ΛA, are adjusted by the escape factor (Λ) due to radiation reabsorption (applicable to n=2 to 7 transitions, although practically negligible). The escape factor, Λ, correlates with the physical quantity τ, representing the "optical thickness," which measures the radiation reabsorption's impact. When τ is much less than 1, Λ equals 1, signifying optical thinness. Conversely, when τ exceeds 1, ΛA is less than Λ, indicating optical thickness. The specific form of the escape factor varies depending on the model and assumed conditions.

**The escape factor Λ:**

This section introduces the escape factor of the central plasma, a parameter commonly applied in cylindrical plasma setups. Two methods are typically employed to determine the escape factor: direct integration and the eigen mode expansion technique. Calculating the escape factor at any given position demands considerable effort, especially when the spatial distribution of the upper level is known. Consequently, throughout history, various simplifying assumptions have been adopted to streamline calculations. Assuming a Gaussian spectral shape (dictated by Doppler broadening), spatial uniformity (where temperature remains consistent throughout space), and negligible induced emission (resulting from low upper-level density), the optical thickness (τ) can be determined using Eq. (1), incorporating the appropriate mass number (e.g., 4 for helium),

$$\tau\left(=\tau_{pq}\right) = 1.17\times 10^{-8} f_{pq} \lambda_{qp} {A_M}^{0.5} \frac{n_p}{{T_p}^{0.5}} L_q \quad (1)$$

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Thus, the factors governing the escape factor encompass the temperature [K] of the lower level, the density [$m^{-3}$], and the length [m] to the modal boundary relative to the upper level (referred to as the radiation capture radius), while $f_{pq}$ represents the oscillator strength of the p → q transition. Phelps provided a numerical solution for the eigenvalues, representing the escape factor, whereas Fujimoto devised a user-friendly approximation [13,14].

$$\Lambda(\tau) = \frac{1.9-\left(\frac{1.3}{1+\tau^{1.2}}\right)}{(\tau+0.6)\sqrt{(\pi \ln(1.4+\tau))}} \quad (2)$$

The equation above originates from the Phelps-Fujimoto model. It yields an escape factor applicable when the radial distribution of upper levels follows a bell-shaped pattern. While the spatial distribution of upper levels aligns with the utilized eigenfunction, resulting in a spatially uniform escape factor as an eigenvalue, practical implementation reveals non-uniformity [15], particularly near boundaries.

**Escape factor Λ and optical thickness τ:**

In a line integral measurement, the density ratio serves as a reflection of the central bright region's value, rendering the use of the escape factor of the center a reasonable approximation. Nevertheless, according to the derivation process, employing the Phelps-Fujimoto equation (Eq. 2) is inappropriate when the radial distribution of the upper levels deviates from a bell-shaped curve. Conversely, the Otsuka-Iida equation is unsuitable when dealing with non-uniform distributions [16].

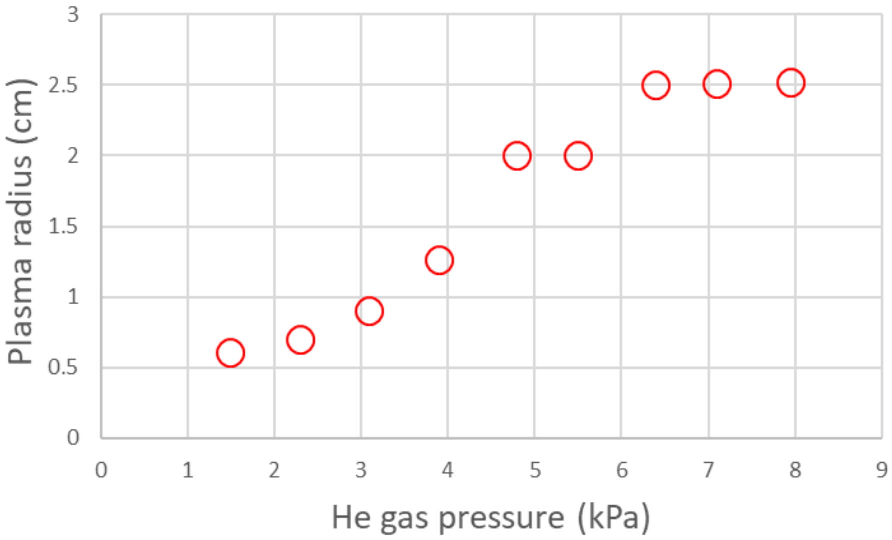


Figure 2: He gas pressure dependence of the plasma distribution.

The main ambiguity of the τ axis is due to the plasma radius, so the upper-level distribution and the plasma radius giving the escape factor at the line center. High pressure plasma produces optical thick plasmas as the plasma radius increases in Fig. 2 and optical escape factor decreases. Electron density saturates for high pressure arc plasmas because of increasing plasma radius with the gas pressures, which requires more investigations.

**Experimental verification of the radiation reabsorption effect:**

A CR model incorporating radiation reabsorption was used for MAP-II helium discharges by Iida et al [5]. A review article on the MAP-II apparatus was published in the Journal of the Japan Society of Mechanical Engineers [17]. In this paper, we recognized that the value of $L_q$ is model-dependent and $n_p$ is treated as a free parameter. Specifically, the Otsuka-Iida equation using direct integration method was used to compare the plasma diameter of 25 mm in the MAPII system as $L_q$=0, is the result of the conventional CR model, which does not take radiation reabsorption into account. In the measurement code that passes through the center of the MAP-II plasma, it is appropriate to use a plasma radius of about 25 mm as $L_q$. However, it was pointed out that $L_q$ remains arbitrary, and the evaluated value of electron density is affected by this arbitrariness. We use a consistent value to get rid of this vagueness.

On the other hand, Nishijima [18] et al. measured ($4^1D$ state Doppler broadening), and $L_q$ in the PISCES-A device, with the vessel diameter (100 mm) instead of the plasma diameter (20 mm). They concluded that Otsuka's equation [16] could be used by using the Doppler broadening of the atom temperature. In reference [18], the use of the measured atomic temperatures plays a role in reducing the ambiguity of the $\tau$ and fits well with the probe values. The results are in good agreement with the probe values. However, from the viewpoint of universal applicability of the model, it is necessary to consider that the spread of the distribution of excited levels (above n=3) is about 20 mm which is closer to Gaussian than to the bell-shaped. Whereas the distribution of judging from the current state of knowledge, it is difficult to say that the model is self-contained, since the distribution for n=2 is unlikely to extend over the entire vessel. However, this is the experimental demonstration of a change in the escape factor due to a relative change in $\tau$. A vacuum vessel of 450 mm diameter has been used in this article.

The hypothetical development of the Phelps-Fujimoto equation, since there was no model to obtain a usable form of the spatial distribution of the escape factor. It was assumed that the Phelps-Fujimoto equation to the plasma periphery, where there is a large inflow of photons from the center. The effect of radiation reabsorption would be underestimated. This results in an abnormally high $T_e$ measurement compared to the probe measurement. It has been reported that the results of NAGDIS-II are abnormally high compared to those measured by probes. The strong radiation from the plasma center at the edge of the plasma which is optically thicker. The term "optically thick" in the radiation reabsorption process refers to the thicker plasma core. "Optically thick" in the radiation reabsorption process means that the contribution of the global radiation reabsorption to the local collisional radiation process is large in the local radiation process. It does not mean that the absorption of emissions in the absorbing medium spread of the lower level. In other words, the appropriate value of $\tau$ at the periphery is larger than that at the center, $\Lambda$ is smaller than the $\tau$ at the center.

**Method for determining the effective radiation capture radius:**

Taking radiation reabsorption into account, the density of excited levels in the CR model is a function of $n_e$, $T_e$, and $\Lambda$ ($\tau$ ($n_p$, $T_p$, $L_q$)) [see Eq. (1)]. The escape factor was calculated using the Otsuka-Iida formula [16] and incorporated into the CR model. The pressure is 1.3 Pa and the atomic temperature is 400 K for the calculation of escape factor using Molisch formula [4]. The gas pressure is relatively high and the radiation even under relatively high gas pressure conditions where the radiation reabsorption process is likely to take effect, $n(3^1P)/n(4^1P)$ is 2-8 eV (about the level of ionization progression plasma at low electron temperatures), and the dependence of $n(3^1P)/n(4^1P)$ depends on $n_e$ and $L_q$ [19]. In other words, if $n_e$ is determined by another measurement method, the effective $L_q$ (effective-L) can be determined experimentally (applicable up to about 10 eV for lower gas pressures).

Using the electron density measured by the electrostatic probe, $n(3^1P)/n(4^1P)$, the $L_q$; effective-L is 70 mm, which is the same as the plasma size of the MAP-II plasma, at the center and increases to ~ 500 mm toward the outer side of the mean radius. Using this $L_q$ and $T_e$ from the CR model, the abnormal increase in $T_e$ at the periphery of the vessel was suppressed. Naturally, the value of radiation capture radius $L_q$ itself has no direct relationship with the physical quantity and are the same as the values obtained in the Otsuka-Iida model. When the capture radius is set to the radius of capture in the Otsuka-Iida model, is the same as that of $L_q$. If the shape of the distribution of the upper levels of the transition is different, the value of each emission line should be different. $L_q$ to be taken for each different emission line, however, the same value is used as the expected value including the ambiguity caused by these effects. Sometimes it is not comfortable that the electron density is measured and used as a probe may contribute to the decision as a kind of constraint condition. However, since an error in either $n(3^1P)/n(4^1P)$, $n_e$, or $L_q$ directly affects the other. Therefore, the determination of $L_q$ is positioned as an indicator of the $L_q$ to be adopted, and the other bright emission lines should be taken into account when determining $n_e$ and $T_e$. Of course, it is also possible to use ideally, $n_e$, $T_e$, and $L_q$ should be determined simultaneously. In this study, $L_q$ was taken as a constant value.

**Lyman Line Profile:**

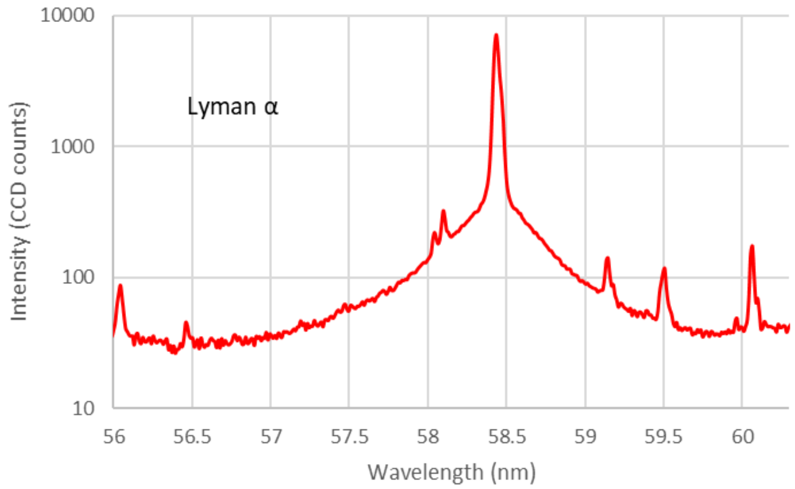


Figure 3: Lyman ray profile observed in high density discharge.

In recent LHD experiments, high-density discharges with electron densities exceeding $10^{15}$ $cm^{-3}$ have been realized. The observation of the Lyman α line from the bulk plasma yields a spectrum with a concave center [6,20], as seen in Fig. 4 for He arc plasmas of density ~$10^{-13}$ $cm^{-3}$. He line intensity decreased in the high density regions owing to the effect of increasing radiation reabsorption.

The Lyman α emission as shown in Fig. 3 for high density discharge, which is emitted mainly near the surface of the plasma, is partially absorbed by the He atoms that exist outside the plasma. If we ignore the small effects of microstructure and the Zeeman effect, the light emitted from an atom is absorbed only by atoms with the same velocity component as the emitting atom in the line-of-sight direction. However, in the center of the spectrum, the intensity attenuation is large due to the large number of atoms that can absorb it, and in the case of extremely high atomic densities, the spectra are concave in the center. Therefore, the size and shape of the concavity obtained by observation can be used to evaluate the atomic density at the periphery of the plasma. A measurement method to evaluate the atomic density in the periphery of the plasma from the size and shape of the observed concavity is considered as an application [6].

In fusion plasma spectroscopy, the Balmer α ray intensity of hydrogen atoms is used to determine the penetration flux of atoms into the plasma. Even if the absorption of the Balmer α-line itself is small, as in this example, the radiation reabsorption of the Lyman series line is significant as shown in Fig. 4 for dense He plasmas, the entire atomic density distribution of the excited levels will be affected. Note that, the effective ionization velocity is also affected.

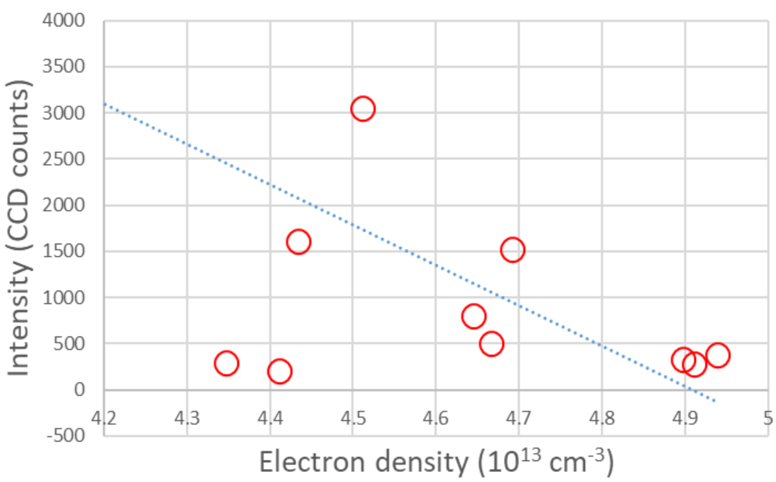


Figure 4: Emission line intensities of He atoms (Lyman α).

**Emission line intensity ratio of He atoms:**

Electron temperature and density measurements using emission line intensity ratios of He atoms have recently been utilized for various plasmas [12]. This measurement method is based on the ground state of the He atom and the electron temperature and density of the plasma. This method is based on the electron impact excitation of He atoms from the ground state to the singlet and triplet levels. Electron temperature dependence of the rate coefficient is different between the excitation to the singlet level and the excitation to the triplet level. The density distribution between levels with the same principal quantum number strongly depends on the electron density.

The atomic density of each excited level in the plasma can be calculated by the CR model given the electron temperature and electron density [1,11]. In the CR model, collisional and radiative transitions between levels are considered and radiative transitions between levels calculates the density of excited atoms such that the production and annihilation of atoms in each excited level are balanced. Using this model, the density of excited atoms in each excited level obtained and calculated from spectroscopic measurements. The electron temperature and electron density can be determined as parameters that reproduce the atomic density of each excited level obtained from spectroscopic measurements.

**Quantitative understanding of radiation reabsorption:**

Radiative reabsorption is a puzzling problem in quantitative spectroscopy. The mechanism of optical reabsorption as an elementary process is not well understood. The absorption process can be easily compensated by using the CR model. However, this is not so easy in practice. The probability of the electron impact transition is determined by the electron density and electron temperature at a location. Even if the object of interest is limited to a particular local location, the consistency of the entire plasma must be considered in order to correctly determine the density of the excited atoms at that location. In addition, the intensity of the radiation field at each location affects the intensity of the radiation field of all locations. The density distribution of the excited states of He atoms was calculated from the observed He atom emission intensity as shown in Fig. 4. In the usual analysis of He atomic emission lines, the electron temperature and electron density are the fitting parameters to be determined. The production of excited atoms in the $3^1P$ and $4^1P$ levels, which originates from the absorption of the $1^1S$-$3^1P$ and $1^1S$-$4^1P$ lines, can be neglected due to the low electron density. In LHD, it is important to consider the contribution to be known quantitatively. The atomic temperature in the plasma also can be evaluated by analyzing the radiation reabsorption. The rigorous analysis methods of radiation reabsorption found in [7,21].

## SUMMARY

In the analysis of heated Helium (He) plasmas, the technique of plasma spectroscopy plays a pivotal role in evaluating the population distribution across various energy levels linked to each emission line. The sophisticated Collisional Radiative (CR) model is then harnessed to precisely quantify the influence of radiation reabsorption on this population. This involves a comprehensive analysis utilizing the radiation transport equation, providing a nuanced understanding of how radiation reabsorption impacts the distribution of energy levels.

To further delve into this complex scenario, a crucial aspect is highlighted, employing a Monte Carlo treatment for radiation reabsorption. This computational approach becomes indispensable in accurately quantifying the contribution of radiation reabsorption to the overall population dynamics. However, it is imperative to acknowledge that addressing this intricate matter poses a substantial challenge in the field, underscoring the need for innovative methodologies and collaborative research efforts to enhance our grasp of plasma behavior in He plasmas under heating conditions.

Recent studies have investigated the use of optical emission spectroscopy and collisional-radiative modeling in low-temperature argon plasmas, revealing significant progress in understanding radiation trapping and non-equilibrium conditions [22]. Extensive collisional-radiative models for argon glow discharges and nitrogen mixtures have also been developed, providing valuable insights into effective atomic levels and their effects on

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plasma behavior [23,24]. Moreover, new research has examined the interaction of radiation with excited states and electron energy distributions in hydrogen plasma, presenting a detailed view of non-equilibrium dynamics [25].

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