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Cite as: AIP Advances 10, 025225 (2020); https://doi.org/10.1063/1.5143481
Submitted: 24 December 2019 . Accepted: 06 February 2020 . Published Online: 27 February 2020

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Emission spectroscopy of He lines in high-density plasmas in Magnum-PSI

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ABSTRACT
Helium (He) line emissions have been utilized to measure the electron density ($n_e$) and temperature ($T_e$), and validity checks have been conducted in various linear devices. In this study, we performed optical emission spectroscopy (OES) of He line emissions in the linear plasma device Magnum-PSI, where the used density range was $1 \times 10^{20}$ m$^{-3}$, which was much higher than those used until now. We observed nine line emissions in the wavelength range of 388–728 nm and deduced $n_e$ and $T_e$ based on comparisons with a collisional radiative model. From the variation of the difference between the experiments and calculations, the joint probability distribution of $n_e$ and $T_e$ was deduced. We will discuss the effect of radiation trapping, in particular, based on comparisons between OES measurement results and Thomson scattering measurements.

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I. INTRODUCTION

Helium (He) line emissions from fusion edge/divertor plasmas provide important information for plasma diagnostics. A line intensity ratio method using several He line intensities has been utilized to measure the electron density, $n_e$, and the temperature, $T_e$, in various fusion devices including TEXTOR, JET, LHD, ASDEX Upgrade, and JT-60U. In some cases, a thermal He-beam has been used for diagnostic purposes; because He atoms are produced by the nuclear fusion reaction of deuterium and tritium, the emissions will be available even without an additional injection of He atoms from outside in future fusion devices.

Feasibility studies have been mainly conducted in linear devices: NAGDIS-I, MAP-II, NAGDIS-II, and PISCES-A. It has been revealed that radiation trapping is an important effect to understand the population distribution of He atoms. Here, radiation trapping is mainly caused by the re-absorption of resonance lines ($1^3S-n^1P$), where $n$ is the principal quantum number. However, the density range used in the linear devices was mainly less than $10^{19}$ m$^{-3}$, which was lower than the actual fusion conditions.

In this study, we performed optical emission spectroscopy (OES) of He lines in the Magnum-PSI device, where the plasma density can be higher than $10^{20}$ m$^{-3}$. After describing the experimental setup, we show two typical cases to make a detailed comparison with the collisional radiative (CR) model. For the two cases, it is shown how the difference in the population distribution between the CR model and OES results alters when changing $n_e$ and $T_e$ used for the CR model. The joint probability distribution will be deduced from the difference between the CR model and experiments. Then, using the joint probability distribution, $n_e$ and $T_e$ from the OES are compared with those measured by laser Thomson scattering (TS) measurements.

II. PREPARATION

A. Setup

Experiments were conducted in the Magnum-PSI device. We used pure He discharges in the present study; helium gas was fed from the source region for discharge and additional He gas was also introduced from the downstream. Figure 1 shows a schematic of the
FIG. 1. A schematic of the experimental setup representing the Thomson scattering and optical emission spectroscopy.

The experimental setup. Magnum-PSI has a TS system, which can measure the radial distribution of $n_e$ and $T_e$ with a single laser shot. Recently, a collective TS system was developed to measure the ion temperature and the flow velocity. The laser passed through the vertical windows, and TS signals were observed from a transversal direction. There are other optical ports at the same axial position, and the OES was performed at the same location. A lens collected the emission from the plasma, and the light was transferred to the spectrometer through a mirror and optical fibers. A Czerny-Turner type monochromator was used in the spectrometer. We observed nine line intensities shown in Table I in the wavelength range of 388.9–728.1 nm. The corresponding optical transitions were from the upper states with $n = 3–5$ to the lower states with $n = 2$. The spectrometer can cover a wavelength range of $\sim 150$ nm with an exposure; one image covered 667.8 nm, 706.5 nm, and 728.1 nm with an exposure, and another image covered the other lines. The plasma was produced in a steady state. When scanning parameters, we first measured spectra as scanning the plasma parameters at one of the grating positions, and then, measured remains at the other grating position as scanning the plasma parameters again. It is noted that the reproducibility of plasma condition is very good in the Magnum-PSI device; we have confirmed from TS measurements that the variation in the parameters was negligible.

B. Examples

Figures 2(a)–2(c) show the emission profiles, the profiles of intensities normalized to those at the center, and the profiles of $n_e$ and $T_e$ measured with the TS system, respectively. The discharge current was 80 A, and the neutral pressure, $P$, was 0.3 Pa. This is a typical low-density and low-pressure case. We call this as case (i) (low-density case) in this study. The emission region was about 5 mm in radius, and $n_e \approx 10^{20}$ m$^{-3}$ and $T_e \approx 1.5$ eV at the center of the plasma column. It is seen that 501 nm ($3^1P$) line has a clear wing, and 728 nm ($3^1S$) and 668 nm ($3^1D$) also have a small wing at radii $>10$ mm. This was the same tendency observed in PISCES-A. The phenomenon was well explained by the excitations of radiation from

| Wavelength (nm) | Upper state | Lower state |
|-----------------|-------------|-------------|
| 728.1           | $3^1S$      | $2^1P$      |
| 706.5           | $3^3S$      | $2^3P$      |
| 501.6           | $3^3P$      | $2^3S$      |
| 388.9           | $3^3P$      | $2^3S$      |
| 667.8           | $3^1D$      | $2^1P$      |
| 492.2           | $4^3D$      | $2^3P$      |
| 447.1           | $4^3D$      | $2^3P$      |
| 438.8           | $5^3D$      | $2^3P$      |
| 402.6           | $5^3D$      | $2^3P$      |

FIG. 2. (a) The emission profiles of the nine line emissions, (b) the profiles of intensities normalized to those at the center, and (c) the profiles of $n_e$ and $T_e$ measured with the TS system in case (i). The discharge current was 80 A, and the neutral pressure was 0.3 Pa.
the plasma column as the effect was simulated qualitatively using ray tracing calculations.

Figures 3(a)–3(c) show the emission profiles, the profiles of intensities normalized to those at the center, and the profiles of $n_e$ and $T_e$ under a different condition: the discharge current of 160 A and $P$ of 3.1 Pa. This corresponds to a typical high-density and high-pressure case, and we call this as case (ii) (high-density case) in this study. Intensities do not decrease sharply in radius, and the emission is strong even at $r > 10$ mm. The peak density is $6 \times 10^{20}$ m$^{-3}$ and decreases with radius to $0.5 - 1 \times 10^{20}$ m$^{-3}$ at $r = 10$ mm; the low temperature ($< 1$ eV) plasma existed around the region. In Fig. 3, different from the low-density case, it was likely that the plasma expanded and the plasma column size became wider. The plasma widening in low-temperature plasmas has been observed in PISCES-A$^{17}$ and NAGDIS-II$^{18}$ together with an enhancement of fluctuation, suggesting that similar phenomena also occurred in Magnum-PSI.

### C. Comparison with CR model

Population distribution of He atoms is compared with the CR model that was developed by Goto.$^{19}$ In this study, we used the so-called formulation II in Ref. 19, where the quasisteady-state approximation is applied for all the states, including the two metastable states ($2^1S$ and $2^3S$). Although the importance of the transport of metastable states was discussed in the NAGDIS-II device recently,$^{20}$ we neglect the effect in this study, because the plasma density is much higher in Magnum-PSI.

To calculate the population distribution using the CR model, the optical escape factor (OEF) is used to consider radiation trapping. The OEF in cylindrical geometry with Doppler broadening is defined as follows:

$$g_0 \sim \frac{1.92 - 1.3/\left[1 + (\kappa_0 R_{\text{OEF}})^{6/5}\right]}{(\kappa_0 R_{\text{OEF}} + 0.62)\left[\pi \ln(1.357 + \kappa_0 R_{\text{OEF}})\right]^{1/2}},$$

where $R_{\text{OEF}}$ is the radius of the spatial distribution of the excited atom (OEF radius) and $\kappa_0$ is the absorption coefficient at the center of the spectrum having a Gaussian profile.

In the formulation II of the CR model, the population of the $p$ state, $n_{cal}(p)$, is expressed by the summation of two terms as

$$n_{cal}(p) = R_0(p)n_i n_1 + R_1(p)n_i n(1^1S),$$

where $n_i$ is the ion density, $n(1^1S)$ is the ground state density, and $R_0(p)$ and $R_1(p)$ are reduced population coefficients, which can be calculated by solving a set of rate equations and have $n_e$ and $T_e$ dependences. In this study, we assume $n_i = n_e$.

### III. RESULTS AND DISCUSSION

#### A. Population distributions

Figures 4(a) and 4(b) and Figs. 4(c) and 4(d) show comparisons of relative population distributions in cases (i) and (ii) shown in Figs. 2 and 3, respectively. Figures 4(a) and 4(c) and Figs. 4(b) and 4(d) correspond to the cases at the column center and 10 mm from the center, respectively. To compare the relative population distribution, we offset the calculation results from $n_{cal}(i)$ to $n'_{cal}(i)$, where $B$ is a coefficient, and $B$ is chosen so that the following relation is satisfied:

$$\sum_i \left[\log_{10}(n_{\text{exp}}(i)) - \log_{10}(n'_{\text{cal}}(i))\right] = 0.$$

Here, $n_{\text{exp}}(i)$ is the $i$ state density obtained experimentally, and the summation should be taken for all the used states. Markers represent experimentally obtained population densities at $y = 0$ mm and 10 mm, where $y$ is the radial distance from the center of the plasma column. The densities for each state were deduced from the calibrated line emission intensities divided by the photon energy and the Einstein $A$ coefficient for the corresponding transitions. Four cases from the CR model calculations are shown: calculated population distributions using $n_e$ and $T_e$ from TS at $r = 0$ mm and 10 mm with $R_{\text{OEF}} = 0$ mm and 10 mm for each $r$ value.

From Figs. 4(a) and 4(b), it is seen that the population distribution at $y = 0$ mm was quite different from that at $y = 10$ mm. The populations in $3^1P$ and $3^1S$ states were significantly enhanced.

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**FIG. 3.** (a) The emission profiles of the nine line emissions, (b) the profiles of intensities normalized to those at the center, and (c) the profiles of $n_e$ and $T_e$ measured with the TS system in case (ii). The discharge current was 160 A, and the neutral pressure was 3.1 Pa.
in a relative manner. This can be explained by the radiation transfer from the center of the plasma column. Although it is rather easy to explain the effect of radiation trapping at the center of the plasma column by using the OEF, it is not so simple to assess the effect at the periphery of the plasma column because of the existence of the radiation from the center. In Fig. 4(b), the experimental results at \( y = 0 \) mm and 10 mm did not differ so much. This was probably because the size of the plasma column became wider. The population distribution agrees well with the calculation, in particular, with \( n_e \) and \( T_e \) at \( r = 0 \) mm and \( R_{\text{OEF}} = 10 \) mm, respectively. Details will be discussed in Sec. III C.

B. Joint probability distribution

We use the same error function for the optimization used in Ref. 20, which is defined as

\[
f(T_e, n_e) = \sum_p \left( \frac{\rho_{\text{exp}}(p) - \rho_{\text{cal}}(p(T_e, n_e))}{\rho_{\text{exp}}(p)} \right)^2,
\]

Here, the function \( \rho(p) \) is the normalized density written as

\[
\rho(p) = \frac{n(p)}{\sum_i n(i)},
\]

where the summation of \( n(i) \) represents the sum of the upper states of the line emission used for the analysis, and \( \rho_{\text{exp}} \) and \( \rho_{\text{cal}} \) in Eq. (4) correspond to the values from the experiment and the CR model calculation, respectively. Because \( \rho_{\text{cal}} \) is a function of \( T_e \) and \( n_e \), \( f \) also depends on \( T_e \) and \( n_e \).

Figures 5(a)–5(d) and Figs. 5(e)–5(h) show the logarithm of joint probability distributions of \( n_e \) and \( T_e \), \( \log_10[p(T_e, n_e)] \), for cases (i) and (ii), respectively. Here, we assume that \( \rho_{\text{OEF}} = 10 \) mm and \( n(1^3S) \) is spatially uniform and can be determined from the measured \( P \). Thus, \( n_e \) and \( T_e \) are the sole parameters, which determine the \( f \) value. Note that this joint distribution can be computed as

\[
p(T_e, n_e) = C \exp \left( \frac{f}{2\sigma} \right)
\]

where \( C \) is a coefficient and \( \sigma = f(n_e^{\text{opt}}, T_e^{\text{opt}})/(N - 2) \), with \( n_e^{\text{opt}} \) being the optimum density and \( T_e^{\text{opt}} \) being the optimum temperature. Figures 5(a) and 5(e), Figs. 5(b) and 5(f), Figs. 5(c) and 5(g), and Figs. 5(d) and 5(h) correspond to \( p(T_e, n_e) \) using three lines (\( \lambda = 667.8 \) nm, 706.5 nm, and 728.1 nm), \( f \) four lines (the three lines + \( \lambda = 501.6 \) nm), five lines (the four lines + \( \lambda = 477.1 \) nm), and the nine lines shown in Table 1, respectively. The red and blue markers represent \( n_e \) and \( T_e \) from TS at \( r = 0 \) mm and 10 mm, respectively, and the white markers represent \( n_e^{\text{opt}} \) and \( T_e^{\text{opt}} \). Here, the error bar shows the range where \( f < f(n_e^{\text{opt}}, T_e^{\text{opt}}) + \sigma \).

In case (i), \( n_e^{\text{opt}} \) and \( T_e^{\text{opt}} \) for all the four line-selection cases were quite different from those of TS. Except for the three-line case, the error minimum deduced a significantly lower temperature than those from TS. In case (ii), \( n_e^{\text{opt}} \) and \( T_e^{\text{opt}} \) from the three lines (Fig. 5) are quite different from TS values. While \( n_e^{\text{opt}} \) and \( T_e^{\text{opt}} \) in the four-line case were almost the same as those from the three-line case, the four-line case has a rather broad high-probability red colored region. For the five and nine-line cases, \( n_e^{\text{opt}} \) was consistent with \( n_e \) from TS at the center, though \( T_e \) was slightly lower.

One of the ambiguities in our assumptions is in the neutral density/temperature. In the above two cases, the neutral density deduced from the measured pressure is \( 7.8 \times 10^{19} \) and \( 7.6 \times 10^{19} \) \( \text{m}^{-3} \), respectively, which is lower than or comparable to \( n_e \). The ground state density can be decreased by, for example, an ionization process or transportation to the outer region after charge exchange process. In addition, although we assumed that the neutral temperature is at the room temperature, the temperature could be higher.
A decrease in the neutral density influences the population distribution in two ways; it can effectively change $R_{\text{OE}}$ and also the ratio between the ionizing and recombining components, which are the first and second term of Eq. (2), respectively. An increase in the neutral temperature decreases $R_{\text{OE}}$ effectively as well.

In Figs. 6(a) and 6(b) and Figs. 6(c) and 6(d), log$_{10}$[$p(T_e, n_e)$] of cases (i) and (ii), respectively, are shown. Here, we assumed that the neutral pressure in the calculation, $P_c$, was $0.5 \times P$ [Figs. 6(a) and 6(c)] and $0.2 \times P$ [Figs. 6(b) and 6(d)]. In case (i) [Figs. 6(a) and 6(b)], $n_{\text{opt}}^e$ and $T_{\text{opt}}^e$ did not change so much at $0.5 \times P$, while $n_{\text{opt}}^e$ significantly shifted to a higher density region at $0.2 \times P$. In case (ii) [Figs. 6(c) and 6(d)], $n_{\text{opt}}^e$ shifted to a lower density region, and the high probability region slightly expanded to the high-temperature direction. Although, it is difficult to see what the best choice for $P$ is, the results show that $n_{\text{opt}}^e$ and $T_{\text{opt}}^e$ can be altered by the neutral density, and it can be an important factor to assess the joint probability distribution.

It seems from the joint probability distribution maps that the five lines are at least necessary to deduce appropriate $T_e$ and $n_e$, and the usage of the nine lines is better than the other sets. Next, setting aside which lines should be chosen in a practical sense, we will make comparisons between TS and OES methods using all the nine lines.

### C. Comparisons

Figures 7(a) and 7(b) show comparisons of $n_e$ and $T_e$, respectively, between TS and OES; values were plotted as a function of $n_e$ or $T_e$ from TS at $r = 0$ mm. Red markers represent TS values at...
r = 10 mm. First, let us take a look at the OES without radiation trapping, namely, $R_{\text{OEF}} = 0$ mm (blue open circles). The density was always assessed to be higher than TS values (dotted lines). When taking into account the radiation trapping with $R_{\text{OEF}} = 10$ mm (closed circles), $n_e$ became plausible values. They were in between TS values at $r = 0$ mm and 10 mm almost in all the cases, except for several cases that were presented with a gray color. When $0.2 \times P$ was used for the neutral pressure (green triangles), similar to the cases shown in Fig. 6, these points became consistent with the TS values within the error range.

When it comes to $T_e$, it was also overestimated in many cases without considering the radiation trapping; in several cases, underestimation also occurred. When considering the radiation trapping effect with $R_{\text{OEF}} = 10$ mm, the overestimation was well compensated when $T_e > 1.1$ eV. However, for the underestimated cases, the temperature became further lower, and the discrepancy increased. In addition, when $0.3 < T_e < 1.1$ eV, the overestimation was not compensated. Green triangles show the cases when the radiation trapping was taken into account with $0.2 \times P$. The underestimation was mitigated, and the values with error bars were marginally overlapped with TS values at 10 mm. One of the typical underestimation cases corresponds to case (i) (the low-density case), which has been discussed in Fig. 2. Although the mechanism to cause the discrepancy is not clear, because the population distributions at $y = 10$ was quite different from that at $y = 0$ mm, as shown in Fig. 4(a), it may be of importance to take into account the radial emission profile. Concerning some overestimation cases in the range of $0.3 < T_e < 1.1$ eV, the discrepancy could not be compensated even when changing $R_{\text{OEF}}$. Although not shown in Fig. 7(b), the difference could not be entirely explained even with higher $R_{\text{OEF}}$. For the plasma conditions investigated, no apparent non-Maxwellian component has been identified in the high quality TS spectra measured in Magnum-PSI. However, to get a more accurate picture of the influence of fluctuations and the existence of small non-Maxwell components, advanced signal averaging techniques can be applied in the future.

IV. CONCLUSIONS

We performed OES of He line emissions in high-density plasmas in the Magnum-PSI device. The typical density and temperature ranges were $1 \times 10^{20}$ m$^{-3}$ and 0.3–3.5 eV, respectively. Line intensity ratios have been used to deduce $n_e$ and $T_e$; we deduced the joint probability distribution from the difference between the CR model and OES results using three lines ($\lambda = 667.8$ nm, 706.5 nm, and 728.1 nm), four lines (the three lines + $\lambda = 501.6$ nm), five lines (the five lines + $\lambda = 447.1$ nm), and all the measured nine lines (the five lines + $\lambda = 388.9$ nm, 492.2 nm, 438.8 nm, and 402.6 nm) in two typical high and low-density cases. The deduced $n_e$ and $T_e$ from the joint probability distribution were quite different from TS values in the three-line and four-line cases. The five-line and nine-line cases were close to each other.

We used the nine lines to measure $T_e$ and $n_e$ from OES and compared with TS values. Without taking into account the effect of radiation trapping, $n_e$ was always overestimated and $T_e$ was contradicted with the TS measurements. When taking into account the radiation trapping using the optical escape factor, $n_e$ was almost consistent with the TS value; one can say that the radiation trapping is essential to understand the population distribution in the high-density regime as well. The optical escape factor has sensitivity to the neutral density, temperature, and $R_{\text{OEF}}$. Because there are ambiguities in the neutral density and temperature, we discussed the sensitivity as changing $R_{\text{OEF}}$ by assuming that the neutral density is spatially uniform and the temperature was at the room temperature. In this study, because the emission profile expanded in the radial direction and the measurements could not cover the whole area especially when the temperature was $<1$ eV, it was difficult to use Abel inversion; we used line-integrated emission intensities. In some cases, $R_{\text{OEF}} = 10$ mm was too much, probably because of a higher neutral temperature or a decrease in the neutral density at the plasma center. Concerning $T_e$ assessment, when taking into account the effect of radiation trapping, $T_e$ from the OES was in between the TS values at 0 mm and 10 mm, except for ten cases out of 24 conditions, as shown in Fig. 7 with green markers. In five out of the ten cases, the difference was not well explained with the variations in
$R_{OEF}$ and/or neutral density. The mechanism has yet to be understood well; considerations of the radial emission profile using Abel inversion/tomographic reconstruction, plasma fluctuation, and electron energy distribution function may be necessary. It is of interest in the future to investigate the mechanisms that cause the discrepancy in a detailed manner.

ACKNOWLEDGMENTS

This work was supported in part by a Grant-in-Aid for Scientific Research, Grant Nos. 19H01874, 16H02440, and the Fund for the Promotion of Joint International Research, Grant No. 17KK0132, from the Japan Society for the Promotion of Science (JSPS).

REFERENCES

1. O. Schmitz, I. L. Beigman, L. A. Vainshtein, B. Schweer, M. Kantor, A. Pospieszczyk, Y. Xu, M. Krychowiak, M. Lehn, U. Samm, B. Unterberg, and TEXTOR Team, Plasma Phys. Controlled Fusion 50, 115004 (2008).
2. Y. Andrew, S. J. Davies, D. Elder, L. D. Horton, G. F. Matthews, A. Meigs, P. D. Morgan, M. O'Mullane, M. Stamp, R. Prentice, and P. C. Stangeby, J. Nucl. Mater. 266-269, 1234 (1999).
3. M. Goto and K. Sawada, J. Quant. Spectrosc. Radiat. Transfer 137, 23 (2014).
4. M. Griener, E. Wolfrum, M. Cavedon, R. Dux, V. Rohde, M. Sochor, J. M. Munoz Burgos, O. Schmitz, and U. Stroth, Rev. Sci. Instrum. 89, 10D102 (2018).
5. H. Kubo, M. Goto, H. Takenaga, A. Kumagai, T. S. S. Sakurai, N. Asakura, S. Higashijima, and A. Sakasai, J. Plasma Fusion Res. 75, 945 (1999).
6. M. Agostini, P. Scarin, R. Cavazzana, L. Carraro, L. Grando, C. Talerico, L. Franchin, and A. Tiso, Rev. Sci. Instrum. 86, 123513 (2015).
7. S. Sasaki, S. Takamura, S. Watanabe, S. Masuzaki, T. Kato, and K. Kadota, Rev. Sci. Instrum. 67, 3521 (1996).
8. Y. Iida, S. Kado, A. Okamoto, S. Kajita, T. Shikama, D. Yamazaki, and S. Tanaka, J. Plasma Fusion Res. SERIES 7, 123 (2006); available at http://www.jspf.or.jp/JPFP/JPFP2006_07-123.pdf.
9. Y. Iida, S. Kado, and S. Tanaka, J. Nucl. Mater. 438, S1237 (2013).
10. S. Kajita, N. Ohno, S. Takamura, and T. Nakano, Phys. Plasmas 13, 013301 (2006).
11. F. B. Rosmej, N. Ohno, S. Takamura, and S. Kajita, Contrib. Plasma Phys. 48, 243 (2008).
12. D. Nishijima and E. M. Hollmann, Plasma Phys. Controlled Fusion 49, 791 (2007).
13. S. Kajita, N. Ohno, S. Takamura, and T. Nakano, Phys. Plasmas 16, 029901 (2009).
14. J. Rapp et al., Fusion Eng. Des. 85, 1455 (2010).
15. H. J. van der Meiden et al., Rev. Sci. Instrum. 83, 123505 (2012).
16. H. J. van der Meiden, J. W. M. Vernimmen, K. Byströ, K. Jesko, M. Y. Kantor, G. De Temmerman, and T. W. Morgan, Appl. Phys. Lett. 109, 261102 (2016).
17. E. M. Hollmann, C. Brandt, B. Hudson, D. Kumar, D. Nishijima, and A. Y. Pigarov, Phys. Plasmas 20, 093303 (2013).
18. H. Tanaka, K. Takeyama, M. Yoshikawa, S. Kajita, N. Ohno, and Y. Hayashi, Plasma Phys. Controlled Fusion 60, 075013 (2018).
19. M. Goto, J. Quant. Spectrosc. Radiat. Transfer 76, 331 (2003).
20. S. Kajita, K. Suzuki, H. Tanaka, and N. Ohno, Phys. Plasmas 25, 063303 (2018).
21. T. Fujimoto, J. Quant. Spectrosc. Radiat. Transfer 21, 439 (1979).
22. Y. Iida, S. Kado, and S. Tanaka, Phys. Plasmas 17, 123301 (2010).
23. S. Kajita and N. Ohno, Rev. Sci. Instrum. 82, 023501 (2011).
24. S. Kajita, H. Ohshima, H. Tanaka, M. Seki, H. Takano, and N. Ohno, Plasma Sources Sci. Technol. 28, 105015 (2019).