

Measurement of Gas Composition Ratio of H-He Mixture Plasmas in Divertor Simulator MAP-II

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The gas composition ratio in the divertor region of a fusion reactor must be measured in order to evaluate its atomic-molecular processes precisely. In this research we propose a method to measure the gas composition ratio of He, H and H₂ of the H-He mixture plasmas in divertor simulator MAP-II by using passive spectroscopy of the Balmer series of hydrogen atoms, the Fulcher- α band of hydrogen molecules and the He I emissions.

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1. Introduction

In the divertor region of a fusion reactor many neutral species are mixed: desorbed or puffed hydrogen molecules, dissociated hydrogen atoms, helium atoms produced through the fusion reaction, etc [1]. Since each of these species has a different effect on the edge plasmas [2], a precise measurement of their composition ratio can be used to optimize the divertor operation scenario. Knowledge of the peripheral neutral gas composition is also useful in the interpretation of the fusion plasma diagnostic data, e.g. modeling of the overall neutral balance and the escaping neutral particle fluxes.

In this study we propose a method to measure the gas composition ratio of the H-He mixture plasmas in divertor simulator MAP-II by using spectroscopy [3]. We have earlier proposed a method to measure the atomic-molecular ratio in hydrogen plasmas. We now extend this method to include the emissivity of helium atoms.

2. Principles

2.1 Ro-vibrational structure of H₂

In order to obtain the density of molecular hydrogen, N_{H_2} , we measure the ro-vibrational distribution in the ground electronic state of hydrogen molecules from the Fulcher- α band. The Fulcher- α band is an emission with a transition from $d^3\Pi_u$ to $a^3\Sigma_g^+$ and its wavelength is about 600-640 nm. The ro-vibrational structures of the Fulcher- α system, $X^1\Sigma_g^+$, $d^3\Pi_u^{+/-}$ and $a^3\Sigma_g^+$, can be labeled by the vibrational (v) and rotational (J) quanta using the prime symbols (X, v, J), ($d^{+/-}, v', J'$) and (a, v'', J''), respectively [4].

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In a low-density plasma, the coronal model can be applied and then we have the rate equation,

$$\frac{dN_{d-v'J'}}{dt} = n_e \sum_{v,J} [N_{XvJ} R_{XvJ \rightarrow d-v'J'}^{H_2}] - N_{d-v'J'} \sum_{v'',J''} A_{av''J''}^{d-v'J'} \quad (1)$$

The quasi-steady state solution yields the intensity of the Fulcher- α band written as

$$\begin{aligned} \mathcal{E}_{Fulcher}^{d-v'J' \rightarrow av''J''} &= N_{dv'J'} A_{av''J''}^{d-v'J'} \\ &= n_e \frac{A_{av''J''}^{d-v'J'}}{\sum_{v'',J''} A_{av''J''}^{d-v'J'}} \\ &\quad \times \sum_{v,J} [N_{XvJ} R_{XvJ \rightarrow d-v'J'}^{H_2}], \end{aligned} \quad (2)$$

where $\mathcal{E}_{Fulcher}^{d-v'J' \rightarrow av''J''}$ is the emissivity from (d^-, v', J') to (a, v'', J''). n_e and $A_{av''J''}^{d-v'J'}$ are the electron density and spontaneous transition probability, respectively. $R_{XvJ \rightarrow d-v'J'}^{H_2}$ is the electron impact excitation rate of hydrogen molecules from (X, v, J) to (d^-, v', J'), given as a function of the electron temperature, T_e . N_{XvJ} is the ro-vibrational distribution of the ground electronic state, for which Boltzmann distributions having vibrational (T_{vib}^X) and rotational temperatures (T_{rot}^X) are assumed. Namely,

$$N_{XvJ} = \frac{N_{X0}(2J+1)g_{as}^J \exp\left[-\frac{F_X(J,v)}{T_{rot}^X} - \frac{\Delta G(v)}{T_{vib}^X}\right]}{\sum_J (2J+1)g_{as}^J \exp\left[-\frac{F_X(J,v)}{T_{rot}^X}\right]} \quad (3)$$

$$\text{with } N_{X0} = \sum_J N_{X0J}, \quad (4)$$

where g_{as}^J is the degeneracy for the nuclear spin $F_X(J, \nu)$ is the rotational energy and $\Delta G(\nu) \equiv G(\nu) - G(0)$ is the vibrational energy. The best fitted T_{rot}^X and T_{vib}^X are obtained from the Fulcher- α band emissivities using equations (2) and (3), and we then can obtain N_{XvJ} [5, 6].

2.2 Gas composition ratio

The sum of N_{XvJ} over all vibrational and rotational levels, ν and J , can be regarded as equal to the density of hydrogen molecules, N_{H_2} in the present case. Equation (2) can then be rewritten as

$$\varepsilon_{\text{Fulcher}}^{d^- \nu' J' \rightarrow a \nu'' J''} = n_e B_{\text{total loss}}^{d^- \nu' J' \rightarrow a \nu'' J''} N_{\text{H}_2} \langle R_{X \rightarrow d^-}^{\text{H}_2} \rangle_{\text{eff}}, \quad (5)$$

where $B_{\text{total loss}}^{d^- \nu' J' \rightarrow a \nu'' J''}$ is the branching ratio of the single line of the Fulcher- α band to the total loss from the d^- state, namely,

$$B_{\text{total loss}}^{d^- \nu' J' \rightarrow a \nu'' J''} \equiv \frac{N_{d^- \nu' J'} A_{a \nu'' J''}^{d^- \nu' J'}}{\sum_{\nu', J'} \sum_{\nu'', J''} N_{d^- \nu' J'} A_{a \nu'' J''}^{d^- \nu' J'}}. \quad (6)$$

$\langle R_{X \rightarrow d^-}^{\text{H}_2} \rangle_{\text{eff}}$ is the effective excitation rate from X to d^- as a function of T_e , T_{vib} and T_{rot} , which is defined by

$$\langle R_{X \rightarrow d^-}^{\text{H}_2} \rangle_{\text{eff}} \equiv \frac{\sum_{\nu', J'} \sum_{\nu, J} [N_{XvJ} R_{XvJ \rightarrow d^- \nu' J'}^{\text{H}_2}]}{\sum_{\nu, J} N_{XvJ}}. \quad (7)$$

In order to compensate for the errors in the emission measurement, we use the summation of all of the observed Fulcher- α lines.

On the other hand, in order to determine the density of atomic hydrogen in the electronic ground state, N_{H} , we apply the collisional radiative (CR) model [7] to the emissivity of the Balmer series ($n = 2 \leftarrow p$), $\varepsilon_{\text{H}}(p)$, which can be expressed as

$$\varepsilon_{\text{H}}(p) = n_e \left[N_{\text{H}} R_0^{\text{H}}(p) + N_{\text{H}} R_1^{\text{H}}(p) + N_{\text{H}_2} R_2^{\text{H}}(p) \right] A_{2 \leftarrow p}^{\text{H}}, \quad (8)$$

where R_0^{H} , R_1^{H} and R_2^{H} are the population coefficients of recombining, ionizing and dissociative components, which are calculated using the hydrogen CR model for given n_e and T_e . Because in the present case the electron temperature is higher than 1 eV, the recombining component is two orders of magnitude smaller than the others and can be neglected.

As in the case of atomic hydrogen, a CR model can be applied to He I emissions [8]. The emissivity of He I is described as

$$\varepsilon_{\text{He}}(p) = n_e \left[N_{\text{He}^+} R_0^{\text{He}}(p) + N_{\text{He}} R_1^{\text{He}}(p) \right] A_{q \leftarrow p}^{\text{He}}. \quad (9)$$

The recombining component, R_0^{He} , can also be neglected. This He I CR model considers the effect of the radiation trapping as the optical escape factor [9].

From equation (5), (8) and (9), the ratio of the Balmer series emission, the Fulcher- α emission and the He I emission, measured in the same viewing chord using the same optical system, can be related to the gas composition ratio, $N_{\text{H}} : N_{\text{H}_2} : N_{\text{He}}$. The ratio $N_{\text{He}}/N_{\text{H}_2}$ is obtained from the ratio of equation (9) to equation (5), namely,

$$\frac{\varepsilon_{\text{He}}(p)}{\varepsilon_{\text{Fulcher}}^{\text{total}}} = \frac{N_{\text{He}}}{N_{\text{H}_2}} \frac{R_1^{\text{He}}(p) A_{q \leftarrow p}^{\text{He}}}{\langle R_{X \rightarrow d^-}^{\text{H}_2} \rangle_{\text{eff}}}. \quad (10)$$

In the same manner, the ratio $N_{\text{H}}/N_{\text{H}_2}$ is obtained from the ratio of equation (8) to equation (5),

$$\begin{aligned} \frac{\varepsilon_{\text{H}}(p)}{\varepsilon_{\text{Fulcher}}^{\text{total}}} &= \frac{n_e \left[N_{\text{H}} R_1^{\text{H}}(p) + N_{\text{H}_2} R_2^{\text{H}}(p) \right] A_{2 \leftarrow p}}{n_e N_{\text{H}_2} \langle R_{X \rightarrow d^-}^{\text{H}_2} \rangle_{\text{eff}}} \\ &= \frac{R_1^{\text{H}} A_{2 \leftarrow p}}{\langle R_{X \rightarrow d^-}^{\text{H}_2} \rangle_{\text{eff}}} \left(\frac{N_{\text{H}}}{N_{\text{H}_2}} + \frac{R_2^{\text{H}}}{R_1^{\text{H}}} \right). \end{aligned} \quad (11)$$

The gas composition ratio, $N_{\text{H}} : N_{\text{H}_2} : N_{\text{He}}$, can then be obtained.

3. Experimental Setup

The experiments for hydrogen and helium mixture plasmas were conducted in the target chamber of the divertor/edge plasma simulator MAP-II [3]. The MAP-II consists of dual chambers, a higher density source chamber (upstream) and a lower density target chamber (downstream), which are connected to each other with a drift tube.

For optical emission spectroscopy (OES), a 1 m Czerny-Turner scanning monochromator equipped with a 2400 grooves/mm holographic grating and a cooled photomultiplier tube (PMT) (Hamamatsu R928) were used. The wavelength resolution was less than 0.02 nm for a 30 μm slit width. The sightline was vertical to the magnetic field lines, and spectroscopic data was obtained at each 5 mm increment from the center of plasma.

The working gas for the DC arc discharge was hydrogen and helium. T_e and n_e were measured using a Langmuir probe. The plasma condition was as follows: the discharge voltage and current were 88.6 V and 45 A, respectively, and the total pressure was 3.3 mTorr.

4. Results and Discussion

The electron temperature and density obtained using a probe are shown in Fig. 1(a) and (b). The rotational and vibrational temperature from Fulcher- α analysis are shown in Fig. 1(c) and (d). The horizontal axis is the distance from the center of plasma.

Because the observed emissions are the integrated data along the viewing chord, the Abel inversion is needed. For the Abel inversion, the radial profile of each emission was obtained using a charge-coupled device (CCD) detector and a wavelength-tunable filter [10, 11]. A wavelength-tunable filter transmits a particular wavelength (whose tunable range is 400–720 nm) and a 2-dimensional profile of

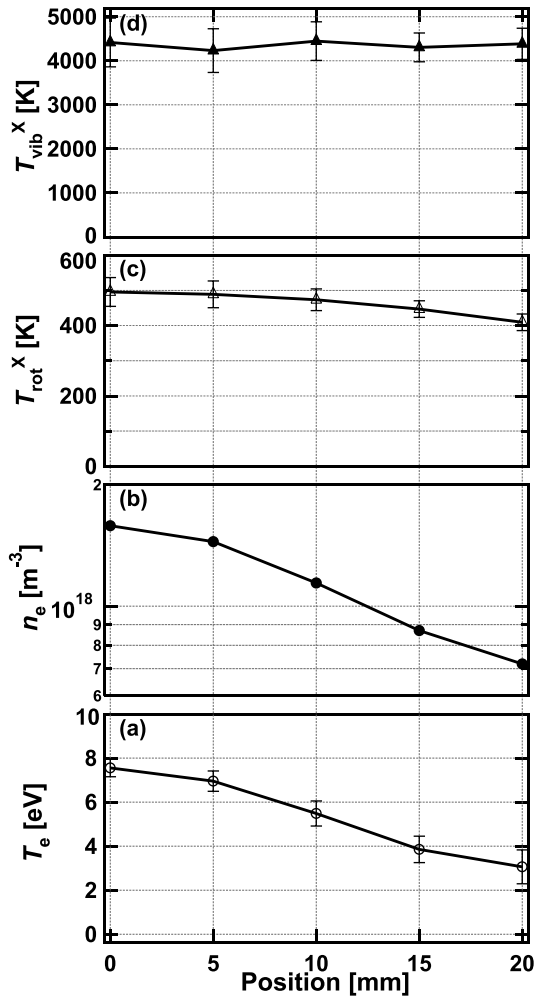


Fig. 1 Radial profile of the plasma parameters in the target chamber, (a) electron density, (b) electron, (c) rotational and (d) vibrational temperature. Abel inversion for each line intensity is performed for (c) and (d).

it can be obtained. The view of the CCD covers the radial positions between 10–70 mm. Note that this CCD system cannot be used for measuring molecular emissions because the bandpass of this filter is about 7 nm and the $\Delta\lambda$ of the Fulcher- α band is about 0.1 nm. However, the emission profile including some lines of the Fulcher- α band can be regarded to be same as each other because they are derived from the same electronic state.

It was confirmed that the profile data obtained with this CCD system agreed with a 1 m monochromator data in the 0–20 mm observation range of the spectrometer. The Abel inversion was then performed and the local emissions were obtained at each point.

The H_δ line was used as the hydrogen atom emission because the population coefficient of the dissociative component is small. As for the helium atom emission, we used the lines from 4^1S , 4^1D , 4^3S , 4^3D , 5^1S , 5^1D , 5^3S and 5^3D states, and averaged all N_{He} obtained using each line. The lines from the P states were not used because these are greatly affected by radiation trapping [9]. For the Fulcher- α band the 12 lines of $(v'-v'') = (0-0)-(3-3)$ and $J' = 1-3$ from

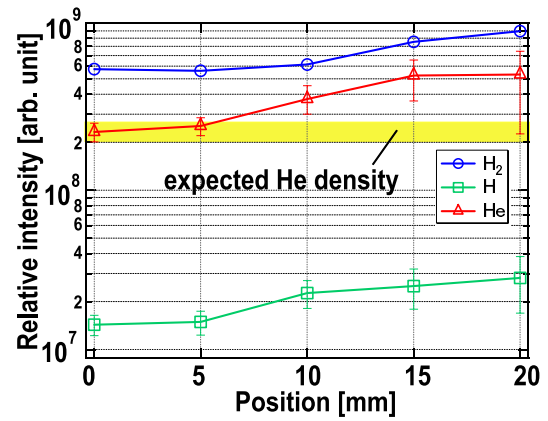


Fig. 2 Relative density of hydrogen atoms (open square), molecules (open circle) and helium atoms (open triangle). This dependence on position cannot be expected in the present condition.

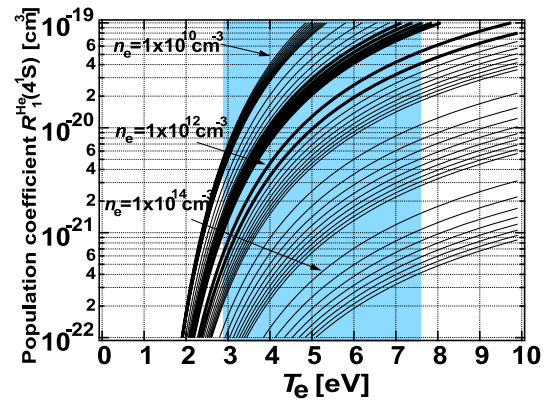


Fig. 3 Dependence of population coefficient of ionizing component $R_1^{He}(4^1S)$ on T_e for various n_e calculated by He CR model [8].

the Q branch were used because it has been reported that P and R branches exhibit intensity anomaly [12].

The obtained relative density of helium atoms, hydrogen atoms and hydrogen molecules are shown in Fig. 2. Only the effects of the errors in the electron temperature are considered for the evaluation of error bars in Fig. 2. Because the degree of ionization can be regarded as less than 1 %, it cannot be assumed that the density of helium has the radial distribution, but the result shows that it rises in the outer area. The possible reason is discussed in the following paragraphs.

Fig. 3 shows the dependence of the population coefficient of the ionizing component of He I (4^1S) on T_e for various n_e . The thick lines and shaded area indicate the regions of n_e and T_e of this experiment, respectively. The absolute values are sensitive to T_e around less than 4 eV. Therefore, around this region the value of the density can be affected by the errors in the electron temperature. In fact, the density at $r = 15$ and 20 mm, where T_e is less than 4 eV, can have large errors. For example, if $T_e < 3$ eV, an error of $\Delta T_e = 0.1$ eV can result in a 30 % error in density,

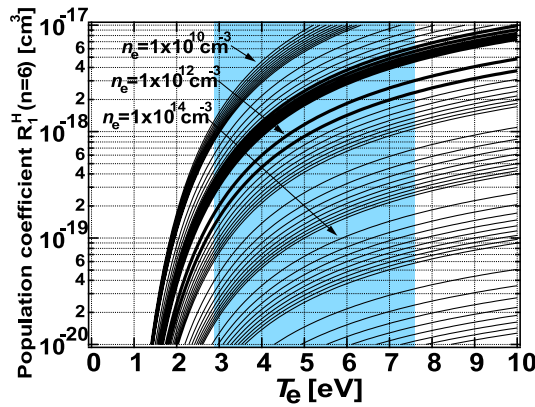


Fig. 4 Dependence of population coefficient of ionizing component $R_1^H(n=6)$ on T_e for various n_e calculated by H CR model [7].

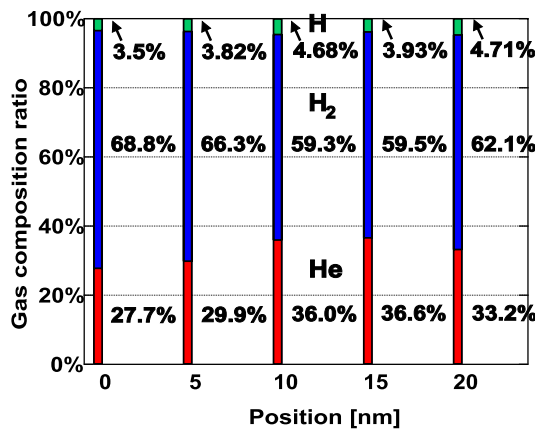


Fig. 5 Spatial profile of the gas composition ratio.

and if $T_e < 2$ eV, an error of $\Delta T_e = 0.1$ eV can result in a 60 % error. Therefore, precise measurement of the electron temperature is required.

Regarding hydrogen, as in the case of atomic helium, the population coefficient of the ionizing component is greatly affected by the electron temperature around $T_e < 4$ as shown in Fig. 4. In the case of the hydrogen CR model, however, the population coefficient of $n = 2$ has a relatively weak dependence on the electron temperature. If the Lyman α line can be used, the effect of the T_e error is small for $T_e > 2$, so that we can expect to obtain the density of hydrogen atoms more precisely [13].

The regions where R_1^{He} and R_1^{H} are sensitive to T_e and n_e , are similar to each other. Therefore, in the case of the measurement of the gas composition ratio (shown in Fig. 5), the effect of the errors on T_e and n_e can be small because the errors' effects may cancel each other. The dependence of the ratio of $R_1(4^1S)$ of He to $R_1(n=6)$ of H on T_e and n_e becomes weak for $T_e > 3$. In this regime, an error of $\Delta T_e = 0.1$ eV results in less than a 10 % error in the gas composition ratio. Therefore, the obtained gas composition ratio (Fig. 5) is assumed to be within an error range of several tens of percent.

5. Summary

We have proposed a method to measure the gas composition ratio of H-He mixture plasmas by using passive spectroscopy and applied the method to the plasma in MAP-II. Because the population coefficient of H and He can be sensitive to T_e and n_e , measurement of the density profile of each gas species cannot be reliable for $T_e < 4$ eV.

On the other hand, in the case of the measurement of a gas composition ratio, because the dependency of the population coefficient on T_e and n_e is similar, the reliability is higher for $T_e > 2$ eV. Therefore if the density profile of a particular species can be obtained by using another method such as LIF (Laser-Induced Fluorescence), the density profile of the other species can be obtained from the gas composition ratio obtained by this method for $T_e > 2$ eV.

In case of the $T_e < 2$ eV, the degree of ionization is small and the density profile of helium is assumed to be uniform. In this case, the partial pressure of helium measured by another method such as that utilizing quadrupole-mass analyzer can be used. The density of hydrogen molecules and atoms can then be obtained from the remaining partial pressure and the atomic/molecular ratio obtained using this method [14].

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