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Study of Impurity Ion Radiation Intensities using Collisional-Radiative Model in the GAMMA 10 Plasma

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Abstract

Impurity ion radiation intensity has been studied in the GAMMA 10 plasma using both collisional-radiative model (CR-model) calculation and absolute vacuum ultraviolet, ultraviolet and visible spectroscopic measurements. Steady state CR-model calculation for carbon ions is used to obtain the carbon ion emissivities in the plasma. The CR-model calculation results of carbon ion radiation intensities are comparable to the results obtained by the impurity ion spectroscopy. Then we use the CR-model calculation results for plasma parameter diagnostics using impurity ion spectroscopy.

Keywords:

collisional-radiative model, VUV spectroscopy, UV/V spectroscopy, GAMMA 10, impurity ion radiation

1. Introduction

Impurity ion radiation measurements are important study for fusion plasmas. They have lot of important information of the fusion plasmas, such as impurity transport, plasma density, and plasma temperature, etc. We have studied impurity ion radiation intensities in the fusion plasma GAMMA 10 with comparing the collisional-radiative model (CR-model) calculation results to the measured impurity ion spectra using absolutely calibrated spectrograph systems for plasma diagnostics. The CR-model has been developed in anywhere [1-4]. We used CR-model calculation code originally made by T. Kato at National Institute of Fusion Science (NIFS) for carbon ions, CII (C^{+}) and CIII (C^{2+}) [3,4].

In this paper, we show the impurity ion (carbon ion) line radiation intensities in the GAMMA 10 plasma and compare the impurity ion emission intensities obtained by CR-model calculation to those obtained by the vacuum ultraviolet (VUV), ultraviolet and visible (UV/V) spectroscopic systems in GAMMA 10.

2. CR-model calculation

In CR-model calculation, the population density $n_z(i)$ is shown in eq. (1).

$$
\begin{aligned}
\frac{dn_z(i)}{dt} &= \left(\sum_{j\neq i} C_{ji} n_e n_z(i) + \sum_{j>i} A_{ji} n_z(i)\right) \\
&- \left(\sum_{j\neq i} C_{ij} n_e n_z(i) + \sum_{j<i} A_{ij} n_z(i)\right) \\
&- \left(\sum_{l} \alpha_z(i,l) + \sum_{k} S_z(i,k)\right) n_z(i) n_e + \sum_{l} \alpha_{z+1}(i,l) n_{z+1}(l) n_e \\
&+ \sum_{k} S_{z-1}(k,i) n_{z-1}(k) n_e + \sum_{l} \alpha_{z+1}{}^{CX}(l,i) n_{z+1}(l) n_e . \qquad (1)
\end{aligned}
$$

Here, $n_z(i)$ is the population density of level i of an ion z, n_e is electron density, C_{ij} and C_{ji} are the electron impact excitation and de-excitation coefficients, respectively, A_{ij} shows the transition probability from level i to level j, $S_z(i,k)$ is ionization rate coefficient from level i of ion z to level k of ion z+1, $\alpha_z(i,l)$ is electron impact recombination rate coefficient from level i of ion z to level l of ion z-1, and $\alpha_{z+1}{}^{CX}(l,i)$ is charge exchange recombination rate coefficient. Transition probabilities for CII and CIII ions are basically taken from [5,6]. For CII ions, transition probabilities are taken from [7] for n = 2 and from [5,6] for n = 3, where n indicates the principal quantum number. We have used the excitation data published in [8] and Mewe empirical formula [9]. For CIII ions, transi-

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tion probabilities are taken from [10,11]. We have used the excitation data published in [12] for n = 2-2 and [13] for n = 2-3 and 3-3 transitions. The total ionization and recombination rate coefficients are from [14]. The ionization rate coefficients from the excited states are calculated by the Lotz formula [15]. Then we can calculate the density and temperature dependence of the line intensities with the CR-model for all carbon atom and ions including the levels up to 3 or 4 under the steady state condition. It is convenient to define the effective emission rate coefficients ε_{ij}^{eff} to estimate the line intensity as follows:

$$\varepsilon_{ij}^{eff} \equiv \frac{n_z(i)A_{ij}}{\sum_i n_z(i)n_e}. \quad (2)$$

Then the line intensity I_{ij} from a plasma with electron temperature T_e and electron density n_e can be given in terms of ε_{ij}^{eff} as

$$I_{ij} = \varepsilon_{ij}^{eff}\,(T_e,n_e)\sum_i n_z(i)n_e. \quad (3)$$

Then we can obtain the theoretical impurity ion radiation intensities of carbon ions.

3. Impurity ion spectroscopy in GAMMA 10

The VUV spectrograph [16-20] was placed in the central cell region of GAMMA 10. In the tandem mirror GAMMA 10 plasma, confinement is achieved by not only a magnetic mirror configuration but also high potentials at the both end regions. The potentials are produced by means of electron cyclotron resonance heating (ECRH) at the plug/barrier region. The main plasma confined in GAMMA 10 hot ion mode operation is produced and heated by ion cyclotron range of frequency (ICRF) power deposition. In plasmas produced in the GAMMA 10 central cell region, typical electron density, electron temperature and ion temperature are about 2×10^{12} cm^{-3}, 80 eV and 5 keV, respectively [21].

The VUV spectrograph can provide spatial and spectral distributions of plasma radiation in the wavelength range of 150-1050 Å. It consists of an entrance slit of limited height (100 μm × 6 mm), an aberration-corrected concave grating with varied spacing grooves (Hitachi P/N001-0464), and an image-intensified two-dimensional detector system. One can observe the upper half of the plasma with a field of view of about 25 cm diameter. The spectral images of VUV spectrograph are recorded by a MOS type camera (Reticon MC9256) and typical frame rate of the camera is 50 frames/s. Absolute calibration experiment for VUV spectrograph has been performed on the overall sensitivities for the wavelength of synchrotron radiation produced at the Photon Factory in the High Energy Accelerator Research Organization [16-20].

The UV/V spectrograph system views the plasma column vertically [16,17]. The spectrograph covers the range from $x = -20$ cm to $x = 20$ cm. The observable wavelength of the spectrograph is in the range of 2500 Å to 7000 Å. The output images of the spectrograph are recorded by the CCD camera whose frame rate is 30 frames/s. The spectrograph was absolutely calibrated by using tungsten ribbon filament lamp.

4. Impurity ion spectra

By using the CR-model calculation code, we obtained the impurity ion radiation spectra of carbon ions in the GAMMA 10 plasma parameter, T_e = 50 eV and $n_e = 2 \times 10^{12}$ cm^{-3}. Figure 1 (a) and Fig. 1 (b) show the CII and CIII ions spectra obtained by CR-model calculation, respectively. Figure 2 shows the absolute VUV spectrum in the GAMMA 10 plasma using VUV spectrograph.

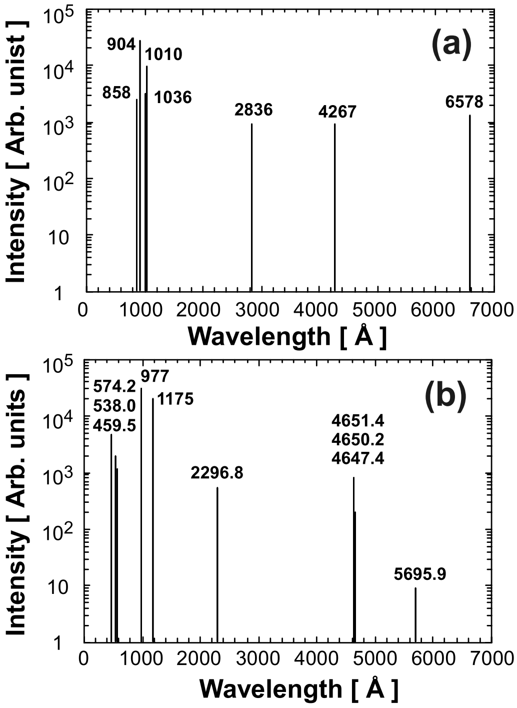

Fig. 1 Figure 1 (a) and 1 (b) show the CII (C^+) and CIII (C^{2+}) ions spectra obtained by CR-model calculation, respectively.

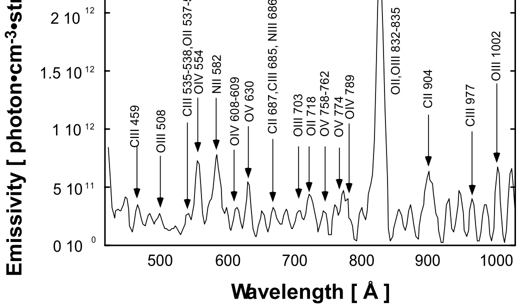

Fig. 2 The absolute VUV spectrum in the GAMMA 10 plasma using VUV spectrograph.

Figures 3 show the effective emission rate coefficient, $R_{ij} = \frac{I_{ij}}{n_e}$, from level i to level j as a function of the electron temperature for six different electron densities for the two lines in the ionizing plasma, (a) for CII ($2s2p^2\ ^2P \rightarrow 2s^22p\ ^2P$, 904 Å) and (b) for CIII ($2s2p\ ^1P \rightarrow 2s^2\ ^1S$, 977 Å), respectively. In the region of the GAMMA 10 plasma, 10eV < T_e < 100 eV and 1×10^{11} cm^{-3} < n_e < 2×10^{12} cm^{-3}, the ionizing effect is dominant from the CR-model calculation. Calculated intensity ratio between CII ($2s^24f\ ^2F \rightarrow 2s^23d\ ^2D$, 4267 Å) and CII ($2s^23p\ ^2P \rightarrow 2s^23s\ ^2S$, 6578 Å) is shown in Fig. 4. Observed intensity ratio using UV/V spectroscopy in the center of the plasma is also shown in Fig. 4, where the electron temperature was measured by X-ray measurement, independently.

Density profiles of impurity ions were deduced using absolute emissivities of impurity lines and the CR-model calculation. Figure 5 shows the time dependent radial distributions of impurity ion densities of CII and CIII ions obtained by both CII (904 Å) and CIII (977 Å) line emissions and the CR-model calculation (Fig. 3). The solid lines show that the densities before ECRH and dotted lines show those during ECRH. The carbon ion densities of CII and CIII ions are about the order of 10^8 cm^{-3}.

5. Discussion

In the CR-model calculation, there is about 10 % of error, which comes from the atomic data calculations. Impurity ion emissivities were measured with the error of about 20 %, which was obtained by the calibration experiments.

Comparing the Fig. 1 and 2, the deduced intensity of carbon ions from CR-model calculation are almost the same as the spectroscopic results. Moreover the intensity ratio measurements of UV/V spectroscopy (Fig. 4) show that the CR-model calculation results are comparable to the spectroscopic results. Then the CR-model calculation for our plasma parameter region is useful for plasma spectroscopy. However it is very hard to use for detailed plasma diagnostics, because the intensity ratio is small compared with signal to noise ratio of recording system of the spectrographs. Then, we tried to find new line pairs for temperature measurement using CR-model calculation results. Our VUV spectroscopy has more than 20 % of error, then, the variation of the intensity ratio of

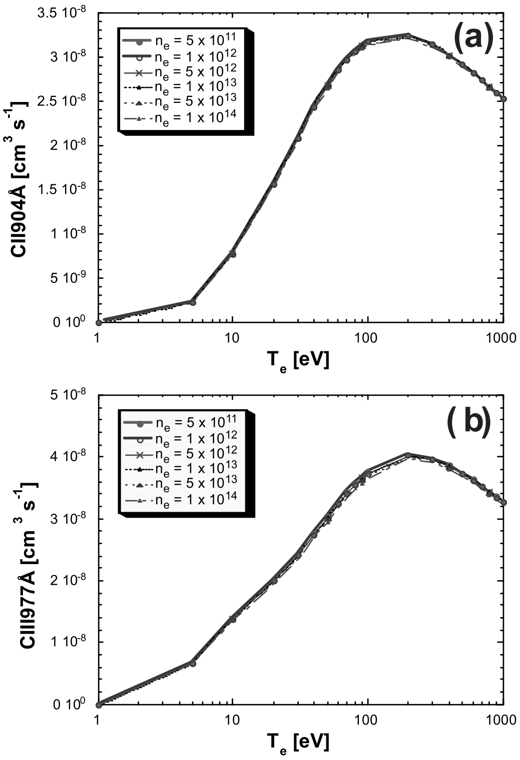

Fig. 3 The effective emission rate coefficient, (a) for CII ($2s2p^2\ ^2P \rightarrow 2s^22p\ ^2P$, 904 Å) and (b) for CIII ($2s2p\ ^1P \rightarrow 2s^2\ ^1S$, 977 Å), respectively.

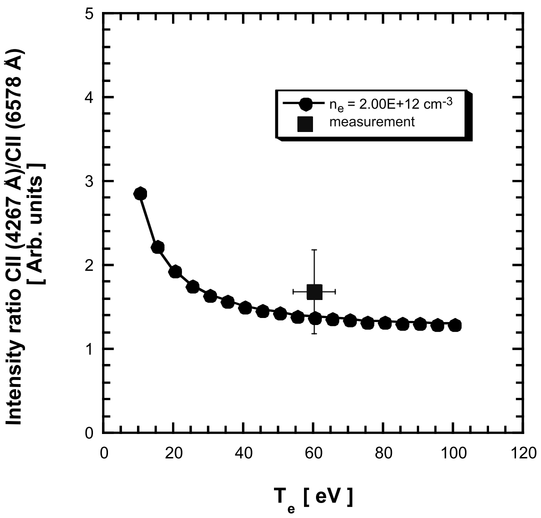

Fig. 4 Intensity ratio between CII ($2s^24f\ ^2F \rightarrow 2s^23d\ ^2D$, 4267 Å) and CII ($2s^23p\ ^2P \rightarrow 2s^23s\ ^2S$, 6578 Å).

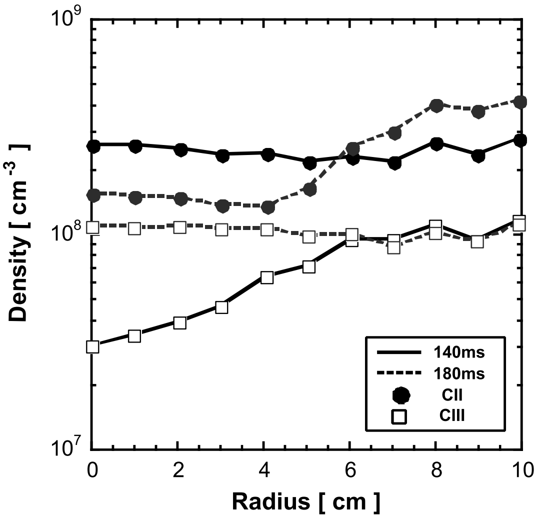

Fig. 5 The time dependent radial distributions of impurity ions obtained by CII (904 Å) and CIII (977 Å) line emission measurements.

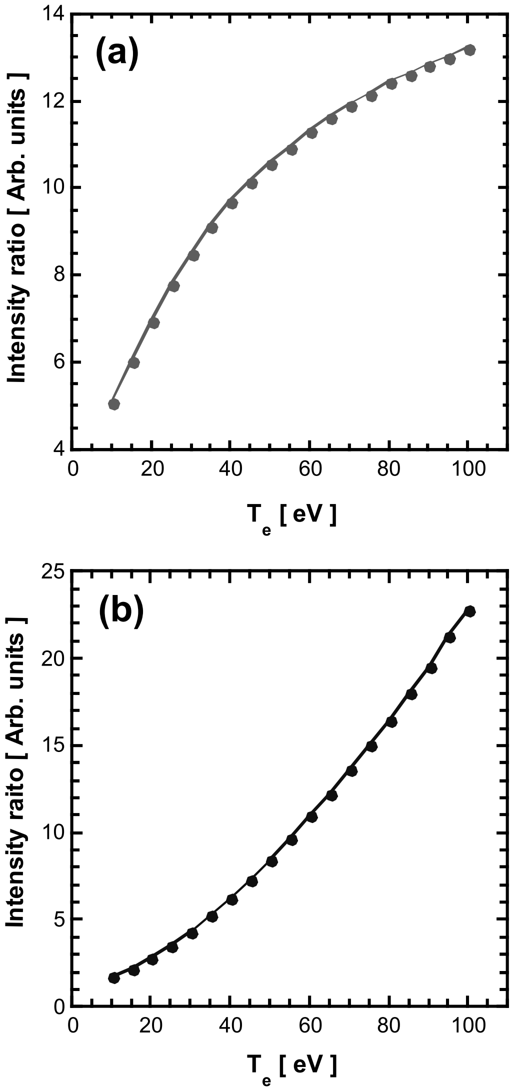

Fig. 6 In Fig. 6 (a) and (b), we show the intensity ratio between CII ($2s^23s\ ^2S \rightarrow 2s^22p\ ^2P$, 858 Å) and CII ($2s2p^2\ ^2P \rightarrow 2s^22p\ ^2P$, 904 Å) lines, and CII ($2p^2\ ^4S \rightarrow 2s2p^2\ ^4P$, 1010 Å) and CII ($2s2p^2\ ^2P \rightarrow 2s^22p\ ^2P$, 904 Å) lines against electron temperatures, respectively.

line pairs must be larger than the experimental error. In Fig. 6 (a) and Fig. 6 (b), we show the intensity ratio between CII ($2s^23s\ ^2S \rightarrow 2s^22p\ ^2P$, 858 Å) and CII ($2s2p^2\ ^2P \rightarrow 2s^22p\ ^2P$, 904 Å) lines, and CII ($2p^2\ ^4S \rightarrow 2s2p^2\ ^4P$, 1010 Å) and CII ($2s2p^2\ ^2P \rightarrow 2s^22p\ ^2P$, 904 Å) lines against electron temperatures with $n_e = 1 \times 10^{12}$ cm^{-3}, respectively. These line pairs show the large intensity ratio against electron temperature. When we use these line pairs for electron temperature measurements, we have to improve the recording system of the spectrographs with the wavelength resolution up to 2 Å and its intensity resolution about 12 bits.

We obtained the time dependent impurity ion density profiles using absolute impurity ion emission measurements. In Fig. 5, during ECRH the CII ion density decreases and CIII ion density increases in the plasma center caused by ECRH. This indicates that the ionization from CII to CIII ions increase, because the electron temperature and electron density increase by ECRH. The decrease of the CII ion density and the increase of the CIII ion density in the center of the plasma are comparable to the results of the CR-model calculation. Then we have constructed the observing methods for impurity ion density behaviors in the GAMMA 10 plasma.

6. Conclusion

We studied impurity ion radiation intensity using both collisional-radiative model (CR-model) calculation and absolute VUV spectroscopic measurements in the GAMMA 10 plasma for plasma diagnostics. Steady state CR-model calculations for carbon ions are used to obtain the carbon ion emissivities in the plasma. The CR-model calculation results of carbon ion radiation intensities are comparable to the results obtained by impurity ion spectroscopy in GAMMA 10.

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