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Study of Radiated Spectral Intensities in the HANBIT Plasma for Plasma Diagnostics

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Abstract

Intensities of radiation from impurity ions have been studied in the HANBIT plasma for plasma spectroscopic diagnosis using a collisional-radiative model (CR-model). Absolute sensitivity of a vacuum ultraviolet (VUV) spectrometer is obtained using the CR-model for hydrogen. The hydrogen line intensities are measured by using the VUV spectrometer and an absolutely calibrated ultraviolet and visible spectrometer. Therefore, we can study the absolute intensities of the radiation spectra in the wavelength range from vacuum ultraviolet to visible in the HANBIT plasma. We obtain the neutral hydrogen and carbon ion densities in the HANBIT plasma. Moreover, we measure the electron temperature using the intensity ratio method for plasma diagnostics.

Keywords:

collisional-radiative model, VUV spectroscopy, UV/V spectroscopy, HANBIT

1. Introduction

In these days, a collisional-radiative model (CR-model) is an important model for the plasma spectroscopy. The CR-models for hydrogen, carbon and oxygen have been developed [1-7]. The CR-model for hydrogen is normally used for neutral density measurements in many fusion plasma devices [7-8]. However, the comparison between the calculated results using the CR-model for impurity ions and the experimental results must be carried out in many types of plasmas to construct the model for plasma diagnostics [5-13]. Then, we have studied impurity ion spectral intensities in the HANBIT plasma at Korea Basic Science Institute, Korea, in order to compare the spectroscopic results with the calculated results using the CR-model for plasma diagnostics. HANBIT is a suitable plasma device for lower charged ions of CR-model calculations. We carry out the absolute calibration experiments of a vacuum ultraviolet (VUV) spectrometer using the CR-model for hydrogen. The absolute hydrogen line intensities are measured by using the VUV spectrometer and a 5-channel ultraviolet and visible (UV/V) spectrometer. We study neutral hydrogen and carbon ion intensities for plasma diagnostics using the CR-models in the HANBIT plasma.

2. CR-model calculation

In the CR-model of neutral hydrogen, the population density of an excited level of principle quantum number i is given by

$$\begin{aligned}\frac{\mathrm{d}n(i)}{\mathrm{d}t} &= \left\{\sum_{j\neq i} C_{ji} n_e n(j) + \sum_{j>i} A_{ji} n(j)\right\} \\ &- \left\{\sum_{j\neq i} C_{ij} n_e n(i) + \sum_{j<i} A_{ij} n(i) + S(i) n(i) n_e\right\} \\ &+ \{\alpha_1(i) n_e + \beta_1(i)\}\, n_e n_1 + \gamma_1(i) n_e n_{H_2}, \qquad (1)\end{aligned}$$

where n_e and n_1 are the electron density and the proton densities, respectively, A_{ji} is the spontaneous transition probability from level j to level i, C_{ij} is the excitation or deexcitation rate coefficient by electron impacts from level i to level j, $S(i)$ and $\alpha_1(i)$ are the ionization rate coefficient by electron impacts and the three-body recombination rate coefficient, respectively, and $\beta(i)$ and $\gamma(i)$ are the radiative recombination rate and the dissociative excitation coefficients from molecular hydrogen. [1-9].

In the CR-model calculation for impurity ions, the population density $n_z(i)$ is shown in eq. (2).

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$$\frac{\mathrm{d}n_z(i)}{\mathrm{d}t} = \left\{\sum_{j\neq i} C_{ji} n_e n_z(j) + \sum_{j>i} A_{ji} n_z(j)\right\} - \left\{\sum_{j\neq i} C_{ij} n_e n_z(i) + \sum_{j<i} A_{ij} n_z(i)\right\} - \left\{\sum_{l} \alpha_z(i,l) + \sum_{k} S_z(i,k)\right\} n_z(i) n_e + \sum_{l} \alpha_{z+1}(i,l) n_{z+1}(l) n_e + \sum_{k} S_{z-1}(k,i) n_{z-1}(k) n_e + \sum_{l} \alpha_{z+1}{}^{CX}(l,i) n_{z+1}(l) n_e \quad (2)$$

Here, $n_z(i)$ is the population density of level i of an ion z, n_e is electron density, $S_z(i,k)$ 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. The effective emission rate coefficients ε_{ij}^{eff} is shown as

$$\varepsilon_{ij}^{eff} \equiv \frac{n_z(i) A_{ij}}{\sum_i n_z(i) n_e}. \quad (3)$$

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

$$I_{ij} = \varepsilon_{ij}^{eff}(T_e, n_e) \sum_i n_z(i) n_e. \quad (4)$$

Transition probabilities, excitation data, ionization, and recombination rate coefficients in the calculations are

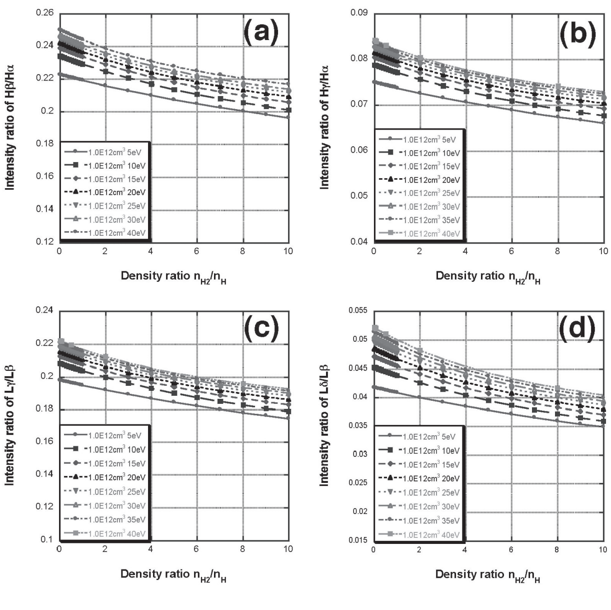


Fig. 1 Intensity ratios of hydrogen Balmer and Lyman series lines, H_β/H_α, (a), H_γ/H_α, (b), L_γ/L_β, (c), and L_γ/L_β, (d), calculated using the CR-model.

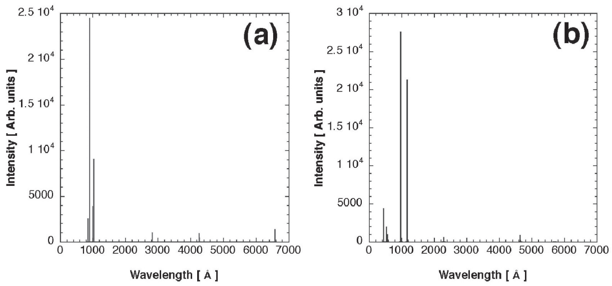


Fig. 2 Calculated radiation intensities of carbon ions, CII (a) and CIII (b) when $n_e = 3\times10^{12}$ cm^{-3} and $T_e = 40$ eV.

obtained from refs. [4,9]. We compare the line intensity I_{ij} and the measured spectral intensity in order to obtain the plasma parameters, such as neutral hydrogen or carbon ion densities and the electron temperature.

Figure 1 shows the intensity ratios of hydrogen Balmer and Lyman series lines, H_β ($4d^2D\rightarrow 2p^2P^0$, 4861Å)/H_α ($3d^2D\rightarrow 2p^2P^0$, 6563 Å), (a), H_γ ($5d^2D\rightarrow 2p^2P^0$, 4340 Å)/H_α, (b), L_γ ($4p^2P^0 \rightarrow 1s^2S$, 972 Å)/$L_\beta$ ($3p^2P^0 \rightarrow 1s^2S$, 1025 Å), (c), and L_δ ($5p^2P^0 \rightarrow 1s^2S$, 949 Å)/$L_\beta$, (d), obtained by CR-model calculation. Figure 2 shows calculated radiation intensities of carbon ions, C II (a) and C III (b) in $n_e = 3\times10^{12}$ cm^{-3} and $T_e = 40$ eV.

3. Experimental apparatus

HANBIT device consists of a simple mirror at the center with a baseball coil based minimum-B mirror and a short axisymmetric mirror on each end of the central cell. Detailed machine descriptions are given in refs. [14,15]. The HANBIT device is normally operated with ion cyclotron resonance heating (ICRH) for plasma production and heating. In these experiments, ICRH power was 60 kW. The typical electron temperature and electron density measured by Langmuir probe are 40 eV and 2×10^{12} cm^{-3}, respectively. Figure 3 shows the radial profiles of n_e and T_e.

A 5-channel UV/V spectrometer consists of collection lenses, a 5-channel 10-m long quarts optical fiber, and a focal length of 1.33 m Czerny-Turner spectrometer [16]. The detector consists of a 1024 × 256 pixel array (pixel size 26 μm) with a micro-channel plate (MCP) gated intensifier. The reciprocal linear dispersion is 0.0085 nm/pixel and the time resolution is 31 ms/frame. Five optical chords are installed on the HANBIT central cell for the multi-chord spectroscopy. Total observing range is about 24 cm in the upper half of the plasma. The UV/V spectrometer is absolutely calibrated by a standard irradiance lamp. Then, we can obtain the absolute intensities of

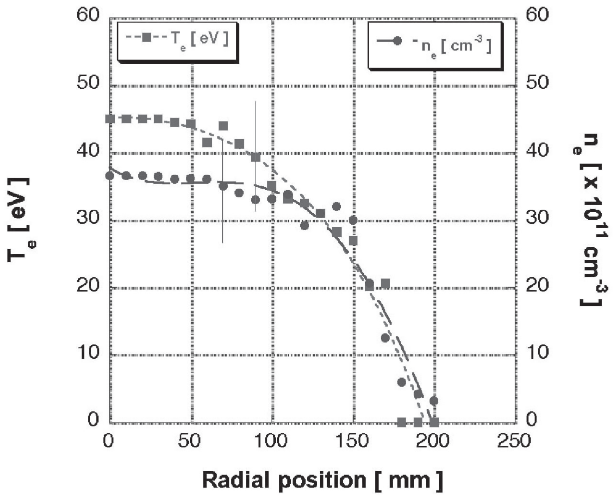


Fig. 3 The radial profiles of n_e and T_e.

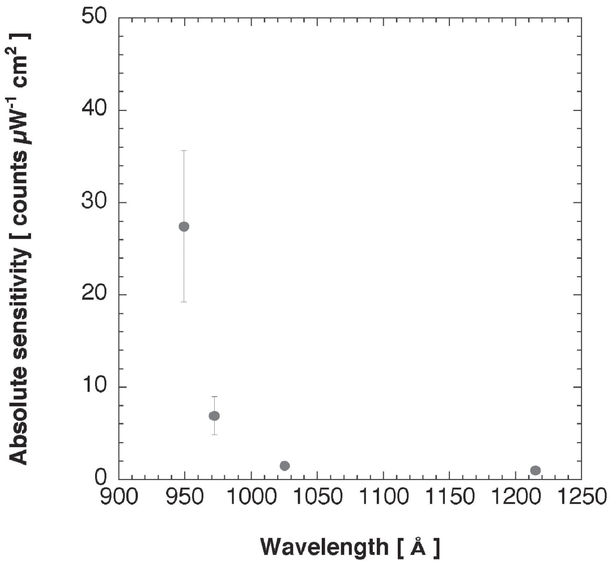


Fig. 5 The absolute sensitivity of the VUV spectrometer.

line spectra in the UV/V wavelength range from the HANBIT plasma. A Seya-Namioka type VUV spectrometer is used with an MCP, a phosphor plate and a photoionization detector. The VUV spectrometer observes the center chord of the plasma. Its reciprocal linear dispersion is 0.058 nm/pixel and the time resolution is 35 ms/frame.

4. Spectroscopy in HANBIT

First we measure hydrogen Balmer series line emissions (H_α, H_β and H_γ) using the 5-channel UV/V spectrograph and Lyman series line emissions (L_α (2p $^2P^0 \rightarrow 1s^2S$, 1215 Å), L_β, L_γ and L_δ) using the VUV spectrometer, simultaneously. Figure 4 shows the typical VUV spectrum. By comparing the CR-model calculation results of intensity ratios of H_β/H_α and H_γ/H_α, we can calculate intensity ratios of L_γ/L_β and L_δ/L_β. Moreover, the absolute intensities of H_α, H_β and H_γ show the population densities $n(3)$, $n(4)$, and $n(5)$ of neutral hydrogen atoms. From the CR-model calculation, we obtain the relative population densities, $n(i)/n(1)$. Then, we can calculate the population densities of $n(1)$ and $n(2)$. The absolute emissions of L_α, L_β, L_γ and L_δ are calculated. We compare the measured intensities of the VUV spectrometer of Lyman lines with the calculated intensities, in order to obtain the absolute sensitivity of the VUV spectrometer. Figure 5 shows the absolute sensitivity of the VUV spectrometer. It is almost constant with the wavelength range from 1000 to 1250 Å. However, in the wavelength range from 900 to 1000 Å, the sensitivity is changed extremely. The reason of this sensitivity change is not clear. In any case,

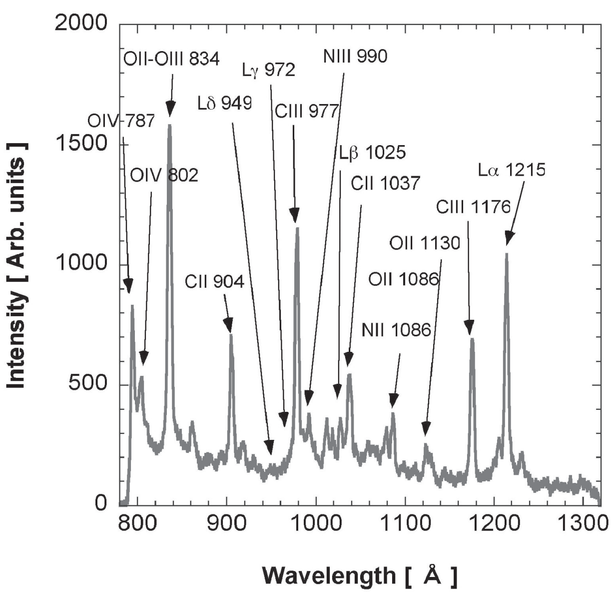


Fig. 4 Typical VUV spectrum in the HANBIT plasma.

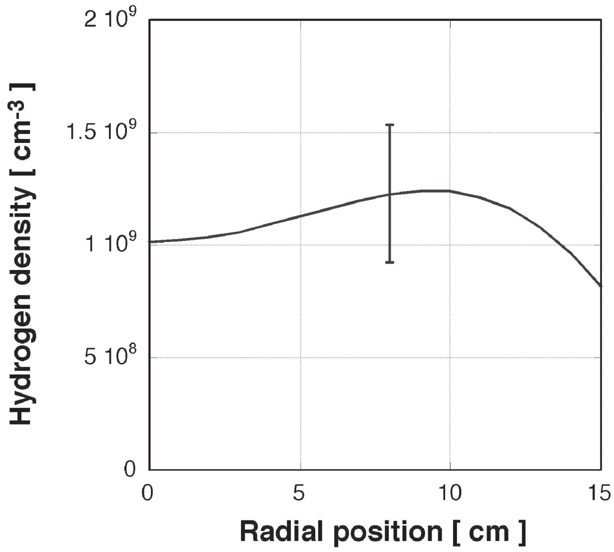
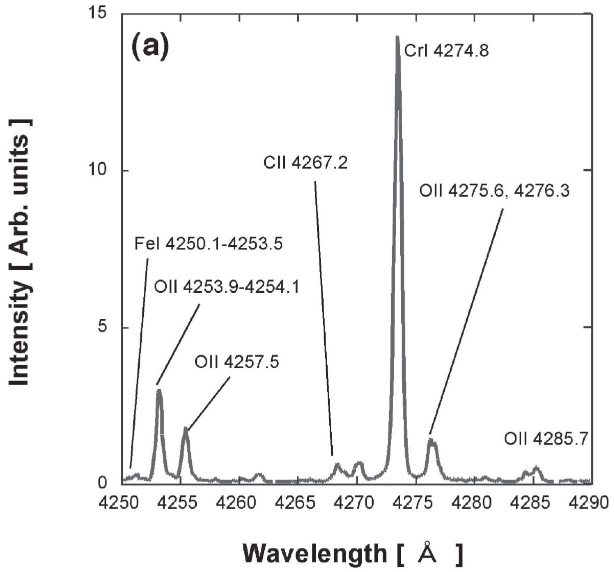


Fig. 6 Radial profile of neutral hydrogen density is obtained using the CR-model calculation.



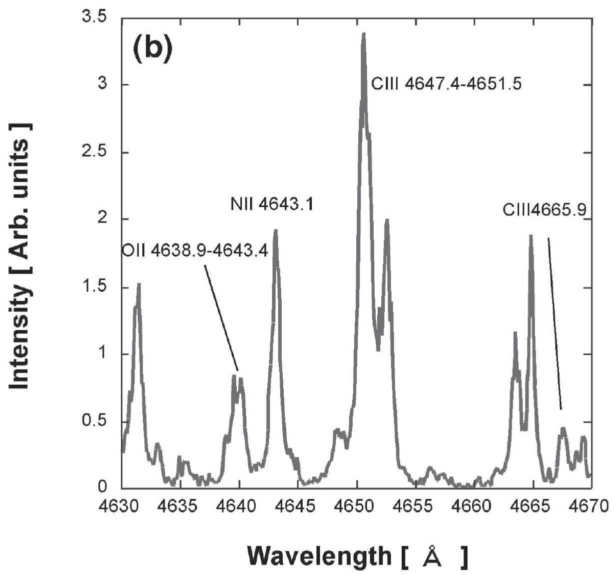


Fig. 7 The UV/V spectra of CII (4267 Å) and CIII (4650 Å) are shown in (a) and (b), respectively.

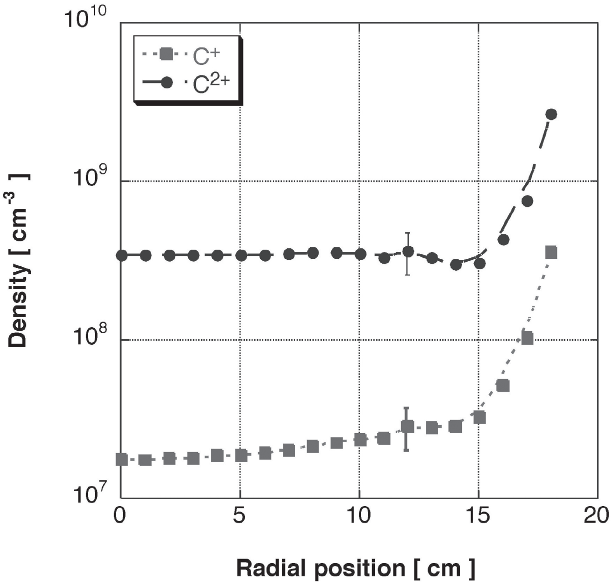


Fig. 8 Radial density profiles of carbon ions C^+ and C^{2+} are shown in squares and circles, respectively.

we can observe the absolute spectral intensities in UV/V and VUV spectral range in the HANBIT plasma.

By using the CR-model calculation, radial profile of neutral hydrogen density is shown in Fig. 6. Figures 7 (a) and (b) show the UV/V spectra of C II ($2s^24f^2F \rightarrow 2s^23d^2D$, 4267 Å) and C III (3p $^3P^0 \rightarrow 3s^2S$, 4647.4 – 4651.5Å), respectively. Figure 8 shows the radial density profiles of carbon ions of C^+ and C^{2+}. In the HANBIT plasma, the neutral hydrogen density at the center of the plasma is about 1.2×10^9 cm^{-3}. C^+ and C^{2+} ion densities are about 2×10^7 cm^{-3} and 5×10^8 cm^{-3}, respectively. We compare the C II and C III line intensities in the UV/V spectral range with those in the VUV spectral range. Intensities of C II (4267 Å) and C II ($2s2p^2$ $^2P \rightarrow 2s^22p$ ^2P, 904Å) are about 1.0 μW cm^{-2} and about 35 μW cm^{-2}, respectively. Intensities of C III (4650 Å) and C III (2s2p $^1P \rightarrow 2s^2$ ^1S, 977Å) are about 3.2 μW cm^{-2} and about 457 μW cm^{-2}, respectively. These are almost comparable to the CR-model calculation results within 30 % of error. This shows that our calibration method for VUV spectrometer is useful.

Next, we adopt the intensity ratio method with the CR-model to the plasma diagnostics in order to measure the electron temperature. Intensity ratio method for electron temperature measurement was used with intensity ratio between C II ($2p^3$ $^4S \rightarrow 2s2p^2$ ^4P, 1010Å) and C II (904 Å) [9]. The intensity ratio is about 7, then the electron temperature is about 40 eV in the error of 30 %. It is compared with the results of the electron temperature measured by the Langmuir probe.

5. Conclusion

We carry out the absolute calibration experiments of the VUV spectrometer using the CR-model for hydrogen. The absolute hydrogen line intensities are observed by using the VUV spectrometer and the 5-channel UV/V spectrometer. Then, we prepared the spectroscopic system with the wavelength range from VUV to visible in HANBIT. The neutral hydrogen and carbon ion intensities are absolutely observed in order to obtain the plasma particle densities and electron temperatures using the CR-model. We successfully obtain the electron temperature using intensity ratio method with CR-model.

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