J. Plasma Fusion Res. SERIES, Vol.7 (2006) 45-49

Study of Carbon Ion Behavior by Using Collisional Radiative Model in the GAMMA 10 Tandem Mirror

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(Received: 4 October 2004 / Accepted: 28 April 2005)

Abstract

In a plasma experiment, collisional radiative model (CRM) is very useful model to evaluate impurity behaviors and plasma parameters with line emission from a plasma. CRMs for carbon and oxygen have been developed. However verification and application of the model for analysis of experimental results are not enough. Then we applied CRM calculation results to observed impurity spectra in the GAMMA 10 tandem mirror to evaluate the impurity density profile and the particle balance of each charge state of carbon ion. We calculated the effective ionization rate for each charge state of carbon ion and obtained the density profile of each ion. Moreover, we calculated absolute emission intensities from all carbon ions.

Keywords:

collisional radiative model, impurity ion, spectroscopy, GAMMA 10

1. Introduction

Impurity emission spectra from a fusion plasma have a lot of important information of the plasma, such as temperatures and densities of impurities, radiation loss and rotation velocity of ions. These informations are very useful to evaluate the impurity transfer and energy loss from a plasma. Moreover the radial profile of electron density, temperature and electric field in the plasma are obtained by using a collisional radiative model (CRM) and the relation between the profile of spectra and plasma parameters [1]. By using the CRM, ratio of an excited state population density to ground state in an impurity ion is described as a function of the electron temperature and the electron density under an assumption of the ionizing plasma. CRMs for carbon and oxygen have been developed [2,3]. However verification and application of the model to experimental results are not enough. Then we applied CRM calculation results to the analysis of observed spectra in the GAMMA 10 tandem mirror to evaluate the impurity density profile and the particle balance of each charge state of carbon.

In the GAMMA 10 tandem mirror, space and time resolved spectra are observed and analyzed in order to evaluate the plasma parameters and impurity transfer. Emission lines from the C II (C^+) , C III (C^{2+}), O II (O^+), O III (O^{2+}), O IV (O^{3+}) and O V (O^{4+}) ions dominate the observed spectra in GAMMA 10. In any experimental setup in GAMMA 10, spectra from highly ionized carbon ions, such as C IV (C^{3+}), C V (C^{4+}) and C VI (C^{5+}) are not observed by any spectroscopic measurement systems [4]. Therefore it has been believed that highly ionized carbon ions run away in the confinement time. Then we calculated C II and C III density profiles using both absolute calibrated spectra and CRM calculations under an assumption of the ionizing plasma. We estimate the all carbon ions density profiles by particle balance of each charge state of carbon ion with considering the impurity ion confinement and calculated absolute emission intensity from all carbon ions. In this paper, we present the results of CRM calculation for C II and C III and experimental results of carbon ion emission in the GAMMA 10 tandem mirror. Moreover we discuss the particle balance of each charge state of carbon ion and the confinement of carbon in the plasma.

2. Collisional radiative model

In fusion plasmas, the population densities of the excited states must be determined by CRM. In CRM, both collision and radiation effects are considered. Each effect is introduced with the electron impact (de) excitation, ionization, recombination rate and radiative transition rate, and expressed as C_z, S_z, α_z and A_z, respec-

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tively, in the following rate equation (1).

$$\frac{\mathrm{d}n_z(i)}{\mathrm{d}t} = \left\{ \sum_{j\neq i} C_z(j,i) n_e n_z(j) + \sum_{j>i} A_z(j,i) n_z(j) \right\}$$
$$- \left\{ \sum_{i\neq j} C_z(i,j) n_e n_z(i) + \sum_{j<i} A_z(i,j) n_z(i) \right\}$$
$$+ \left\{ \sum_{l} S_{z-1}(l,i) n_e n_{z-1}(l) \right\} - \left\{ \sum_{k} S_z(i,k) n_e n_z(i) \right\}$$
$$+ \left\{ \sum_{k} \alpha_{z+1}(k,i) n_e n_{z+1}(k) \right\} - \left\{ \sum_{l} \alpha_z(i,l) n_e n_z(i) \right\}, \tag{1}$$

where $n_z(i)$ is population density of i level of z charged ion and j, k and l is a level of z charged ion, $z-1$ charged ion and $z+1$ charged ion, respectively. We assume quasi-steady-state and use ionizing plasma approximation. Then, we can obtain the population densities of the excitation states with the following expression.

$$\begin{aligned} n_z(i) &= R_{z-1}(i) n_e n_{z+1}(0) + R_z(i) n_e n_z(0) \\ &\quad + R_{z+1}(i) n_e n_{z+1}(0) \\ &\simeq R_z(i) n_e n_z(0) \\ &= R'_z(i) n_e n_z, \end{aligned} \tag{2}$$

where $R'_z(i)$ is an effective population rate coefficient for the i state ($i = 0$: ground state) and n_z is z charged ion density. An effective ionization rate coefficient is shown as follows:

$$S_z^{eff} = \frac{\sum_i S_z(i) n_z(i)}{\sum_i n_z(i)}, \quad \sum_i n_z(i) = n_z. \tag{3}$$

We can calculate the source term to $z+1$ charged ion from z charged ion as follows:

$$Source_{z+1} = S_z^{eff} n_e n_z. \tag{4}$$

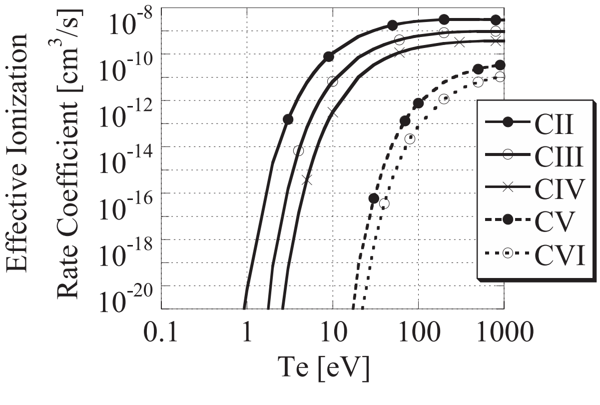

Fig. 1 Effective ionization rate coefficient of each charge state of carbon.

We calculated effective population rate coefficients for C II – C VI. Figure 1 shows effective ionization rate coefficients vs. T_e with $n_e = 1\times10^{12}$ cm^{-3} for C II – C VI. We can see that S_{CV}^{eff} is smaller than S_{CIV}^{eff}, significantly. Because C V is helium like ion, the ionization energy of C V is very high (392 eV), compared to that of C IV (64 eV).

3. Experimental apparatus

3.1 GAMMA 10

GAMMA 10 is a 20 m long tandem mirror consisting of a 5.6 m long axisymmetric central cell, anchor cells for suppressing MHD instabilities and axisymmetric end mirrors for forming the plug/thermal barrier potentials [5]. A plasma in the central cell is produced and heated by ECR heating and/or by ICRF heating. The magnetic field at the center is 0.4 T. The central cell mirror ratio is about 5. In the central cell, the electron density is measured by the 4 mm microwave interferometer with movable horns which directly measure the line averaged density and an X-ray absorption method, an X-ray pulse height analyzer and a semiconductor detector are used to measure the electron temperature. The typical n_e is 2×10^{12} cm^{-3} and electron temperature, T_e, is 60 eV at the center of plasma in the central cell.

3.2 Spectroscopic system

In GAMMA 10, two absolutely calibrated ultraviolet(UV)/visible spectroscopic systems are installed on both the central and the anchor cells [6,7]. The UV/visible spectroscopic measurement system views the plasma column horizontally in the central cell and vertically in the anchor cell. The plasma emission from a cylindrical plasma is collected by a quartz lens and then transferred to a spectrometer through an 8 m long bundled optical fiber array. Each optical fiber consists of a quartz core with a diameter of 400 μm. The light collection system covers the range $x = -20$ cm to $x = 20$ cm with a channel separation of 1 cm. The optical fibers are connected to the entrance slit of a 1 m long Czerny-Turner spectrometer with a grating of 2400 grooves/mm. The observable wavelength is in the range from 200 to 700 nm. The upper limit is determined by the grating of the spectrometer, and the lower limit is determined by the transmission of the quartz fiber. At the exit plane the light from each fiber gives the spectrum from each spatial position. The image of the exit plane is focused onto an image intensifier tube coupled with a CCD TV camera. The frame rate of the CCD TV camera is 30 frames/s and an exposure time of 10 ms. The output of the CCD camera is a standard TV composite video signal, which is digitized by an 8 bit video capture board installed in a personal computer. The wavelength resolution (full width of half maximum of Hg I spectrum) and dispersion are 0.066 nm and 0.016 nm/pixel, respectively, at λ = 436 nm. The absolute calibrated soft X-ray and vacuum ultra-violet spectrometers are observing the wavelength range 3 – 30 nm and 30 – 110 nm, respectively [8,9].

4. Experimental result and analysis

4.1 Carbon ions spectra

We measured spectra of C II (426.7 nm : $2s^2 4f\,(^2F) - 2s^2 3d\,(^2D)$) and C III (464.7 nm : $2s3p\,(^3P) - 2s3s\,(^3S)$) at ICRF start-up plasma in the central cell of GAMMA 10. Figure 2 shows line integrated emission intensities of C II and C III. Figure 3 shows that emissivities of them which are obtained by the Abel inversion technique. Upper levels population density of each ion is obtained by the emissivity and transition probability as follows:

$$n_z(i) = \frac{4\pi E_z(i,j)\lambda_z(i,j)}{A_z(i,j)hc}, \tag{5}$$

where $E_z\,(i,j)$, $\lambda_z\,(i,j)$, $A_z\,(i,j)$, h and c are emissivity, wavelength and transition probability connected with transition to j level from i level, Planck constant and the velocity of light, respectively. Then, we can obtain density profiles of C II and C III by eq. (2). In Fig. 4 solid lines show obtained radial density profile of C II and C III.

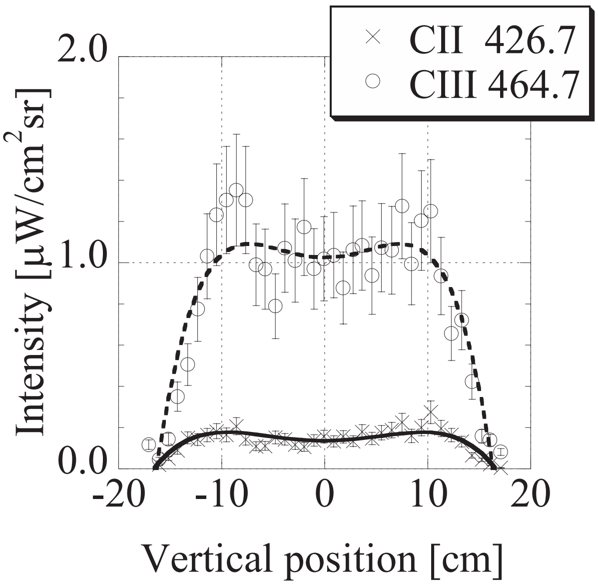

Fig. 2 Line integrated emission intensity of C II and C III.

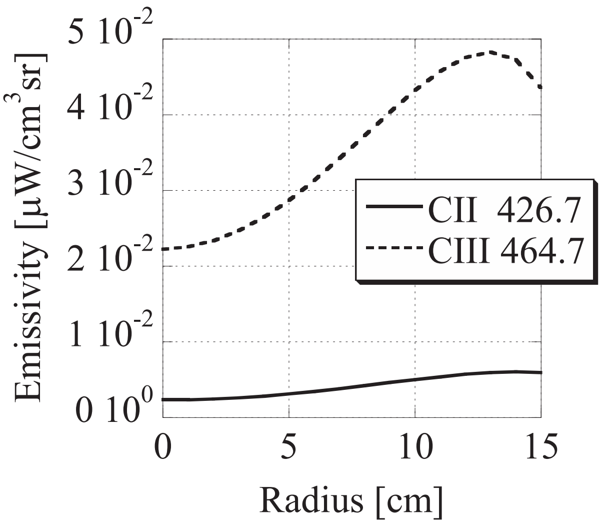

Fig. 3 Emissivities of C II and C III obtained by the Abel inversion technique.

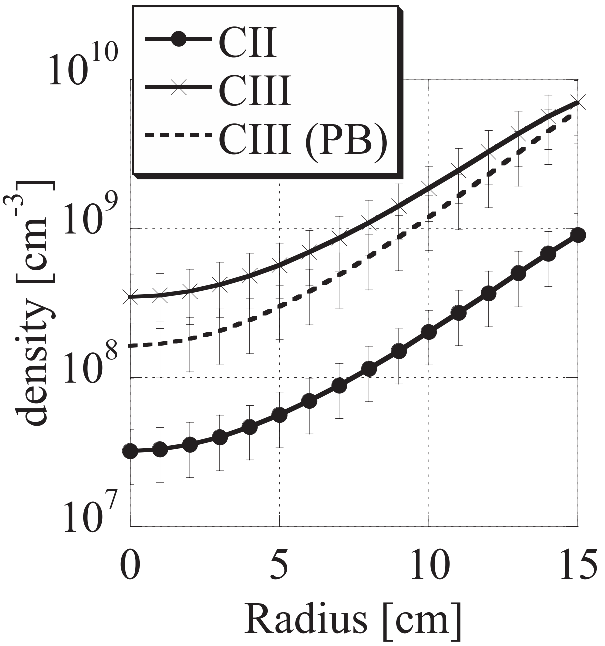

Fig. 4 Solid lines are density profiles of C II and C III obtained by spectroscopic measurements and CRM calculations and broken line is C III density calculated with particle balance equation.

4.2 Particle balance

We used particle balance equatin as follow:

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}n_z =& S_{z-1}^{eff} n_e n_{z-1} - S_z^{eff} n_e n_z \\ &+ \alpha_{z+1}^{eff} n_e n_{z+1} - \alpha_z^{eff} n_e n_z \\ &+ \Gamma_z^{in} - \Gamma_z^{out},\end{aligned} \tag{6}$$

where S^{eff}, α^{eff} and n_z are effective ionization rate coefficients and effective recombination rate coefficients and density of z charged ion, respectively, and Γ^{in} and Γ^{out} are in-flux and out-flux corresponding to impurity transfer. We assumed steady-state condition and made left hand side of eq. (6) equals to zero.

At first, we considered particle balance of C III. In

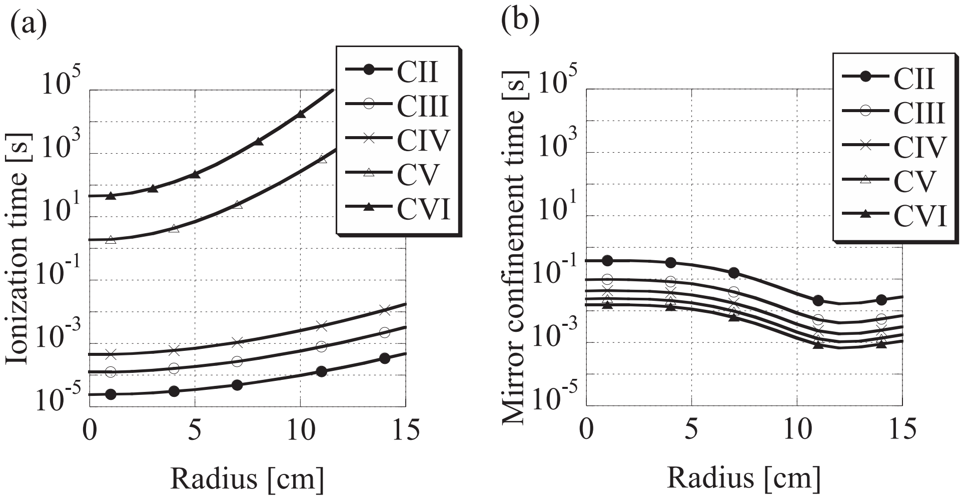

Fig. 5 (a) shows ionization time and (b) shows mirror confinement time of each charge state of carbon in the central cell of GAMMA 10.

GAMMA 10, recombination process can be neglected. Moreover, the ionizing time of C III is the order of 10^{-3} – 10^{-4} s and magnetic mirror confinement time, that is dominant in the magnetic mirror device, is the order of 10^{-2} – 10^{-3} s. Then we can consider the net flux of CIII by transfer, $\Gamma^{in}_{CIII} - \Gamma^{out}_{CIII}$, is small enough. Therefore, eq. (6) for C III is changed as follows:

$$0 = S^{eff}_{CII} n_e n_{CII} - S^{eff}_{CIII} n_e n_{CIII} \qquad (7)$$

We calculated C III density profile by C II density obtained in Sec. **4.1** and eq. (7) and it is shown as broken line in Fig. 4. Both density profiles of C III, obtained in Sec. **4.1** and above, are consistent with each other in the error range. Moreover, difference of each C III density profile in the range of the error means that net flux corresponding to transfer of C III has small positive value.

Next, we considered particle balance of all charge state of carbon ion. In this consideration, we used C II density profile obtained on Sec. **4.1** and estimate density profiles of other charge states. Contribution of recombination is neglected again. While contribution of impurity transfer can not be ignored, because impurity ion confinement time in the magnetic mirror of central cell is shorter than the ionization time of highly ionized carbon ions. Figure 5 (a) shows ionization times (τ^z_S) and Fig. 5 (b) shows mirror confinement times (τ^z_M) of each carbon ion vs. radial position in the central cell. Where mirror confinement time is defined as below:

$$\tau^z_M \equiv \tau_{ih} \ln R. \qquad (8)$$

where R is mirror ratio and τ_{ih} is impurity ion – hydrogen ion collision time. We calculated τ_{ih} with typical electron density and ion temperature in the GAMMA 10 central cell [10].

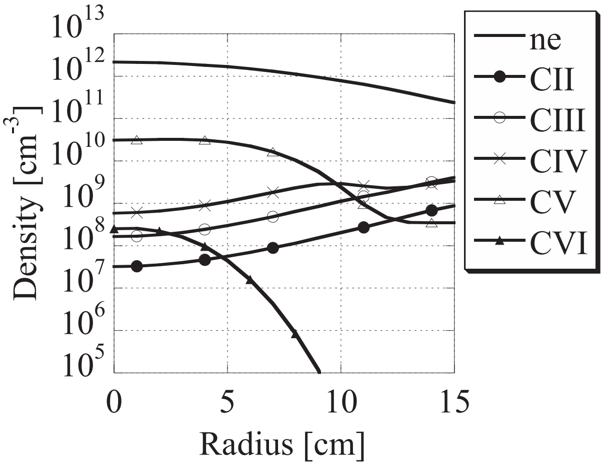

Fig. 6 Density profiles of electron and each charge state of carbon ion estimated by the particle balance.

Then our particle balance equation is changed as follows:

$$n_z = \frac{S^{eff}_{z-1} n_{z-1}}{S^{eff}_z + 1/(\tau^z_M n_e)}. \qquad (9)$$

Figure 6 shows density profile of each charge state by eq. (8), C II density profile and electron density profile. We can see that C V is dominant at the center of plasma and C IV is comparable to C III at the edge region. This estimation is greatly different with that is believed as before. In our estimation, in-flux corresponding to impurity transfer is neglected. If in-flux can not be neglected, the value of highly ionized ion density become more large.

At last, we calculated line emissions from all charge state of carbon ions. By using CRM, the effective emission rate coefficient is obtained as follows:

$$\epsilon^{eff}_z(i, j) = \frac{A_z(i, j) n_z(i)}{n_z n_e}. \qquad (10)$$

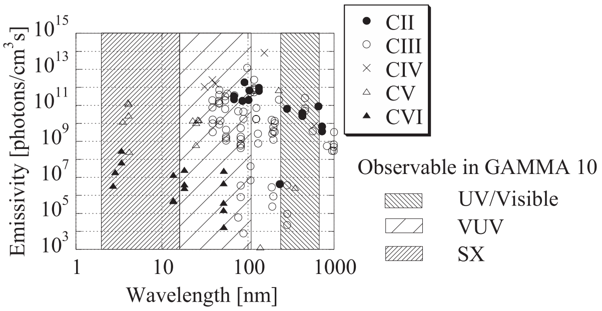

Fig. 7 Absolute line emission intensity from all charge states of carbon ions.

Then the line emission, $I_z(i, j)$, is obtained as follows:

$$I_z(i, j) = \epsilon_z^{eff}(i, j) n_e n_z. \qquad (11)$$

Figure 7 shows absolute line emission from the center of plasma corresponding to carbon ions. C V is helium like ion. It's excitation energy is several hundred eV. The electron temperature in the central cell of GAMMA 10 is under 100 eV. Then C V is not excited enough and not emit enough, even if C V ions are most abundant. Radiation from C IV (154.8 nm : $1s^2 2p(^2P) - 1s^2 2s(^2S)$) is the strongest. However, our spectrometers can not observe this wavelength region so that CIV spectra are not observed. It is necessary to measure the wavelength range 100 – 250 nm to study impurity transfer, radiation loss and Z_{eff}, and we are now planning.

5. Summary

We calculated the CRM of carbon ions to evaluate impurity density profiles. We obtained C II and C III density profiles by measured spectra and effective population rate coefficients. Moreover, we considered particle balance of each charge state of carbon ion, and estimate carbon ions density profiles with ionizing plasma approximation with considering the mirror confinement time. The result of our estimation showed that C V is dominant in the center of plasma and C IV is comparable to C III in edge region. Then C IV spectrum (154.8 nm) is expected to emit the strongest in all carbon spectra.

Acknowledgements

The authors would like to thank members of GAMMA 10 group of the Plasma Research Center, University of Tsukuba and Dr. Goto (National Institute for Fusion Science) for significant discussions.

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