Plasma Electron Temperature Estimation using Line Intensity Ratio of Low Ionized Oxygen Ions

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Synopsis

For the optical measurement of electron temperature of stationary plasma, a line intensity ratio method that utilizes the lines from low ionized oxygen ions is tested. This method is applicable to the low electron temperature between 4 eV and 11 eV, which can not be measured by the usual intensity ratio method. The line intensity of lower ionized oxygen ions, OII, OIII and OIV from TPD-II plasma are measured by a VUV monochromator. Then a calculation of the corresponding line intensity is performed using the rate equations. By comparing their intensity ratios, the electron temperature of the plasma is estimated. The obtained electron temperature agrees well to the result of a Thomson scattering measurement.

KEYWORDS: electron temperature, intensity ratio, rate equation, oxygen ion, TPD-II

Introduction

One of the well-known optical measurements of plasma electron temperature is the line intensity ratio method (1), which utilizes the intensity ratio of two spectral lines emitted by the same ionized state ion. Such a line pair whose intensity ratio is sensitive to electron temperature, however, comes from only higher ionized states of ions. For example, if the oxygen is used, the temperature sensitive lines comes from OV or OVI, which are created in plasma with the electron temperature higher than 10 eV or so. Therefore such an ordinary intensity ratio method can not be used for the plasma with low electron temperature below 10 eV.

Here we try to develop another intensity ratio method for low temperature plasma. In this method, the line intensity ratio from different ionized state ions is used, which is sensitive to electron temperature below 10 eV. The measured intensity ratio is compared with the calculated result derived from rate equations. By making the best fit between them, the electron temperature is estimated. This method is applicable even when the plasma electron temperature is less than 10 eV.

Experimental Setup and Obtained Data

A stationary plasma machine, TPD-II is shown in Fig.1. The He plasma is created by the discharge between a cathode and an anode with floating electrodes to stabilize the plasma. The plasma flows through the hole of the anode and the floating electrodes into the plasma region, where the magnetic field of 5 kG is applied to confine the plasma in axial direction. The trace gas, oxygen is fed through a leak valve into the plasma region.

A two-meter grazing incidence VUV monochromator is used to detect the oxygen lines. It uses a 600 grooves/mm grating, and the angle of incidence is 86° . The entrance slit width is 10 μ m and exit slit width is 20 μ m, which results in a resolution of 0.2 A. The detector is Hamamatsu Photonics R595, a 20-stage

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electron multiplier with CsI coated first dynode. The signal is recorded on a XT recorder chart. The spectral sensitivity calibration was performed by using the branching ratio method in the VUV region (2).

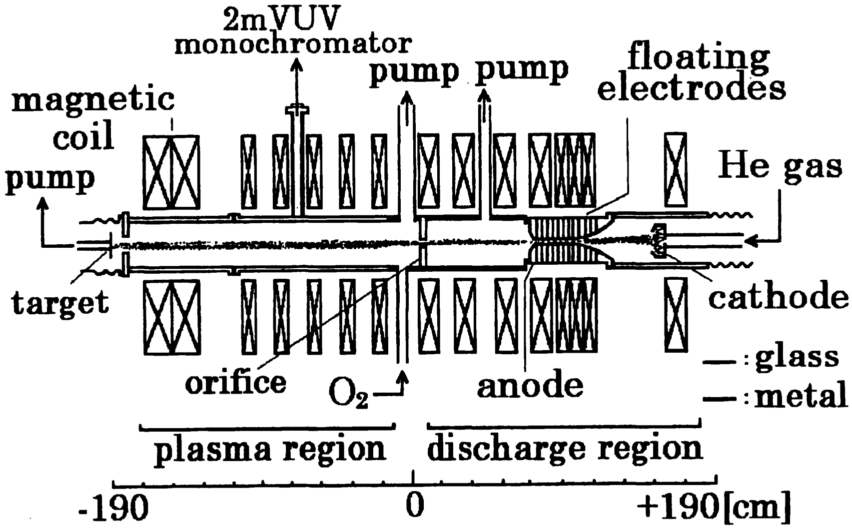

Fig. 1. Schematic drawing of TPD-II machine.

Figure 2 shows examples of the spectral lines near the wavelength of 830 A and near 790 A, where the discharge current is 110 A. The resonance lines OII 834.462 A, OIII 835.292 A, and OIV 790.103/790.203 A lines are used to get the intensity ratio. OV lines are not detected in the present discharge current. The parameters of these lines are summarized in Table. I.

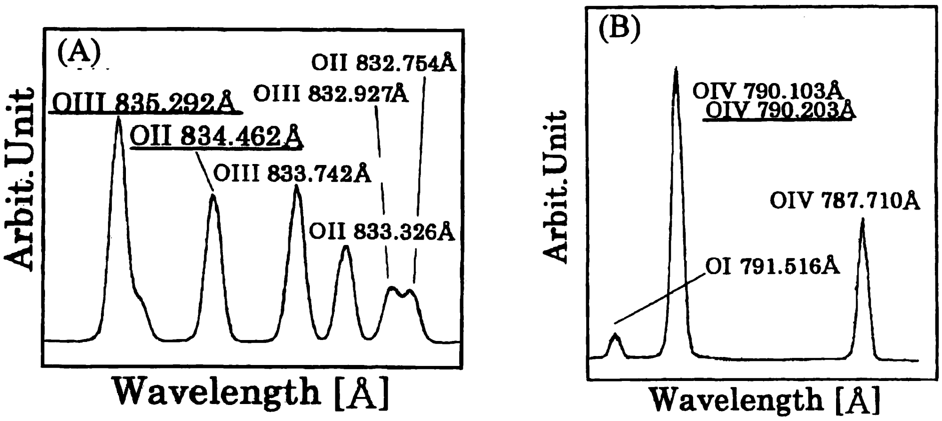

Fig. 2. Examples of spectral lines of OII, OIII (A) and OIV (B).

	Wavelength(A)	Δ E(eV)	fy	Transition	J - J
OII	834.462	14.858	0.21	$2s^22p^3\,{}^4S - 2s^12p^4\,{}^4P$	3/2 - 5/2
OIII	835.292	14.843	0.12	$2s^22p^2\,{}^3P - 2s^12p^3\,{}^3D$	2 - 3
OIV	790.103 790.203	15.690 15.688	0.014 0.13	$2s^22p^1\,{}^2P - 2s^12p^2\,{}^2D$ $2s^22p^1\,{}^2P - 2s^12p^2\,{}^2D$	3/2 - 3/2 3/2 - 5/2

Table I . Parameters of lines for intensity ratio method

The intensity of these lines normalized to the OII line intensity is plotted as a function of the discharge current in Fig.3. As the discharge current increases, the intensity of OIII and OIV lines increases, which shows qualitatively the increase in the electron temperature.

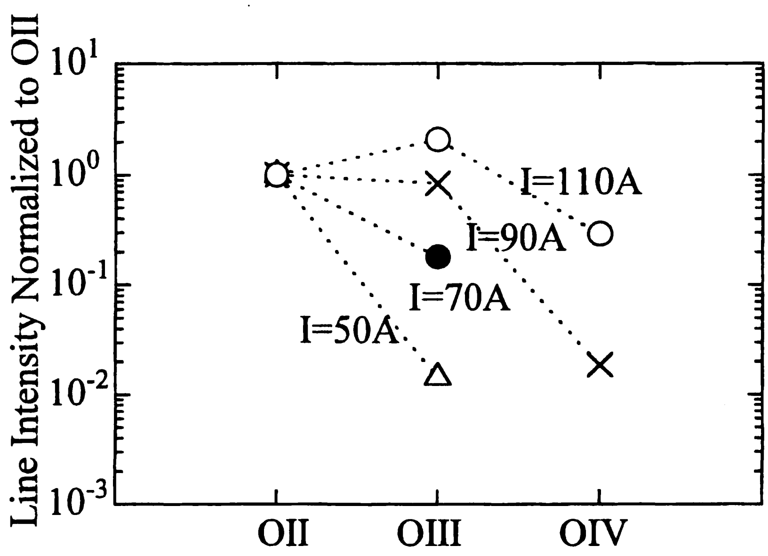

Fig.3. Intensity of OII, OIII, OIV lines as a function of discharge current.

Line Intensity Calculation using Rate Equations

To get the intensity ratio using rate equations, the following simplification is used. First, the electron velocity distribution is Maxwellian, therefore no electron beam exists in the plasma. Second, the plasma is uniform in the radial direction. Then the density of each ionized state ion is calculated by the following zero dimensional rate equations.

$$\frac{dn_1}{dt} = -s_1 n_1 n_e + r_1 n_2 n_e - \frac{n_1}{\tau} + Source.$$

$$\frac{dn_i}{dt} = s_{i-1} n_{i-1} n_e + r_i n_{i+1} n_e - S_i n_i n_e - r_{i-1} n_i n_e - \frac{n_i}{\tau} \quad (1<i<N-1),$$

$$\frac{dn_N}{dt} = s_{N-1} n_{N-1} n_e + r_{l-1} n_2 n_e - \frac{n_N}{\tau}.$$

where n_e is the electron density, S_i is the ionization rate coefficient, r_i is the recombination rate coefficient and τ is the confinement time.

The neutral oxygen is fed constantly through the leak valve, which is the source term. In the present case, since the plasma is stationary, the time derivative in the left side are set to zero. The differential equations reduce to simple simultaneous equations.

The intensity of a line is obtained by the following corona model equation.

$$I = n_e n_i < \sigma v >_{ex}$$

The intensity ratio of two lines calculated in this way depends on two parameters, electron temperature

Te , and the product of the electron density and the confinement time $n_e \tau$. According to a Thomson scattering measurement, the typical electron density of TPD-II plasma is $2 \times 10^{12}/\mathrm{cm}^3$. As for the confinement time, the usual definition can not be used because TPD-II plasma has no confinement in the axial direction. So the confinement time is interpreted here to be the time while an ion with the room temperature passes the discharge tube length, which is 3.8 m. It is 2.8 ms for helium ion and 5.6 ms for oxygen ion. Here the average time 4.2 ms is used as the typical confinement time.

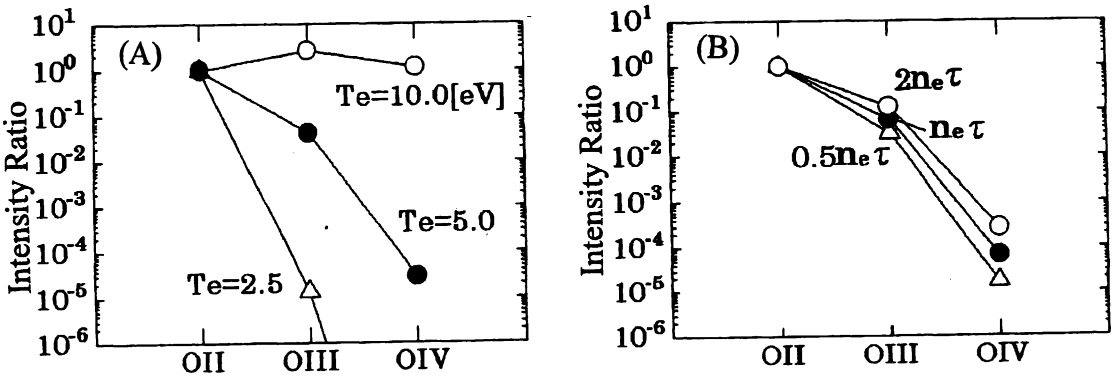

Fig.4. Calculated intensity ratio of OII, OIII, OIV lines. (A) Dependence on *Te* , (B) Dependence on $n_e \tau$

Figure 4(A) shows the dependence of the intensity ratio on the electron temperature, where the above values of n_e and τ are substituted in the equations. When the electron temperature increases by factor four from 2.5 eV to 10 eV, the intensity ratio changes drastically.

Figure 4(B) shows the dependence of the intensity ratio on $n_e \tau$, when the electron temperature is 5 eV. The center values show when $n_e \tau$ is $2 \times 10^{12}/\mathrm{cm}^3 \times 4.2$ ms. When $n_e \tau$ is increased or decreased by factor two, the intensity ratio does not change so much compared to the change with *Te* as shown in (A). So even if there is some ambiguity in $n_e \tau$, rough estimation of electron temperature becomes possible.

Temperature Estimation by Intensity Ratio

Figure 5 shows the calculated electron temperature as a function of the intensity ratio I_{OIII}/I_{OII} and I_{OIV}/I_{OII}. The error bar means the extent of variation due to the change of $n_e \tau$ by factor two.

Because of the background noise and the saturation level of the detecting system, the measurable signal ratio is from 1/100 to 2.5. When *Te* is below 4 eV, the OIII line cannot be detected. Therefore the ratio I_{OIII}/I_{OII} is applicable when *Te* is between 4 eV and 9 eV. When *Te* is below 7 eV, the OIV line cannot be detected. Therefore the ratio I_{OIV}/I_{OII} is applicable when *Te* is between 7 eV and 11 eV. Using both line ratios, the present method is applicable when *Te* is between 4 eV and 11 eV. It might be thought that the measurable *Te* range is very narrow. But since the TPD-II plasma has the temperature in this region, this method is useful for TPD type plasma. When electron temperature exceeds 10 eV, the OV line can be detected, so the usual intensity ratio method becomes applicable.

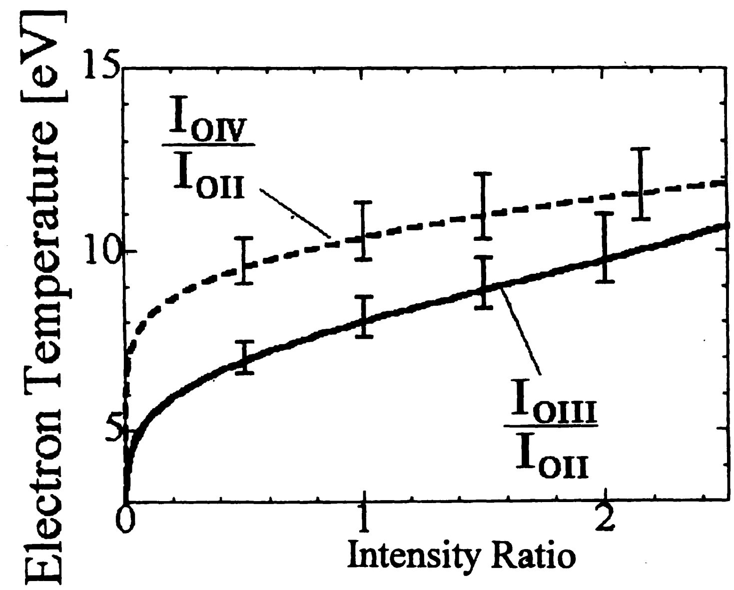

Fig.5. Calculated electron temperature as a function of intensity ratio.

Using the curves in Fig. 5, the electron temperature of TPD-II plasma is estimated from the measured intensity ratio data in Fig. 3. The estimated electron temperature is shown as the white circles in Fig. 6. The error bar shows again the variance due to the change of $n_e \tau$ by factor 2. When the discharge current changes from 40 A to 110 A, the electron temperature changes from 4 eV to 10 eV.

To check the accuracy of the estimated electron temperature, the result of a Thomson scattering measurement in a similar discharge condition is shown as the black circles in the same figure. When the discharge current is between 40 A and 70 A, they agree in 16 % error. When the discharge current is about 80 A, the error becomes 33 %. Since the agreement is quite well, the present intensity ratio method is useful for electron temperature monitoring.

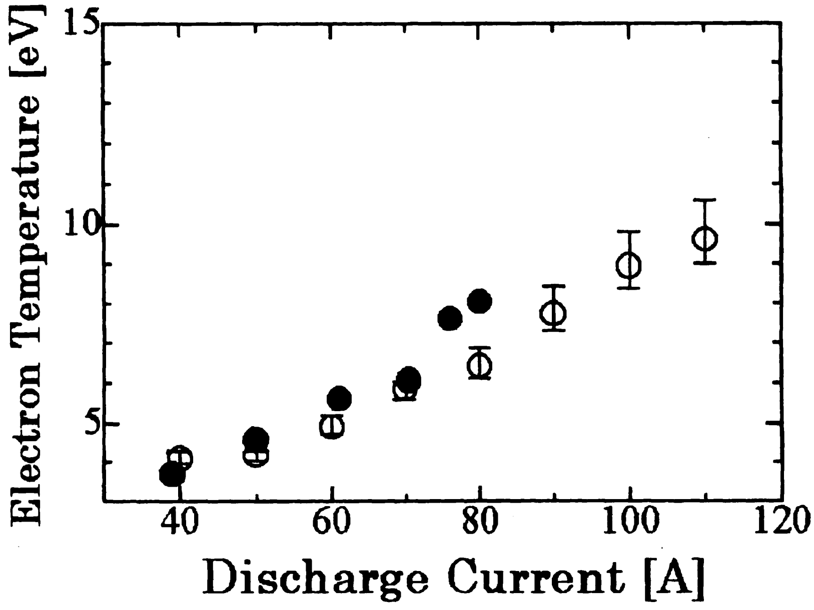

Fig.6. Estimated electron temperature as a function of discharge current (white circle), and result of Thomson scattering measurement (black circle).

Conclusions

In a typical discharge of TPD-II plasma, the calculation of rate equations shows that OIII line is detected when *Te* is higher than 4 eV, and OIV line is detected when *Te* is higher than 7 eV. Using the intensity ratio of these lines to OII line, the electron temperature of TPD-II plasma is estimated. When the discharge current is 40 A to 110 A, the electron temperature is estimated to be 4 eV to 10 eV, which agrees well to the result of a Thomson scattering measurement. Since the usual intensity ratio method is applicable only when *Te* is higher than 10 eV, the present method, which is applicable when *Te* is between 4 eV and 11 eV, will become a useful method as a supplement to the usual intensity ratio method.

Acknowledgements

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