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Measurement of Electron Temperature and Density by an Optical Emission Spectroscopic Method in the DiPS (Diversified Plasma Simulator) Plasma

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1. Introduction

The ratios of He(I) emission line intensities are used to determine electron density and temperature in the Diversified Plasma Simulator(DiPS). He(I) emissions are measured by an optical emission spectroscopic method and are used for the deduction of density and temperature by using the collisional-radiative equilibrium (CRE) model with introduction of a normalized dispersion function.

2. Principle of line-intensity ratio method

2.1 Intensity ratio method

The plasma emissivity ε_{qp} at a specific wavelength λ_{qp} corresponding to an atomic transition from level q to level p can be written as [1]

$$\varepsilon_{qp} = \frac{h\nu_{qp}}{4\pi} n_q A_{qp} \tag{1}$$

where $h\nu_{qp}$ is the photon energy associated to the transition, n_q is the population of the emitting level, A_{qp} is the Einstein coefficient for the trasition. Assuming a uniform plasma, measured intensity I_{qp} (λ_{qp}) at specific wavelength λ_{qp} is given by

$$I_{qp}(\lambda_{qp}) = \frac{1}{4\pi} n_q A_{qp} V\Omega T(\lambda_{qp})\eta(\lambda_{qp}), \tag{2}$$

where V is the plasma volume, Ω is the angle subtended by the collection optics, T and η are the transmission factor of the detector system and the quantum efficiency at λ_{qp}, respectively. Thus intensity ratio for two lines is

$$\frac{I_{qp}(\lambda_{qp})}{I_{ji}(\lambda_{ji})} = \frac{n_q A_{qp} T(\lambda_{qp})\eta(\lambda_{qp})}{n_j A_{ji} T(\lambda_{ji})\eta(\lambda_{ji})} = \frac{1}{C}\frac{n_q A_{qp}}{n_j A_{ji}} \tag{3}$$

where C is the relative calibration factor.

2.2 Steady-State Corona Model

The steady-state corona model assumed that line emission is the result of single collisions between electron and atoms in the ground state followed by the direct radiative de-excitation. Thus in this model, the balance between the rate of collisional excitation from the ground state and the rate of spontaneous radiative decay determines the population densities of the excited levels. Then, the population of the level q(N_q) is given by the expression [2]:

$$n_e n_0 < \sigma v >_{0q} = n_q \sum_{p<q} A_{qp}, \tag{4}$$

where n_o is the population of the ground level population. n_e is the electron density, $\Sigma p<q$ Aqp is the total transition probability from level q to all lower states, and $<\sigma v>_{0q}$ is the excitation rate coefficient for the electron impact excitation of the level q from ground state. Thus, the line ratio expressed in terms of excitation rate coefficients in the steady-state corona model becomes

$$\frac{I_{qp}(\lambda_{qp})}{I_{ji}(\lambda_{ji})} = \frac{1}{C}\frac{E_{qp}(T_e)}{E_{ji}(T_e)} \tag{5}$$

where $E_{qp}(T_e)$ is the emission rate coefficient.

2.3 Collisional Radiative Model

At higher densities($n_e > 10^{11}$cm^{-3}), the occurrence of secondary processes involving collisions with excited or ionized atoms become important. These contributions can be integrated in the line ratio expression by replacing the emission rate coefficients by an apparent or resulting emission rate coefficient $E^*_{qp}(T_e, n_e)$ and $E^*_{ji}(T_e, n_e)$ that include both direct (ground) and indirect (metastables) excitation:

$$\frac{I_{qp}(\lambda_{qp})}{I_{ji}(\lambda_{ji})} = \frac{1}{C}\frac{E^*_{qp}(T_e,n_e)}{E^*_{ji}(T_e,n_e)} \tag{6}$$

We consider ionization and recombination of a plasma and the population densities of various atomic levels in it under a given plasma condition, which is specified by electron and ion densities, n_e and n_i, respectively, and by the electron temperature, T_e. The time development of the population density of a level p is described by the differential equation

$$\frac{dn_p}{dt} = -\left\{\sum_{q\neq p} C_{pq} n_e + \sum_{q<p} A_{pq} + S_p n_e\right\} n_p + \sum_{q\neq p}\left\{C_{pq} n_e + A_{qp}\right\} n_q + \left\{\alpha_p n_e + \beta p\right\} n_i n_e \tag{7}$$

where C_{pq} is the rate coefficient for excitation (p > q) or de-excitation (q < p) by electron collisions from a level p to q, A_{pq} is the spontaneous transition probability from p to q, S_p and α_p are the rate coefficients for ionization by electron collisions from p and its inverse three-body recombination coefficient to this level, respectively, and β_p is the radiative and dielectronic recombination coefficient to this level. The summation q > p means the sum over levels q having higher energy than p. Other processes such as induced emission are neglected.

3. Experiment

A new versatile linear machine, called DiPS (Diversified Plasma Simulator) has been developed for the divertor edge simulation and electric probe technology and its applications. One needs a plasma source with the following plasma parameters: density = 10^6~10^{14}cm^{-3}, electron temperature = 1~10 eV, magnetic field = 0~2 kG, plasma types = RF and DC.

The spectroscopy system is composed of a monochromator, an optical multichannel analyzer (OMA), and an optical fiber. The monochromator has a 500 mm focal length and a 0.05 nm resolution. The spectral response of the OMA is 300~900 nm at 1024×128 pixels. The optical emission spectroscopy system with a monochromator received the light emitted from the plasma. The fast scanning probe system, which is driven by a pneumatic cylinder and have an average operating speed of 0.4~0.7 m/sec and a maximum speed of 2.2 m/sec, measures the electron temperature and the plasma density by using a single probe (0.025 mm in diameter, 1.4 mm in length).

Experiments were performed at test chamber pressure of 2.0×10^{-3} torr, magnetic field of 400 G in the process chamber and 200 G in the source chamber. The plasma were measured using the optical emission spectroscopy system and the fast scanning probe system in the process and source chamber.

4. Result

As the Grotrian diagram, there are a number of possible transitions that can be used. Transitions ending at the ground state 1^1S and at metastable level 2 ^{1}S and 2^3S will not be considered since the plasma is not optically thin with respect to these transitions and the resulting intensities are strongly affected by re-absorption.

In order to measure n_e, D→P transition are better for two reasons. First, excitation transfer cross sections for allowed transitions are much larger than for non-allowed transitions. Second, the excitation transfer is inversely proportional to the energy difference between levels and strongly dependent on n_e. Thus these transitions will be more sensitive to n_e than T_e. In these reasons, we measured He(I) line ratios of 728.13 nm ($3s^1S\rightarrow2p^1P$) / 667.82 nm ($3d^1D\rightarrow2p^1P$) for n_e determination.

Line ratios using S→P transitions are better suited to measure T_e. The contributions from the metastable 2^1S and 2^3S states due to excitation transfer are small since these s-transitions are forbidden and the resulting cross section are small. Also, for a given n level, the energy of the S levels is significantly different than the energy of the other P,D, or F levels. Thus excitation transfer cross sections between S and any of these P,D, or F levels are also small compared to cross section involving only P,D, and F levels. In these reasons, 728.13 nm ($3s^1S\rightarrow2p^1P$)/706.52 nm ($3s^3S\rightarrow2p\ ^3P$) ratio is attractive for T_e determination.

Here we consider a two-dimensional test function as

$$f(T_e,n_e)=\sum_i\left(\frac{R_i^{\exp}-R_i^{cal}(T_e,n_e)}{R_i^{\exp}}\right)^2 \qquad (8)$$

where the summation is over the pairs 728.13 nm /667.82 nm and 728.13 nm/706.52 nm. R_i is the line intensity ratio and the superscripts "exp" and "cal" indicate the experimental and calculational values, respectively. It is a normalized dispersion function to determine the density and temperature simultaneously by comparing the experimental values and calculated ones through iteration, i.e., the electron temperature (T_e) and density (n_e) are simultaneously obtained so as to minimize the test function.

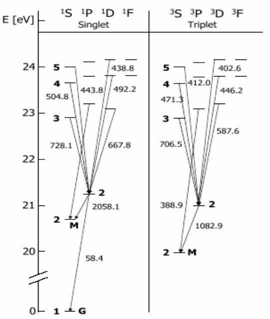

Figure 1. Partial Grotrian diagram of the helium atom with some important transitions.

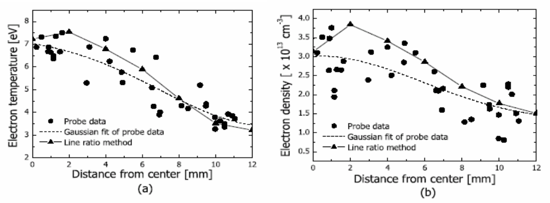

Figure 2. Electron temperature and density profiles obtained in the process chamber.

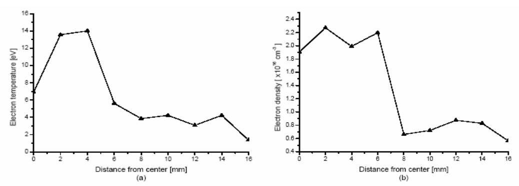

Figure 3. Electron temperature and density profiles obtained in the source chamber.

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[2] R. W. P. McWhiter, Plasma Diagnostic Techniques, ed. R. H. Huddlestone and S. L. Leonard , New York, Academic, ch. 5, 1965.