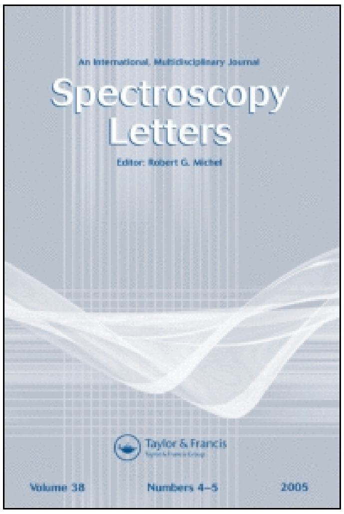

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Spectroscopic Measurements of Electron Temperature and Electron Density in Electron Beam Plasma Generator Based on Collisional Radiative Model

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Abstract: The current work describes a spectroscopic method for determining the electron temperature and electron density in an electron beam generator using argon spectral lines based on a collisional radiative model. Neutral and first-ionized Ar lines emitted from the electron beam generator are studied experimentally. A collisional radiative code was developed to simulate the Ar (I) and Ar (II) spectral emission and to compare the results with the experimental data for electron density and temperature determination. Ar lines and excited level densities were calculated by solving rate equations using the Gauss elimination method. The argon spectrum is recorded experimentally by superposing two discharges, namely a low pressure DC glow discharge and a high current pulsed discharge. Spectral lines between 350 nm and 950 nm were recorded using an integrated signal technique on a charge-coupled device. Electron temperature is determined by the relative intensity ratio

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method of two spectral lines. The relative intensity ratios of each peak are compared in a specific pressure range at various values, and good correlation is reported.

Keywords: Collisional radiative model, electron beam, emission spectroscopy

INTRODUCTION

Several methods are widely used for the determination of electron temperature and electron density using spectral lines emitted from plasmas. These methods mostly depend on certain assumptions of equilibrium for the population densities of the states, such as the corona model or the local thermodynamic equilibrium (LTE) model, depending on the electron density regime. In low-density plasmas, the corona equilibrium applies.[1,2] Respective methods have been applied in measurements of the electron temperature in edge tokamak plasmas from He (I) intensity ratios[3–5] and measurements of electron density from the intensity ratio of Ar(I) and Ar(II) spectral lines in fusion plasma.[6] On the other hand, concerning the measurement of high electron density plasmas, where the densities are described by the LTE, we can determine the temperature from the line ratio of spectral lines from the same ionization stage using the Boltzmann distribution for the population densities and the electron density from two spectral lines ratio from successive ionization stage applying the Saha–Boltzmann equation.[2,7] These methods have a major disadvantage that they are applicable only if atoms and ions are in equilibrium states in a corona or in LTE.

In the current study, we employ a method for measurements of electron temperature and electron density simultaneously based on the collisional radiative model (CR). This method allows us to determine the temperature and the density of various plasmas from spectral line intensities without assumption of any specific equilibrium. The principle of the method is to solve the steady-state rate equations on assumptions that electron temperature and electron density are known. Radiation emitted from the plasma is modeled on the assumption of one plasma parameter (such as electron temperature and density).

In the current work, the intense electron beam plasma generator is obtained by superposing a high voltage pulsed discharge on a DC glow discharge. The characteristics of the produced intense electron beam are very useful in many applications such as microprocessing,[8] X-rays generation, high-power laser preionization, and thin film preparations.[9]

MATERIALS AND METHODS

The electron beam generator is a simple plasma device; its characteristic features have been described in detail by Udrea[10] and Goktas.[11] Figure 1 shows a schematic of the discharge chamber and the detection setup.

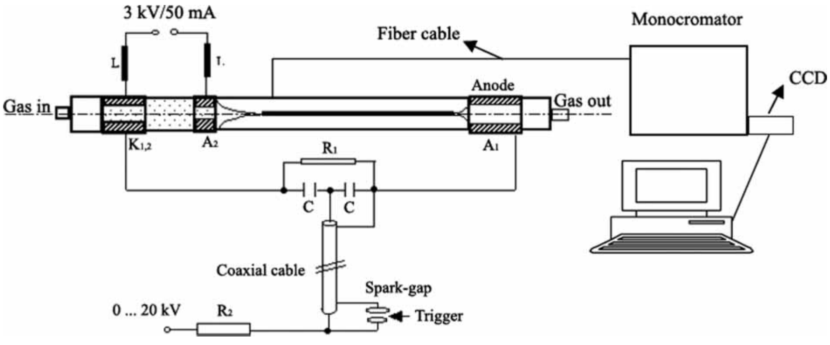

Figure 1. Experimental setup.

Basically, the electron beam is generated in a quartz tube containing three hollow cylindrical electrodes. The first electrode $K_{1,2}$ acts as a common cathode for both discharges while A_1 and A_2 act as anodes for a DC glow discharges and a pulsed discharge. An inductance coil L is used for insulation of the DC power supply from high-voltage pulses. When the high-voltage pulse is applied during the operation of the DC glow discharge, for specific values of current and pressure, a filamentary pulsed discharge is formed along the symmetrical axis of the tube. Within this filamentary discharge an intense electron beam is generated between the anodes A_2 and A_1, while the high-voltage pulse is applied between the common cathode $K_{1,2}$ and the anode A_1. The beam has few centimeters of length, up to 20 A peak current, 100 ns pulse duration, and 70 Hz of repetition rate.

Due to repetitive pulsed low-pressure plasma, integrated signal technique is employed to record the spectrum on a charge-coupled device (CCD). However, a fiber cable is used to illuminate a 50 cm Oriel monochromator equipped with a 1024×250 Hamamatsu CCD camera, and the active area is 24.576×6000 $\{mm(H) \times mm(V)\}$. The emission of the plasma was observed in the side-on direction. The Oriel spectrometer is equipped with two computer-controlled gratings and with the software correcting program for the dispersion curve of the gratings and the CCD. The argon spectral lines in the 300-nm and 1000-nm wavelength range emitted from the generator were recorded using 300 lines/mm grating. A second grating of 1200 lines/mm is used as well for recording spectral lines between 390 and 470 nm. The wavelength calibration of our measured spectra was done by halogen spectral lamps.

Steady-State Collisional Radiative Model

Collisional radiative models are widely used for the analysis of emission spectra in the X-ray[12] and visible[13] spectral regions. In most CR models, a Maxwellian energy distribution is assumed for the electrons.[14–23]

In the current study, a steady-state collisional radiative model is used to analyze the emission spectrum of Ar(I) and Ar(II) emitted from the electron beam generator. Densities of Ar(I) and Ar(II) in steady-state condition were first determined solving the rate equations for balance between ionization and recombination. The rate equations are

$$n_e\{N^{i-1}I^{i-1} + N^{i+1}\lfloor R_{rr}^{i+1} + n_e R_{cr}^{i+1} + R_{de}^{i+1}\rfloor - N^i\lfloor I^i + R_{rr}^i + n_e R_{cr}^i + R_{de}^i\rfloor\} = 0 \quad (1)$$

Here, I and R represent ionization and recombination rate coefficients. The ionization energies and statistical weights for each ion are obtained from Cowan code.[25] The subscripts rr, cr, and de represent radiative, collisional, and dielectronic recombination, respectively. The fractional population of each ionic stage from neutral to bare nuclei is solved using Gauss elimination method.[24] The diameter of the electron beam is measured experimentally and also calculated by using the pinch effect; it is found that the diameter of the beam is of the order micrometers.[25] Because the spectral region is very small, in our calculation the diffusion losses are neglected.

The population densities of Ar(I) and Ar(II) ions excited energy levels were calculated solving a rate equation that included all possible populating and depopulating mechanisms. The general form of a rate equation at steady-state condition for a specific excited level k can be written as

$$\sum_k \{N_k[n_e C_{km} + A_{km} + B_{km}u(\lambda_{km})] - N_m n_e(C_{mk} + B_{mk}u(\lambda_{km}))\} + n_e\{N^{i-1}I^{i-1} - N^i I^i + N^{i+1}[R_{rr} + n_e R_{cr} + R_{de}]\} = 0 \quad (2)$$

where $n_e C_{km}$ and A_{km} represent respective electron collisional excitation and spontaneous radiative decay rates from an arbitrary level k to a lower specific level m. B_{km} $u(\lambda_{km})$ represents photoexcitation from an arbitrary level k to a lower specific level m. N^{i-1}, N^i, N^{i+1} are densities of ionization stages $(i - 1)$, i, and $(i + 1)$, respectively. Densities of ionization stages are obtained from solution of Eq. (1). This linear equations system is solved by the Gauss elimination method.[9] The excited level energies, statistical weights, and oscillator strengths are obtained from the Cowan code[26] and NIST atomic data tables.[27] For the calculation of Ar(I) and Ar(II) spectral lines, 65 and 151 excited levels were used, respectively.

Several sources are used to calculate various rates in the calculation ion densities and excited level densities of argon. In the calculation of Ar(I) and Ar(II) ion densities, the Lotz formula was used for the ionization rates;[28] unless it is indicated, the units are in cgs:

$$I(i) = 6 \times 10^{-8}\left(\frac{R_y}{\chi_i}\right)^{3/2}\left(\frac{\chi_i}{T_e}\right)^{1/2}\left|EI\left(\frac{\chi_i}{T_e}\right)\right| \quad (3)$$

where R_y is Rydberg energy (13.6 eV), x_i is ionization energy for ith ion, and T_e is electron temperature in eV, and the expression EI is the exponential integral. The radiative recombination rate[29] R_{rr} is given by

$$R_{rr} = 5.2 \times 10^{-14} Z\left(\frac{\chi_i}{T_e}\right)^{3/2} \exp\left(\frac{\chi_i}{T_e}\right) EI\left(\frac{\chi_i}{T_e}\right) \tag{4}$$

where Z is the atomic number for a given element. $A_{km,}$ the transition probability of spontaneous decay from level k to level m, is given by

$$A_{km} = \frac{6.6 \times 10^{15}}{\lambda_{km}^2} \frac{g_m}{g_k} f_{mk}, \tag{5}$$

where g_m and g_k are the lower and upper level statistical weights, respectively, f_{mk} is the absorption oscillator strength for the transition, and λ is its wavelength (Å). C_{km} is the collisional excitation rate from level k to level m,[29]

$$C_{km} = 3 \times 10^{-7} \left(\frac{R_y}{T_e}\right)^{1/2} \left(\frac{R_y}{\Delta E_{km}}\right) f_{mk} \bar{g} \exp\left(-\frac{\Delta E_{km}}{T_e}\right) \tag{6}$$

where E_{km} is the energy difference between level k and m, R_y is Rydberg constant (13.6 eV), and g is a gaunt factor obtained from Van Regermorter.[30] When collision strength values are available, the collision rate is calculated from a collision strength expansion given by Von Wyngaarden et al.[31] The de-excitation rate is obtained from the collisional excitation rate using principle of detailed balance:

$$C_{mk} = \frac{g_m}{g_k} \exp(-(E_m - E_k)/kT) C_{km}. \tag{7}$$

The line intensity emitted from the plasma is finally calculated by multiplying the emissivity with an escape factor τ,

$$I(\lambda) = n_k \frac{hc}{\lambda} A_{km} \tau. \tag{8}$$

Escape factors are calculated using the Holstein formula,[32]

$$\tau = \frac{1}{K_0 D \sqrt{\pi \ln(K_0 D)}} \qquad \text{for} K_0 D \geq 2.5 \tag{9}$$

$$\tau = e^{-K_0 D/1.73} \qquad \text{for } K_0 D < 2.5 \tag{10}$$

where D is the plasma length and K_0 is the absorption coefficient calculated[2] by

$$K_0 = \frac{A_{kn}\lambda^3}{8\pi c} \left(\frac{\lambda}{\Delta\lambda}\right) \left[\frac{g_k}{g_n} N_n - N_k\right] \text{ cm}^{-1} \tag{11}$$

where c is the speed of light, full width at half maximum of the line is assumed to be 7Å and plasma thickness is assumed to be 10 μm (10^{-3} cm). Escape factors are applied to all transitions.

RESULTS AND DISCUSSION

For the analysis of the emitted spectrum, a Gaussian shape line profile is used in the theoretical spectrum to fit with the experimental one. The electron temperature of the argon plasma is determined using the line ratio of Ar(II) 4*p*-4*d* to Ar(I) 4*s*-5*p* spectral lines. Figure 2 presents two examples of spectra recorded using the two different gratings: (a) 300 lines/mm and (b) 1200 lines/mm, both emitted from DC glow discharge plasma, namely between $K_{1,2}$ and A_1 region. As shown in Fig. 2a, the solid line presents the experimental Ar spectrum while the dotted ones present a theoretical spectrum between 300 nm and 1000 nm at a pressure of 0.1 Torr. This theoretical spectrum is calculated for 1.9 eV temperature and 1.0×10^{15} cm^{-3} electron density. Fig. 2b presents the experimental and theoretical argon spectrum between 390 nm and 470 nm at a pressure of 0.19 Torr. However, in this case the electron temperature and density are 1.7 eV and 4.0×10^{15} cm^{-3}, respectively.

The recorded spectrum (Fig. 3) from the beginning side of the electron beam, the region between A_1 and A_2, was studied and it showed the experimental and theoretical argon spectrum between 390 nm and 470 nm at a pressure of 0.19 Torr. The average electron temperature and electron density are 1.5 eV and 6.0×10^{15} cm^{-3}, respectively. As shown in Fig. 2 and Fig. 3, good agreement is obtained between experimental and theoretical spectra that are calculated based on the described collisional radiative model, except with some discrepancies, which can be the result of some missed lines.

Comparing the results obtained in Fig. 2b and Fig. 3, the effect of the pulsed discharge that is superimposed on the DC glow discharge indicates that the electron density is increased while the electron temperature is decreased at the same pressure conditions. In order to determine the electron temperature for different pressure conditions, the line ratio of Ar(II) 4*p*-4*d* to Ar(I) 4*s*-5*p* and Ar(II) 4*s*-4*p* to Ar(I) 4*s*-5*p* as a function of the electron temperature has been calculated, as shown in Fig. 4. The corresponding electron temperature for this line is 1.9 eV, where at this temperature the simulated and the experimental spectra fit well enough. Moreover, the results of the electron density and the electron temperature are found by making use of the Stark broadening of the H_β line experimentally as in the previous work,[25] and the H_β line is also compared with the full computer simulation method.[33] The results of the previous work and this work are in good agreement, too.

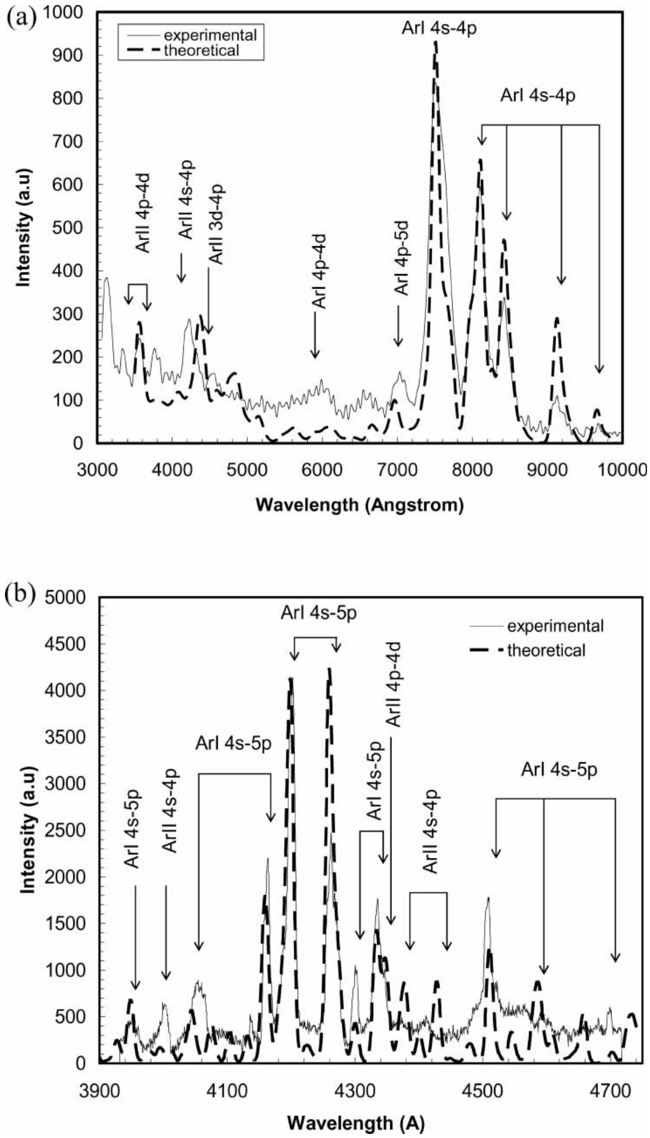

Figure 2. The experimental Ar(I) and Ar(II) spectrum from the glow discharge plasma superimposed on the theoretical spectrum: (a) spectrum between 300 nm and 1000 nm, (b) spectrum between 390 nm and 470 nm.

CONCLUSIONS

In this paper, we present experimental results of Ar(I) and Ar(II) spectral lines for both the DC glow and pulsed discharge simultaneously. Ion densities and

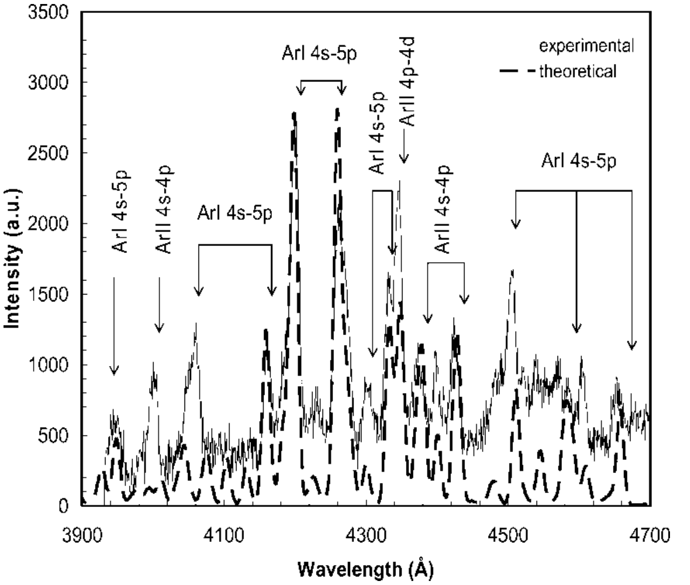

Figure 3. Experimental Ar(I) and Ar(II) spectra superimposed on theoretical spectra for the electron beam side at the generator; region between A_1 and A_2.

excited level densities of each ionic stage as a function of electron temperature and electron density are calculated using a steady-state collisional radiative model. Moreover, Ar(I) and Ar(II) spectra are simulated and good agreement is obtained with experimental spectra. A collisional radiative

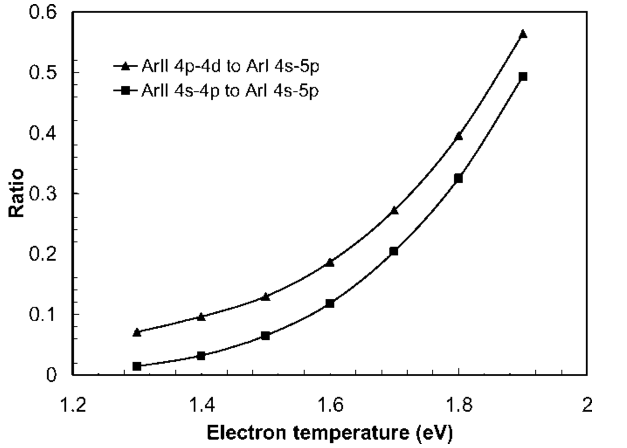

Figure 4. Line ratios of Ar(II) 4*p*-4*d* to Ar(I) 4*s*-5*p* line and Ar(II) 4*s*-4*p* to Ar(I) 4*s*-5*p* as function of electron temperature in eV.

code was developed to analyze the Ar(I) and Ar(II) spectral lines emitted from the intense electron beam generator. The code predicts the electron temperature of the low-pressure Ar DC glow discharge while the pulsed discharge superimposed on it to be between 1.5 and 2.0 eV from line ratio of the Ar(I) and Ar(II) spectral lines, and the density of the electrons is between 1.0×10^{15} and $6.0 \times 10^{15}\,cm^{-3}$ at 0.1–0.2 Torr working pressure range. The recorded spectrum at the exit point of the electron beam indicates that the density of the electrons is higher than the obtained value for the DC part for the same pressure while the temperature of the electrons is lower. Because the accelerated electrons from the high-voltage DC part of the generator collide with the argon gas in the chamber, they ionize the gas and gain a higher electron density. The optimum pressure in argon was between 0.1 and 0.2 Torr for the electron beam generator.

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