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ARTICLE

Spectroscopic Measurement of the Temperature of Electrons in Direct Current Argon Plasma

Atheel Mazen, Yasir A. Aljawadi and **Raied Ahmed Al-Wazzan**

Department of Physics, College of Science, University of Mosul, Iraq.

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Abstract: A laboratory-made spectrometer of the Cherny-Turner type, belonging to the first generation of spectrometers, was used to perform the optical emission spectroscopy measurements. This spectrophotometer is capable of conducting spectrophotometric assessments across wavelengths ranging from 300 to 1000 nanometers, among other functionalities. Utilizing a technique known as the line ratio method, it accurately gauges the intensity of optical emissions to ascertain the temperature of electrons. Through experimentation involving spectroscopic methods within a power spectrum of 15 - 61 watts and a consistent pressure of 6.5 Torr, a direct correlation between electron temperature and applied power was established.

Keywords: Plasma, Spectrum, Electron temperature.

Introduction

In recent years, there has been a significant increase in the focus on plasma sources for various industrial applications, atmospheric studies, the economy of microelectronics, and nanostructures. In the control of ionization, dissociation, and excitation rates within plasma, the electron temperature (Te) of low-pressure, high-density plasma stands as a paramount parameter. One of the most significant types of plasma discovered recently times is argon plasma. Electrostatic sensors are essential diagnostic devices for low-pressure, weakly ionized plasmas. These sensors are utilized frequently to determine the temperatures of plasma electrons, even though the findings are challenging to comprehend. Plasma processes and reaction rates, in general, can be affected to varying degrees by the density and energy of charged particles [1]. Langmuir probe measurements and optical emission spectroscopy are the two basic methods used to analyze the properties of plasma [1]. Optical emission spectroscopy (OES) is utilized the most frequently for researching glow attributes because it is uncomplicated and does not disturb the plasma.

In situations where the excitation temperature and the electron temperature might be the same, determining electron density is possible by examining the brightness contrast between atomic and ionic lines. The Langmuir probe is a straightforward yet reliable method for determining the variables of plasma. To accurately measure the current that is going through the wires into the plasma, it is required to supply the wires with a voltage. This method was employed to assess the quantity of positive ions and electrons per unit volume, with electron energies independently verified [2]. We can rapidly compute the density of an electron and its temperature if we assume that the electron energy distribution function is a Maxwell-Boltzmann distribution. To proceed with this method, it is necessary to have a relative emission intensity from four lines of argon emerging from any one of the 4p argon levels.

Corresponding Author: Yasir A. Aliawadi **Email**: Yasseraljwaady@uomosul.edu.iq

In the expanding field of atmospheric microplasma, where diagnostics are still limited, the suggested model's validity for argon-containing laboratory plasmas is rather broad [3]. This field experiencing rapid growth. Thomson and Rayleigh scattering of laser light can be used to quantify the electron temperature, electron density, and atomic density in plasmas. This can be done for radio waves (rf) that are produced inductively. The test conditions typically involve pressures ranging from 1 to 20 mTorr and RF power inputs between 100 to 500 watts (W) for argon discharges. It has been demonstrated that pressure has a significant impact on the temperature of electrons, but energy has just a minor impact on this parameter. The electron density is notably influenced by the pressure and the forces exerted within the system. There is a discernible reduction in the amount of neutral density in the plasma core as a direct result of the collision of charged particles. These observations were examined in light of a fundamental understanding of plasma formation [4].

It was noted that the floating-type probe provided measurements nearly identical to those of a single Langmuir probe at a variety of RF powers and pressures. For monitoring ion density and electron temperature, a floating-type probe with a CF4-coated tip was used. It is anticipated that the float-type probe will find application in plasma diagnostics because the ion density and electron temperature of the probe remained almost unchanged regardless of the coating that was applied to the probe tip.

Two popular techniques for treating materials with plasma are known as deposition and etching utilizing plasma [5]. It is necessary to research the lattice-biased voltage electron temperature control mechanism to understand inductively coupled Ar discharges. In the diffusion zone, Electron Energy Distribution Functions (EEDFs) can be monitored with a Langmuir probe, and they affect both the electron density and the electron temperature. On the other hand, in the source region, neither electron density nor effective electron temperatures vary significantly. The applied voltage determines a variety of properties, including electron density, electron temperature, and plasma potential in each region [6].

When assessing the mean kinetic energy of electrons through electron temperature measurement and the excitation temperature derived from optical emission spectroscopy, it has been observed that under certain conditions, inelastic collisions can occur. This was discovered through the application of certain conditions utilizing a 32-tier collision radiation model that incorporates the interaction between inelastic argon collisions and electrons within its computations. Inequity presents itself when the diffusion losses are substantial, and the electron density is lower than the equilibrium value [7]. In plasmas that are not in a state of equilibrium, the temperature and electron density can be measured using an optical emission spectrometer (OES). One potential application of this model is to compute the proportional line densities of argon atoms, offering insight into the findings. To determine the specific excitation temperature (in eV), it's imperative to adopt a Boltzmann distribution function for the thermodynamic electron temperature, typically within the range of 1 to 4. We can determine the density of electrons as well as their temperature by fitting experimental models to the relative emission line strengths obtained from the collisional-radiative model (CRM).

The dynamics of the initial excited state of argon take into account electron excitation and elimination, as well as spontaneous light emission, radiation trapping, and electron effect ionization. In addition to that, the model takes into account the cooling effect of diffusion. The ion density was calculated by employing the emission line's relative density (488 nm) coupled with argon, while excitation was assessed using the CRM starting from the ground states of both neutral argon (Ar) and ionized argon (Ar+).

Optical emission spectrometry (OES) and Langmuir probe measurements also validated the conclusions of the investigation, demonstrating an outstanding level of agreement between the ion density measurements and the electron density measurements [9].

There is a strong synergy between optical and sensing technologies. To establish a self-biasing effect for innovative plasma diagnostics utilizing an alternating current bias voltage, a DC-blocking capacitor was inserted between the floating probe and the signal generator. This enabled the effect to be self-driven (kHz). The temperature of the electrons causes the DC self-bias to fluctuate between potential states in addition to the bias voltage provided by the AC.

Because the amplitude of the AC bias voltage is only 3 volts, it is possible to overlook any effects that the high bias voltage may have had on the local ionization caused by the temperature of the electrons and the density of the ions [10].

Using RF-compensated Langmuir probe experiments and OES, we investigate the physical characteristics of an inductively coupled low-pressure argon-oxygen (AR-O2) plasma. It is possible to ascertain the electron density and temperature of each gas discharge by using OES models, and one can then examine the differences and similarities between these values and the information obtained by the probe. As the amount of force and pressure increases, the temperature of the electrons drops, and there is also a rise in the amount of argon gas that is present [11]. It's important to monitor parameters such as air pressure, plasma temperature, and concentration under a wide range of conditions involving thermal and chemical equilibrium as well as a thermochemical imbalance. Many people are under the impression that atmospheric pressure air plasma is in a state of thermodynamic equilibrium because of the rapid collisional exchange of species that occurs at high pressure. Because of the high electron temperatures caused by electrical discharge, optical diagnostics have the potential to produce significant disruptions to the chemical and thermal equilibrium of a system [12].

The electron temperature (Te) and density were deduced by employing an argon plasma spectroscopic technique grounded in a radiation collision model (Ne). When measuring electron density and temperature using the new method, data obtained with the Langmuir probe were compared to the results of the measurements taken with the new method. The findings from the spectroscopic analysis (Te and Ne) are almost identical to the findings from the probe [13].

When the plasma reaches a stable condition, excited species are generated through various mechanisms, such as radioactive decay from higher energy states, electron stimulation from both the ground state and less stable states, and additional influences. Plasmas of either argon or nitrogen are used in the process of determining the values of Te and Ne [14-16]. To determine how the aforementioned variables are related to observable emission spectra, it is crucial to possess a comprehensive understanding of the atomic population distribution within the plasma and its alterations relative to the plasma's thermodynamic characteristics, such as emission and absorption spectra [15 17].

In this study, the researchers wanted to determine how easy it would be to use an optical emission spectrometer (OES). They also wanted to control the wavelengths generated by the lab's argon plasma generator using a high-voltage power supply. This study sought to manage the ionization process of the plasma, enhance its efficiency, deduce the electron temperature from the spectrum of argon gas for different expected functionalities, and illustrate the correlations among these functionalities.

Experimental Setup and Instrumentation

Fig. 1 provides a comprehensive overview of the plasma system utilized for this research project. Due to the necessity of enduring elevated temperatures, the equipment employs a quartz glass tube. The tube measures 70 mm in length and has a diameter of 30 mm at both ends. The enclosure features two gas intake ports and two gas outlet ports. There are two cleaned and polished metal poles inside the structure. The diameter of the poles measures 6 mm on the outside and 4 mm on the inside. A rubber insulates the point at which the bars make contact with the glass tube from both ends preventing gas from escaping the system (O-ring).

The system draws gas in through one end of the cylinder using a specialized argon gas cylinder and then draws gas out through the other end using a vacuum pump. The cylinder itself contains argon gas. The high voltage that was supplied to the cell was evaluated with the assistance of a fluke-type probe (80K-6) that was paired in parallel with a voltmeter that had a 10-ohm input impedance (mega ohm). A 6000-volt constant voltage source was used.

Optical emission technology (OES) was used to generate plasma in the glass tube, and the properties of this plasma were studied. Sunlight is transferred from the plasma to the spectrometer via an optical cable, where it is quantified in terms of its wavelengths before undergoing analysis. The IXon Ultra/Ultra-Life spectrophotometer system was driven by the plasma waveform that was formed (4.32.30000.0). Andor Basic provided data acquisition and macro language control. The procedure included not only processing but also presenting and exporting the finished product.

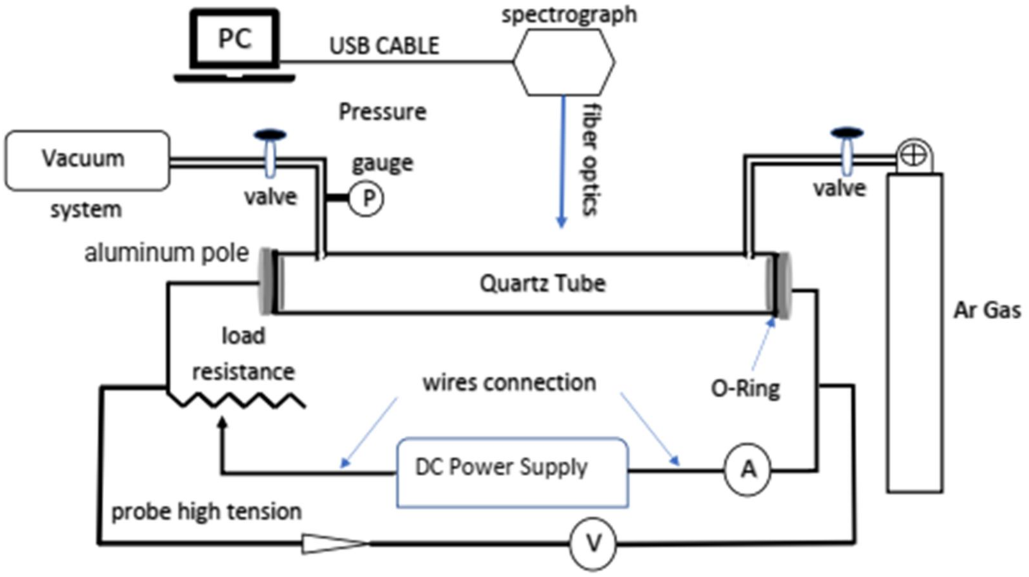


FIG. 1. Detailed depiction of the plasma system.

Results and Discussion

Figure 2 demonstrates the spectral patterns produced when argon gas is continuously discharged within the vacuum cell, subject to a specific power input. These patterns identify argon spectrum lines for comparison with global spectra for calculation purposes. Within the wavelength range spanning from 600 to 1000 nm, various peaks corresponding to molecular emissions of argon gas can be observed. The intensity of these peaks increases proportionally to the applied voltage, as electron energy escalates due to interaction with the electric field.

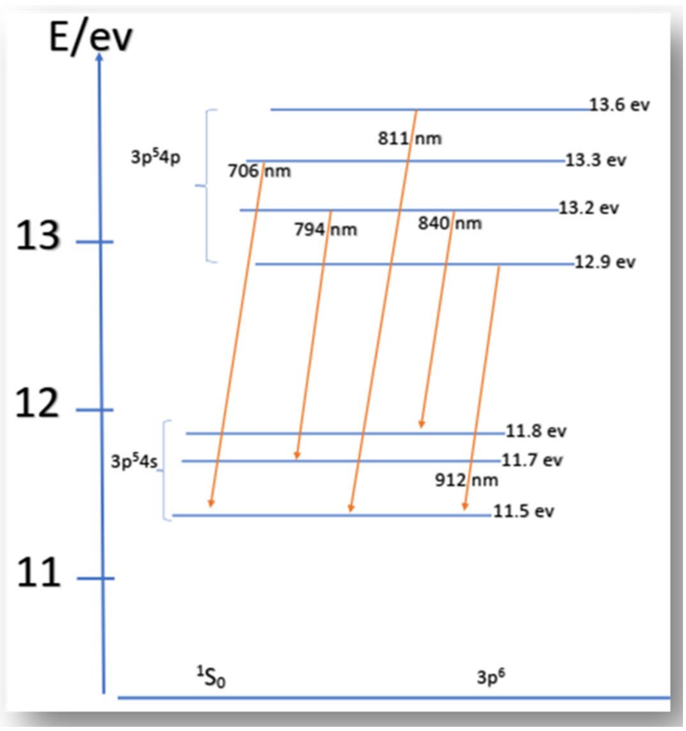


FIG. 2. Various energy levels of the argon atom.

A higher number of atoms or molecules were excited compared to previous instances due to the increase in the excitation cross-section, primarily influenced by electron energy. The optical emission plasma spectra method was employed to determine electron temperature directly, based on the electrical energy supplied to the electrodes, ranging from 15 to 60 watts. This method yields precise results as it directly assesses electron temperature. However, certain results exhibited inconsistency, particularly in specific wavelengths and intensities, influenced by the activity levels in argon's energy states. Argon gas is used for spectroscopic verification in plasma, yielding valuable diagnostics such as electron temperature and saturation processes, resulting in varied data and adjustments in electron temperature estimation [18]. Relevant data can be derived from the spreadsheet containing lines in the NIST Atomic Spectra Database [19].

Consider an argon level configuration similar to that illustrated in Fig. 2 [20], where the four Ar(3p54s) levels are handled separately, along with the two volatile and two resonant levels, while the Ar(3p54p) level represents one aggregated block of levels.

Equation (1) provides the potential energy states for a Maxwell-Boltzmann distribution.

$$n(q) = \frac{g_g\, N_O \exp\left(-\frac{E}{k_B T}\right)}{Z(T)} \quad (1)$$

The above equation can be understood as follows: n(q) is the number density in the quantum state q; No is the overall number density; gq is the emitting state's degeneracy; Eq is the q state's excitation energy; k_B is the Boltzmann constant; T is the absolute temperature; and Z(T) is the partition function at temperature T.

The number density n(q) of a specific quantum state is closely correlated with the absolute emission intensity I for a certain line.

$$I \ \alpha\ n(q)\, A \quad (2)$$

where A represents the probability of spontaneous emission.

The experimentally observed signal, denoted as $I_{measured}$, is influenced by the spectral response of the detection apparatus. In other words, the correction factor f(λ) is contingent upon the optical characteristics of the detection system.

$$I \ \alpha\ I_{measured} \times f(\lambda) \quad (3)$$

Substituting Eqs. (1) and (3) into Eq. (2) gives:

$$\frac{I_{measured} \times f(\lambda)}{gq \times A} \ \alpha\ \exp(-E / k_B T) \quad (4)$$

The Saha equation describes the plasma population ratio between single-charged ions and neutrals under LTE circumstances given by:

$$n_i^2/n_n = (2.4 \times 10^{15} / T^{-3/2}) \exp[- U/k_B T] \quad (5)$$

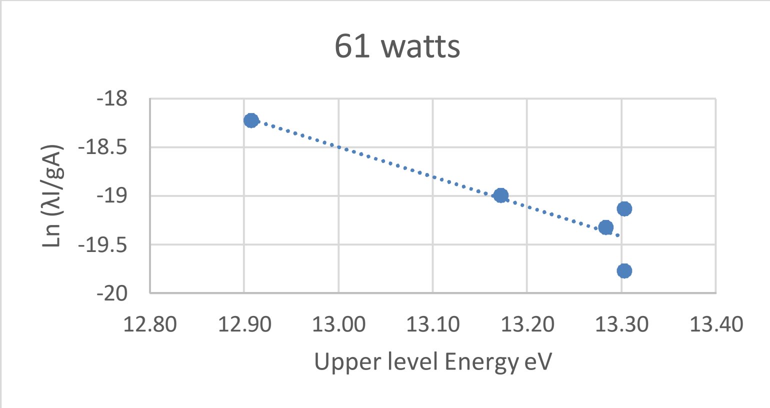
where n_i and n_n are the ion and neutral densities in cm^{-3}, T is the temperature in K, and U_i is the first ionization potential in eV.

In the following equation, Z is the nuclear charge and E_h = 13.6 eV. For a 1 eV barium plasma, where Z = 56 and n = 6, one can find that electron density should be greater than 1.4 × 10^{22} cm^{-3} to ensure LTE conditions [21].

$$n_e \geq 7 \times 10^{18} (Z^6 / n^{17/2}) \times [k_B T / E_h]^{-1/2} \ cm^{-3} \quad (6)$$

The relationships between spectral line intensities and atomic state densities reach equilibrium. By utilizing spectral line intensities, as shown in Fig. 3, plasma temperature can be promptly and precisely estimated. When seeking to ascertain electronic plasma temperature through the relative intensities of two spectral lines, it's imperative to consider a plasma in local thermodynamic equilibrium (LTE). LTE dictates that excitation or ionization processes can only be initiated by the interaction of an electron with a surface. The electronic plasma density and temperature must meet this requirement for it to be true: $n_e \geq 10^{14}$ m^{-3} and $T_e < 1$ *eV*, respectively.

This can be explained by the electronic heating mode transition with pressure. At low pressures, high-energy electrons can penetrate the region of the shell where the non-colliding electron is strongly heated and thus efficiently heated rather than gaining energy through the collision heating process the low-energy electrons are still in the block. It can only accomplish this with a weak collision frequency at low atmospheric pressure and a negligible internal electric field. The electron distribution during a low-pressure discharge typically conforms to a Maxwellian binary electron distribution, which has two distinct electron groups. This characterization contrasts with findings from recent research published in 2022 [22].



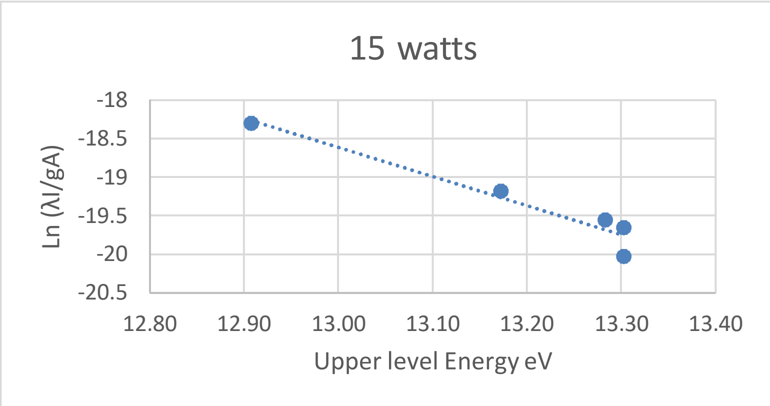


FIG. 3. The measured emission line intensities Imeasured from different energy levels [ln (Imeasured x f(λ)/gqA)].

The examination of discharge traits and electrical performance in low-pressure argon plasma capacitively coupled was conducted utilizing the Langmuir Compensated Radio Frequency (RF) probe, which relies on the Drewstein technique. The study explores the effects of increasing excitation frequencies (15,100 MHz) and energy (10-80 W) applied to the electrodes on the electron potential energy function (EEPF), electron density (Ne), electron temperature (Te), and plasma potential (XR). The results of the experiment are outlined in a study released in 2022 [23] and indicate a progression of the EEPF from a singular Maxwellian distribution to a linear distribution, eventually reaching a Revstein distribution. At 50 MHz, which is characterized by high excitation frequency, the temperature of the low-energy electron group is at its minimum. However, with increasing frequency, electron density rises rapidly before declining again beyond 50 MHz. Effective electron temperature rises with increasing energy at specific frequency limitations but decreases with increasing energy when the frequency reaches 15 or 50 MHz, illustrating the complex influence of discharge parameters on electron behavior. Plasma potential is significantly influenced by both frequency and intensity. With a higher frequency and higher power, it increases significantly and decreases continuously. The mechanism of heating is discussed in terms of the ratio of random heating to ohmic heating at higher frequencies. They differ in size but exhibit the same behavior when the discharge strength is changed. The density of the ions was determined by the probe, while the density of charge carriers was determined by OES as detailed in Ref. [24]. The severe plasma irregularity can explain the disparity. Since the OES provides an integrated spectrum across the entire array's size, the probe can be positioned in an area with denser plasma. This is particularly significant because the ion density was calculated using the patented CRM and did not rely on the plasma's semi-neutrality. Electron and Ar ions densities determined by OES agree well, especially at high levels of the discharge strength. However, discrepancies between electron and ion densities increase with lower discharge intensities. The two approaches' estimates of electron temperature coincide rather well, with the difference between them being less than 10%, which is within the estimated accuracy of electron temperature measurement. Variations in intensity were noted for the ArI spectral lines at various packing pressures and applied voltages, especially at the wavelength of 750.38 nm [25]. When the applied voltage is increased, the spectral lines' intensity rises; when the pressure is increased, it falls. The mean free route of the electron-neutral effects diminishes, the neutral density rises, the frequency of these collisions rises, and the pressure increases. The rate of excitation of the influence of the neutral electron grows when the energy is increased since it causes an increase in both the electron's energy and the degree of ionization. Through interactions and excitation of other particles, the electron transfers energy. Atoms and ions emit spectral lines by de-excitation.

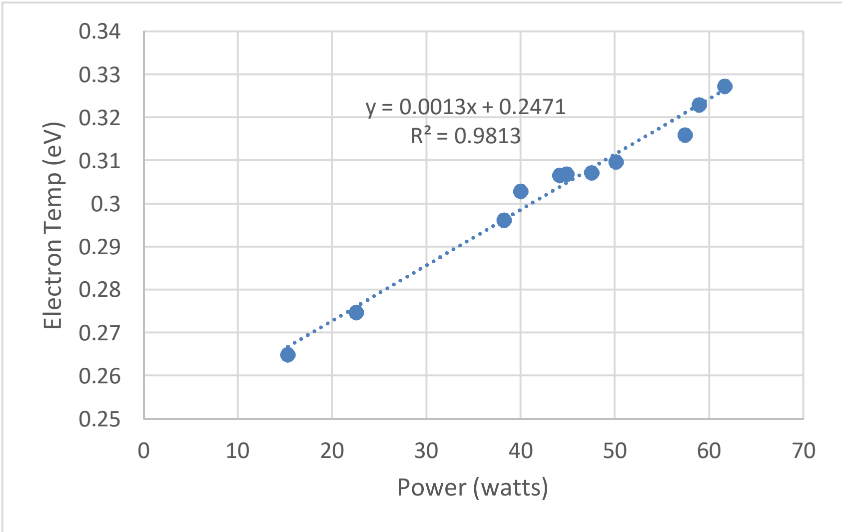


FIG. 4. Increasing the electron temperature with the adoption of higher capabilities for the argon plasma

Conclusion

The electron temperature was determined by analyzing the wavelength and intensity of the spectra. A line ratio method was employed, relating power to electron temperature, to establish a correlation between electron temperature and energy level.

References

[1] Qayyum, A., Ikram, M., Zakaullah, M., Waheed, A., Murtaza, G., Ahmad, R. and Chaudhary, K.A., Int. J. Mod. Phys. B, 17 (14) (2003) 2749.

[2] Donnelly, V.M., J. Phys. D: Appl. Phys., 37 (19) (2004) R217.

[3] Mariotti, D., Shimizu, Y., Sasaki, T. and Koshizaki, N., Appl. Phys. Lett., 89 (20) (2006) 201502.

[4] Hori, T., Bowden, M.D., Uchino, K., Muraoka, K. and Maeda, M., J. Vac. Sci. Technol. A, 14 (1) (1996) 144.

[5] Lee, M.H., Jang, S.H. and Chung, C.W., J. Appl. Phys., 101 (3) (2007) 033305.

[6] Hong, J.I., Seo, S.H., Kim, S.S., Yoon, N.S., Chang, C.S. and Chang, H. Y., Phys. Plasmas, 6 (3) (1999) 1017.

[7] Yanguas-Gil, A., Cotrino, J. and González-Elipe, A.R., J. Appl. Phys., 99 (3) (2006) 033104.

[8] Akatsuka, H., Adv. Phys. X, 4 (1) (2019) 1592707.

[9] Evdokimov, K.E., Konischev, M.E., Pichugin, V.F. and Sun, Z., Resour.-Effic. Technol., 3 (2) (2017) 187.

[10] Hwang, K.T., Oh, S.J., Choi, I.J. and Chung, C.W., Phys. Plasmas, 17 (6) (2010) 063501.

[11] Chung, T.H., Ra Kang, H. and Keun Bae, M., Phys. Plasmas, 19 (11) (2012) 113502.

[12] Laux, C.O., Spence, T.G., Kruger, C.H. and Zare, R.N., Plasma Sources Sci. Technol., 12 (2) (2003) 125.

[13] Kano, K., Suzuki, M. and Akatsuka, H., Contrib. Plasma Phys., 41 (1) (2001) 91.

[14] Zhu, X.M. and Pu, Y.K., J. Phys. D: Appl. Phys., 43 (40) (2010) 403001.

[15] Qayyum, A., Zeb, S., Naveed, M.A., Rehman, N.U., Ghauri, S.A. and Zakaullah M., J. Quant. Spectrosc. Radiat. Transf., 107 (3) (2007) 361.

[16] Qayyum, A., Zeb, S., Naveed, M.A., Ghauri, S.A., Zakaullah, M. and Waheed, A., J. Appl. Phys., 98 (2005) 103303.

[17] Chung, H.K., Song, M.Y., Kwon, J.W., Lee, M.G., Park, J., Bae, N. and Ralchenko, Y., Atoms, 9 (4) (2021) 100.

[18] Mariotti, D., Shimizu, Y., Sasaki, T. and Koshizaki, N., Appl. Phys. Lett., 89 (20) (2006) 201502.

[19] Ralchenko, Y., Mem. Soc. Astron. Ital. Suppl., 8, (2005) 96.

[20] Lao, C., Gamero, A., Sola, A., Petrova, T., Benova, E., Petrov, G.M. and Zhelyazkov, I., J. Appl. Phys., 87 (11) (2000) 7652.

[21] Cristoforetti, G., De Giacomo, A., Dell'Aglio, M., Legnaioli, S., Tognoni, E., Palleschi, V. and Omenetto, N., Spectrochim. Acta Part B: At. Spectrosc., 65 (1) (2010) 86.

[22] Li, J.Q., Xie, X.Y., Zhang, Q.H., Li, S.H. and Lu, W.Q., Phys. Fluids, 34 (6) (2022) 067115.

[23] Riquelme, M.A., Osorio, A., Verscharen, D. and Sironi, L., Astrophys. J., 924 (2022) 52.

[24] Evdokimov, K.E., Konischev, M.E., Pichugin, V.F. and Sun, Z., Resour.-Effic. Technol., 3 (2) (2017) 187.

[25] Ismael, M.E., Iraqi J. Phys., 13 (27) (2015) 14.