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Characteristics of Calcium Plasma Parameters by Laser-Induced Breakdown Spectroscopy Technique

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Abstract

In this work, the effect of laser energy on the properties of a calcium plasma generated by a Q-switched Nd: YAG laser at the fundamental wavelength was studied using spectroscopy. The Boltzmann plot and Stark broadening method were used to measure the main plasma parameters (electron temperature and electron density). The electron temperature ranged (0.169 -0.172) eV, the electron density ranged (2.10 – 2.63) $\times 10^{18} cm^{-3}$ for laser energy range of (400 – 700) mJ. Other basic plasma properties were also measured, including the Debye length, the number of particles in the Debye sphere, and the plasma frequency. Laser energy affects all plasma parameters, according to our results.

Keywords: Ca plasma, LIBS, OES, plasma parameter**s.**

خصائص معلمات بلازما الكالسيوم بتقنية مطيافية الانهيار التي يسببها الليزر

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الخلاصة

في هذا العمل ,تمت دراسة تأثير طاقة الليزر على بلازما الكاليسيوم المتولدة بواسطة ليزر Q-switched Nd:YAG عند الطول الموجي الاساسي بأستخدام التحليل الطيفي . تم أستخدام Boltzmann plot وتوسيع Stark لقياس معلمات البلازما الرئيسية (درجة حرارة الالكترون وكثافة الالكترون) تراوحت درجة حرارة الالكترون (0.169−0.172)eV , وتراوحت كثافة الالكترون ($(2.10-2.63)\times10^{18}(cm^{-3})$ لمدى طاقة الليزر (400−700)mJ . كما تم قياس خصائص البلازما الاساسية الاخرى ,بما في ذلك طول ديباي , وتردد البلازما. تؤثر طاقة الليزر على جميع معلمات البلازما ,وفقا لنتائجنا .

1.Introduction

Laser-Induced Breakdown Spectroscopy (LIBS) is a flexible technology for analyzing samples in their natural state without changing their chemical composition[1]. LIBS is a spectroscopic method that uses emission to describe the elements in materials. It has a variety of applications. When a high-intensity laser pulse is ignited at the sample surface, a plasma column is formed, as a result of which the sample. The separation mass of a substance is in the nanogram to microgram range[2]. The basis of LIBS is the study of the spectral lines that

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a plasma generates when a laser irradiates a substance. The sample surface is irradiated with a focused, high-intensity laser beam, which results in a hot plasma on the surface. When atoms and ions in different excited states shift to lower energy levels in the resulting plasma, they emit light which can be analysed using spectral analysis techniques [3]. Optical emission spectroscopy (OES) is a valuable technology. The properties of the materials that make up the plasma can be determined; OES is one of the most direct and most widespread methods that have been used to estimate plasma parameters [4]. There are many experimental publications in the literature investigating plasma features such as the effect of laser energy, wavelength dependence, and Spatio-temporal behavior. Sheikh et al.(2006)[5] presented a spectroscopic study of air-produced zinc plasma by a pulsed at the Nd: YAG laser three wavelengths (1064, 532, and 355)nm. They note that both the temperature and electron density decrease with increasing distance from the surface of the target and source. At a specific wavelength of 1064 nm and 532 nm, Wang et al.(2018) [6] studied laser impact energy and wavelength in detecting secondary elements in alloy steels . Using tin oxide saturated zinc oxide plasma spectroscopy techniques with different ratios and different laser power, researcher Muna et al . (2019) [7]performed a spectroscopic plasma examination properties like temperature, electron density, and Debye length. When the energy increases, it decreases. The primary objective of this study is to use spectroscopic light emission to investigate the properties of plasmas using spectral lines emitted by pure (Ca) atoms surrounding the plasma.

2.Experimental part

Optical emission spectra of calcium plasma are measured using a laser-generated spectrophotometer as seen in Figure 1

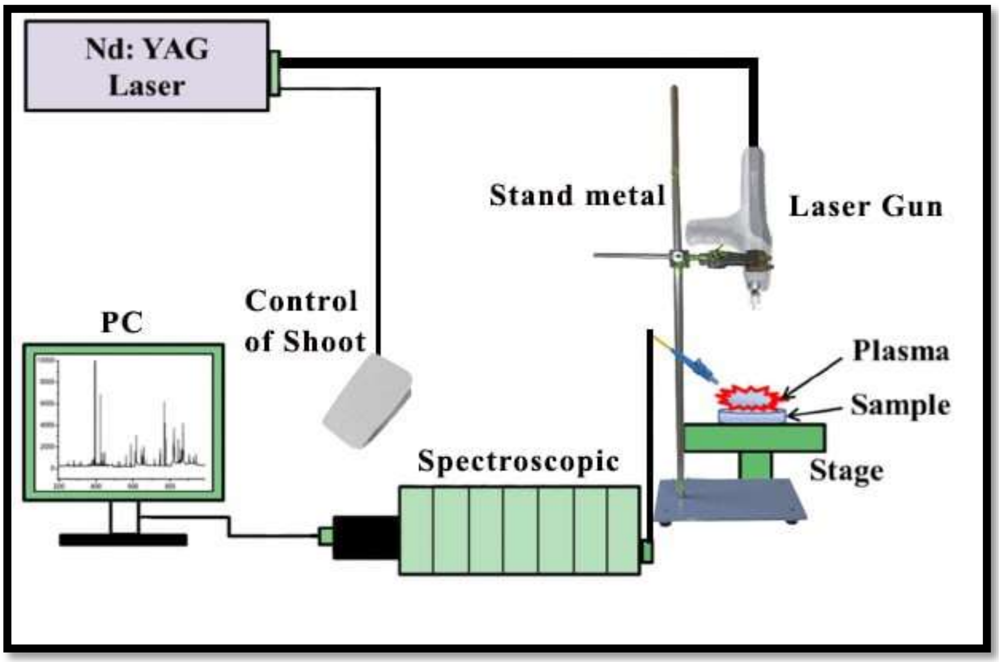

Figure 1: LIBS system schematic diagram

The plasma in this experiment was generated using an Nd: YAG laser with a basic wavelength of 1064 nm and a pulse duration of 10 nm. Repetition frequency 6 Hz, laser power from 400 to 700 (mJ). Calcium powder was placed inside a stainless steel metal cylinder and pressed by a hydraulic press. The powder was then made into a 1 cm thick disc, and the process was completed at room temperature for 10 min. At atmospheric pressure, a quartz lens with a focal length of 10 cm focuses the laser beam on the surface of the target

(Ca). For plasma emission, optical fibers were attached to a Surwit spectrometer (S3000-UV-NIR) and positioned 1 cm above the sample surface.

3. Results and Discussion

3.1. Spectroscopy diagnostics

Calcium plasma was characterized using optical emission spectrometry. the emission spectrum of calcium plasma, light emission is formed when excited species decay in the plasma, and a spectrum is often a number of distinct spectral lines of atoms, ions, or multiple ions. Calcium plasma has a light emission spectrum ranging from 300 nm to 700 nm. the optical emission lines measurements of calcium plasma according to the NIST database were used[8]. The calcium spectrum contains four CaII ion lines at 317.93, 373.69, 393.36, and 422.07 nm, as well as six atomic CaI lines at 364.44, 443.56, 526.55, 559.01, 616.64, and 645.56 nm as shown in Figure 2.

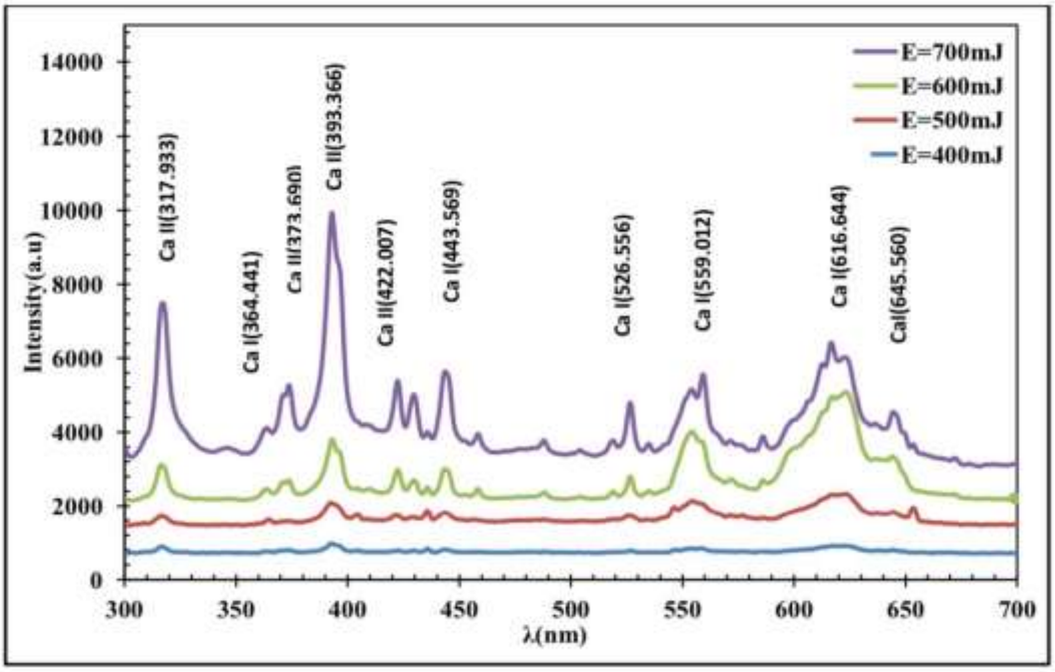

Figure 2: Spectral of plasma emission for Ca target at different laser energies.

Calcium line intensities were measured at 559.012, 616,644 nm, and 645.56 nm using different laser energies. Figure 2 shows the Ca plasma spectra from which the effect of laser energy on the intensity of the spectral lines can be studied. It was found that the intensity of the spectral line emission increases with increasing laser energy. This is due to the plasma absorption of laser photons, at the same time the plasma is relatively transparent on the laser beam so that the target ablation is increased. Increased targeted ablation leads to increased plasma emissions.

3.2 Characterization of plasma

Plasma properties such as electron temperature, electron density, plasma frequency, Debye length, and Debye sphere can be estimated using spectroscopic lines emitted from the calcium plasma. Understanding plasma excitation and atomic ionization processes require knowledge of T_e and n_e.

3.3. Electron temperature

The Boltzmann plot method was used to determine the electron temperature of the Ca plasma, as stated in equation (1)[9], assuming local thermodynamic equilibrium (LTE).

$$\boldsymbol{Ln\left(\lambda_{ji} I_{ji}/g_j A_{ji}\right) = -\left(E_j/k_B T\right) + C} \qquad \text{.......... (1)}$$

Where λ_{ji} is the laser wavelength (nm), g_i is the statistical weight, A_{ji} is the transition potential, and E_j is the upper energy taken from the standard spectrum of the NIST database. For plasma calcium, three atomic lines were used to apply the Boltzmann Plot method. The slope of the $Ln\left(\lambda_{ji} I_{ji}/g_j A_{ji}\right)$ versus energy (eV) graph, shown in Figure 3, was used to calculate the electron temperature; A straight line has an equal slope$\left(-1/k_B T\right)$.

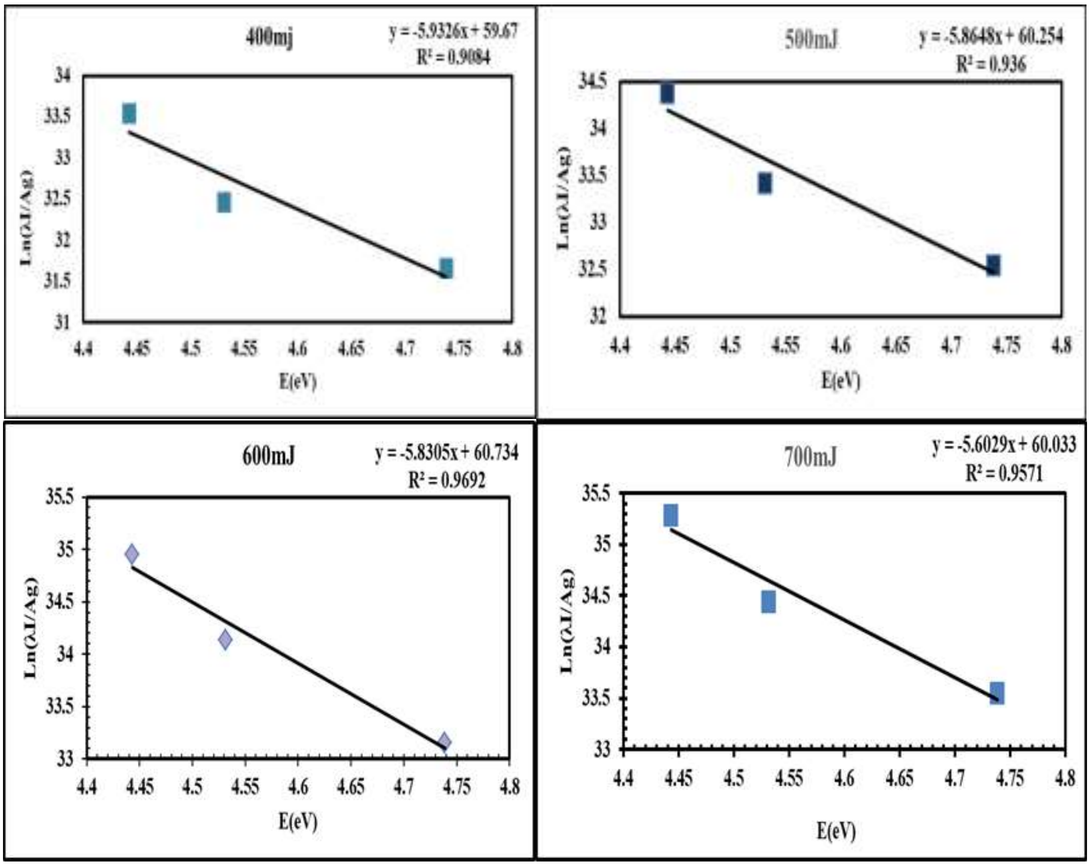

Figure 3: Boltzmann plot of calcium plasma was measured using different laser energies.

The temperature of the calcium plasma is calculated depending on the laser energy starting from 400 to 700 mJ. The value of the T_e range is (0.169-0.179) eV as shown in Table 1.

Table 1: Data analysis from the Boltzmann plots with the linear fitting of R^2 and electron temperature at different laser energies

E(mJ)	R^2	Slope	T_e (eV)
400	0.908	-5.9326	0.169
500	0.936	-5.865	0.171
600	0.969	-5.830	0.172
700	0.9571	-5.603	0.179

3.4. Electron density

The laser-induced calcium plasma emission spectra display bold lines. The primary effect on these emission spectra is Stark broadening, which results from the collision between the emitted atom and the charged particle. As a result of the collision, the electron density can be determined using the width of the spectral lines (2)[10]:

$$n_e\,(cm^{-3}) = \left(\frac{\lambda_{FWHM}}{2\omega}\right) \times 10^{16} \quad \text{......... (2)}$$

Where n_e is the electron density, λ_{FWHM} is the Stark full-Width at half-maximum (FWHM),and ω is the electron impact parameter.

For different laser energies, the electron density was calculated using CaII spectral lines at 393.66 nm. As shown in Table 2, the electron density ranged from 0.6 to 1.5 × $10^{18} cm^{-3}$.

3.5 Determination and characterization of other plasma parameters

The effect of laser energy on other basic plasma parameters such as Debye length (λ_D), Debye sphere (N_D) and plasma frequency (f_p) was determined using T_e and n_e for better characterization of the calcium plasma. We can calculate the length of the Debye from the following equation [11].

$$\lambda_D = \left(\frac{\varepsilon_0 k_B T_e}{n_e e^2}\right)^{1/2} \quad \text{... ... .} \quad (3)$$

We can find the Debye number through the following equation [11].

$$N_D = \frac{4\pi}{3}\lambda_D^3\, n_e \quad \text{... ... ...} \quad (4)$$

We can find the value of the plasma frequency by the following equation[11].

$$f_p = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2} \quad \text{... ... ...} \quad (5)$$

e is the electron charge, n_e is the electron density, m_e is the electron mass, where ε_0 is the permittivity of free space, k_B is the Boltzmann constant. The obtained data are listed in Table 2, revealing that as the laser energy increases, λ_D and N_D decreases. On the other hand, f_p rises when the laser energy goes up.

Table 2: Characteristics of the calcium plasma generated by a 1064 nm laser at different laser energies.

E (mJ)	T_e (eV)	$n_e \times 10^{18}$ (cm^{-3})	$f_p \times 10^{12}$(Hz)	$\lambda_D \times 10^{-5}$(cm)	$N_D \times 10^3$
400	0.169	2.10	13.013	0.210	8.183
500	0.171	2.25	13.470	0.205	8.047
600	0.172	2.40	13.912	0.199	7.860
700	0.179	2.63	14.549	0.194	7.981

Electron temperature and electron density (n_e) are highly dependent on laser energy. can be photographed for It is expected in Figure 4. Note that the electron temperature (T_e) increases with increasing laser power and its values in the range 0.169 to 0.179 eV. Electron density also increases with increasing laser power, values range from 2.10 $\times10^{18}$ to 2.63 $\times10^{18}$ cm^{-3}, With the increase in the laser pulse energy, the electron temperature and electron density increased cause this increase, the laser highest power has a strong and fundamental effect on the intensity of the emission lines in as shown in Figure 4. At the high energy it becomes almost stable because the plasma becomes opaque to the beam The laser that protects the target. Plasma shielding occurs when the plasma itself reduces the transmission of the laser highest energy along the beam path[12] .

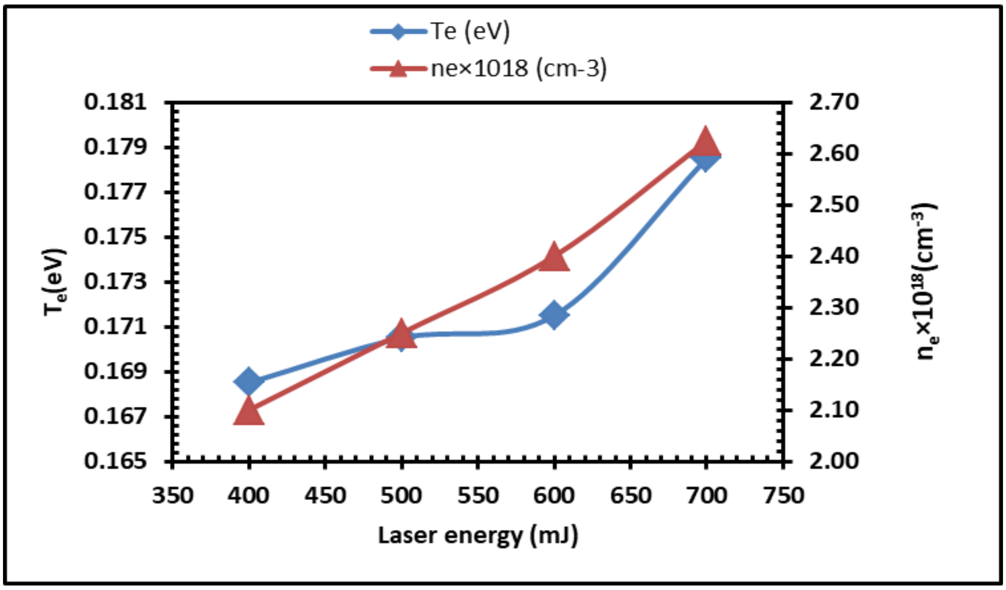

Figure 4: Difference between Te and n_e versus laser power for calcium at different energy values.

Figure 5 shows that when the laser power increases, the plasma frequency increases and the Debye length decreases, and the laser power ranges from 400 to 700 mJ. The frequency values range from 6.956 to 10.998 $\times10^{12}$Hz, and according to equation (5), the frequency is directly proportional to the electron density, and this is normal. When the laser energy increases, the Debye length decreases. The Debye length values range from 0.153 to 0.255×10^{-5} (cm^{-3}) which is inversely proportional to the electron density, according to equation (3) These results are in agreement with Maryam and Kadhim (2021)[13].

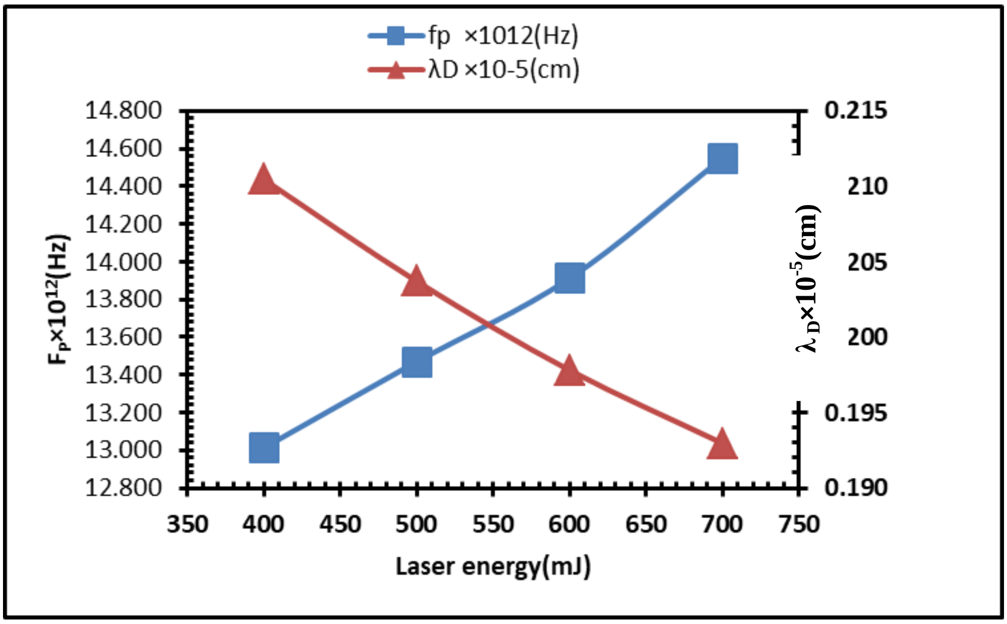

Figure 5: Difference between f_p and λ_D versus laser power for calcium at different energy values.

Debye number decreases with increasing laser energy and N_D showed similar behavior to Debye length as a function of laser energy as in Figure 6, and these results are in agreement with Maryam and Kadhim (2021) [13].

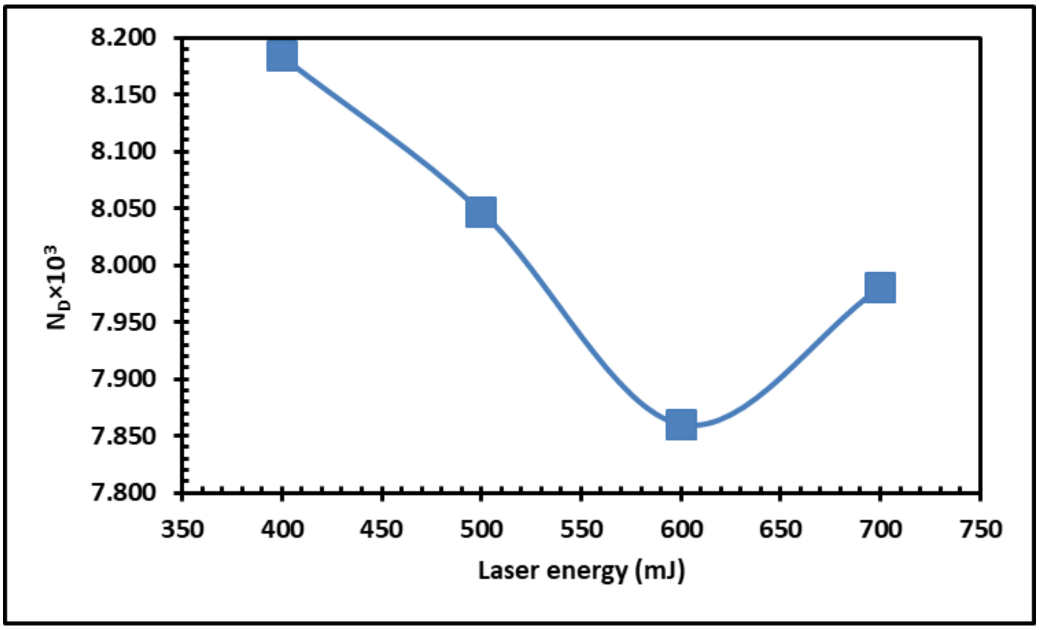

Figure 6: Debye number of Ca plasma at different laser energy

4. Conclusion

In this paper, A Q-switched Nd: YAG laser with a wavelength of 1064 nm and energy from 400 to 700 mJ was used to create the calcium plasma. To determine the relationships of plasma parameters such as electron density and electron temperature, optical emission spectroscopic measurements were performed. The plasma parameters were calculated based on their sensitivity to laser energy. The results showed that when the laser energy increases , the values of T_e, n_e and f_p increase, while the values of λ_D decrease.

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References

[1] I. Rehan, M. Z. Khan, I. Ali, K. Rehan, S. Sultana, and S. Shah, “Spectroscopic analysis of high protein nigella seeds (Kalonji) using laser-induced breakdown spectroscopy and inductively coupled plasma/optical emission spectroscopy,” *Appl. Phys. B Lasers Opt.*, vol. 124, no. 3, p. 0, 2018, doi: 10.1007/s00340-018-6915-z.

[2] S. Jamali *et al.*, “Elemental Analysis of Kohl Using Laser Ablation and Atomic Absorption Spectroscopy (AAS) techniques,” *Phys. B Condens. Matter*, vol. 620, no. August, p. 413278, 2021, doi: 10.1016/j.physb.2021.413278.

[3] A. Iftikhar, Y. Jamil, N. Nazeer, M. S. Tahir, and N. Amin, “Optical Emission Spectroscopy of Nickel-Substituted Cobalt–Zinc Ferrite,” *J. Supercond. Nov. Magn.*, vol. 34, no. 7, pp. 1849–1854, 2021, doi: 10.1007/s10948-020-05734-5.

[4] U. H. Tawfeeq, A. K. Abbas, and K. A. Aadim, “Optical Emission Spectroscopic Analysis of Plasma Parameters in Cadmium by Nd: YAG laser Technique,” *J. Phys. Conf. Ser.*, vol. 2114, no. 1, p. 012049, 2021, doi: 10.1088/1742-6596/2114/1/012049.

[5] N. M. Shaikh, B. Rashid, S. Hafeez, Y. Jamil, and M. A. Baig, “Measurement of electron density and temperature of a laser-induced zinc plasma,” *J. Phys. D. Appl. Phys.*, vol. 39, no. 7, pp. 1384–1391, 2006, doi: 10.1088/0022-3727/39/7/008.

[6] J. Wang, X. Li, C. Wang, L. Zhang, and X. Li, “Effect of laser wavelength and energy on the detecting of trace elements in steel alloy,” *Optik (Stuttg).*, vol. 166, pp. 199–206, 2018, doi: 10.1016/j.ijleo.2018.04.018.

[7] K. A. Aadim, “Spectroscopic study the plasma parameters for SnO2 doped ZnO prepared by pulse Nd:YAG laser deposition,” *Iraqi J. Phys.*, vol. 17, no. 42, pp. 125–135, 2019, doi: 10.30723/ijp.v17i42.447.

[8] NIST Atomic Spectra Database Lines Form, “www.nist.gov/pml/atomic-spectra-database.” .

[9] R. Viskup, C. Wolf, and W. Baumgartner, “Laser Induced Breakdown Spectroscopy of Diesel Particulate Matter Exhaust Emissions Generated from on Road Diesel Engine : Light Duty Vehicles Identification of the Main Matrix,” no. Photoptics, pp. 308–314, 2019, doi: 10.5220/0007618203080314.

[10] K. A. Ahmed, K. A. Aadim, and R. S. Mohammed, “Investigation the energy influence and excitation wavelength on spectral characteristics of laser induced MgZn plasma,” *Proc. III Int. Conf. Adv. Technol. Mater. Sci. Mech. Autom. Eng. MIP Eng. – 2021*, vol. 2402, no. November, p. 080004, 2021, doi: 10.1063/5.0065374.

[11] Q. A. Abbas, “Effect of target properties on the plasma characteristics that produced by laser at atmospheric pressure,” *Iraqi J. Sci.*, vol. 60, no. 6, pp. 1251–1258, 2019, doi: 10.24996 /ijs .2019.60.6.8.

[12] K. A. Aadim and R. H. Jassim, “Determination of plasma parameters and nanomaterial’s synthesis of Zn and Mn using laser induced plasma spectroscopy,” *AIP Conf. Proc.*, vol. 2372, no. November, 2021, doi: 10.1063/5.0067300.

[13] M. M. Shehab and K. A. Aadim, “Spectroscopic diagnosis of the CdO:CoO plasma produced by Nd:YAG laser,” *Iraqi J. Sci.*, vol. 62, no. 9, pp. 2948–2955, 2021, doi: 10.24996/ijs.2021.62.9.11.