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Characteristics of CaFe 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 CaFe 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 (1.295 -1.929) eV, the electron density ranged (2.25 - 3) $\times 10^{18} cm^{-3}$, and the laser energy ranged (400 – 700) mJ. Other basic plasma properties were also measured, including the Debye length, and the plasma frequency. Laser energy affects all plasma parameters, according to our results.

Keywords: CaFe Plasma, LIBS, OES, Plasma Parameters.

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Introduction

Laser-induced breakdown spectroscopy (LIBS) is a useful method for performing elemental analysis on materials in the solid, liquid and gaseous states of their composition. It can be used for things like analyzing materials, monitoring the environment, determining whether or not soil is contaminated, and many types of biomedical research[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 material is excised. The separation mass of a substance is in the nanogram to microgram range[2]. The study of the spectral lines produced by the plasma when material is irradiated with a laser is the basis for laser-induced breakdown spectroscopy (LIBS). Irradiation of the sample surface with a focused laser beam of high intensity causes a hot plasma to be focused on the sample surface. Radiation results when atoms and ions in different excited states move to lower energy levels in the plasma that is the product of these transformations [3]. The technique known as optical emission spectroscopy (OES) is an important technique. OES is one of the most direct and most widespread methods that have been used to estimate plasma parameters. The properties of the materials that make up the plasma can be calculated; OES is also one of the most accurate methods [4]. A plasma is generated after the sample material is heated, melted, ionised, and ionised by the energy of the laser pulse. The plasma will then be spectrophotometrically monitored and examined using a spectrometer and detector. The plasma spectrum formed as a consequence can be used to infer quantitative and qualitative information, such as elemental composition. The emission line's widths, forms, and variations can disclose information regarding plasma temperature and electron density[5]. There are many experimental publications in the literature investigating plasma features such as the effect of laser energy, wavelength dependence, and Spatio-temporal behavior. Muna et al (2019) presented a spectroscopic study of a SnO2-doped ZnO plasma produced in air by a pulse at Nd:YAG laser wavelengths of 1064 nm. Note that both the temperature and electron density increase with increasing laser power [6]. Using CdO: plasma spectroscopy techniques of 0.5 ratio and different laser power, researcher Tamara et al. (2019) [6] performed a spectroscopic examination of plasma properties such as temperature, electron density, and Debye length [7]. The fundamental purpose of this study is to employ spectroscopic light emission to analyse the characteristics of plasmas using spectral lines released by CaFe atoms surrounding the plasma.

Experimental Part

In this experiment, plasma was generated on a solid object using a pulsed laser (CaFe). Figure 1 depicts the LIBS experimental setup (1). The plasma was generated using a pulsed laser (Nd:YAG) with a wavelength of 1064 nm and a frequency of 6 Hz. The laser beam from the target material is focused on the target at an angle of 45 degrees. A laser beam vaporizes and ionizes the target material, resulting in the formation of a plasma column above the target surface. The electron temperature, density, and plasma frequency were determined using the OES approach. Mathematically, the length of the Debye and Debye number is determined. The spectrophotometer used generally should be fast, with consistent reaction times on each shot. Thus, in the setup, a Surwit spectrometer (S3000-UV-NIR) was used to determine the emission wavelengths and has high efficiency targets. For each spectra, a wavelength range (300-800 nm) was obtained. The plasma spectrum with different energy values was generated by mixing Ca with Fe at X = 0.5, while the energy of the laser pulses spanned from 400 to 700 mJ.

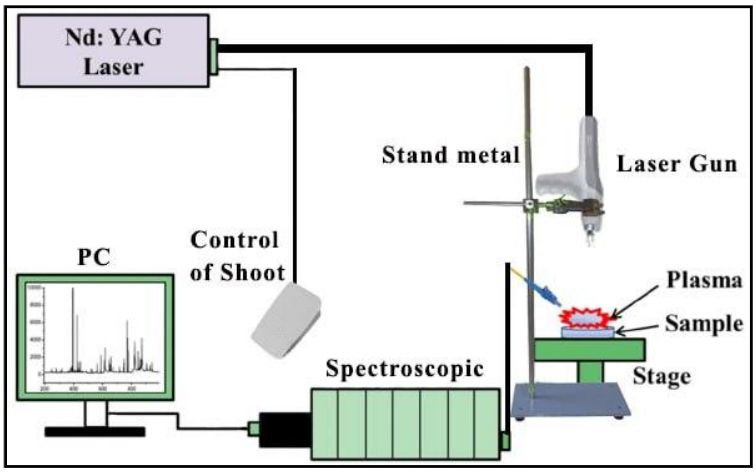


Figure 1: Diagrammatic Representation of LIBS System

Results and Discussion

1. Spectroscopy Diagnostics

CaFe plasma was characterized using optical emission spectrometry the emission spectrum of CaFe 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. CaFe plasma has a light emission spectrum ranging from 300 nm to 700 nm. The optical emission lines measurements of CaFe plasma according to the NIST database were used[8]. The spectrum of CaFe contains four lines of Ca and four lines of Fe as shown in Figure (2).

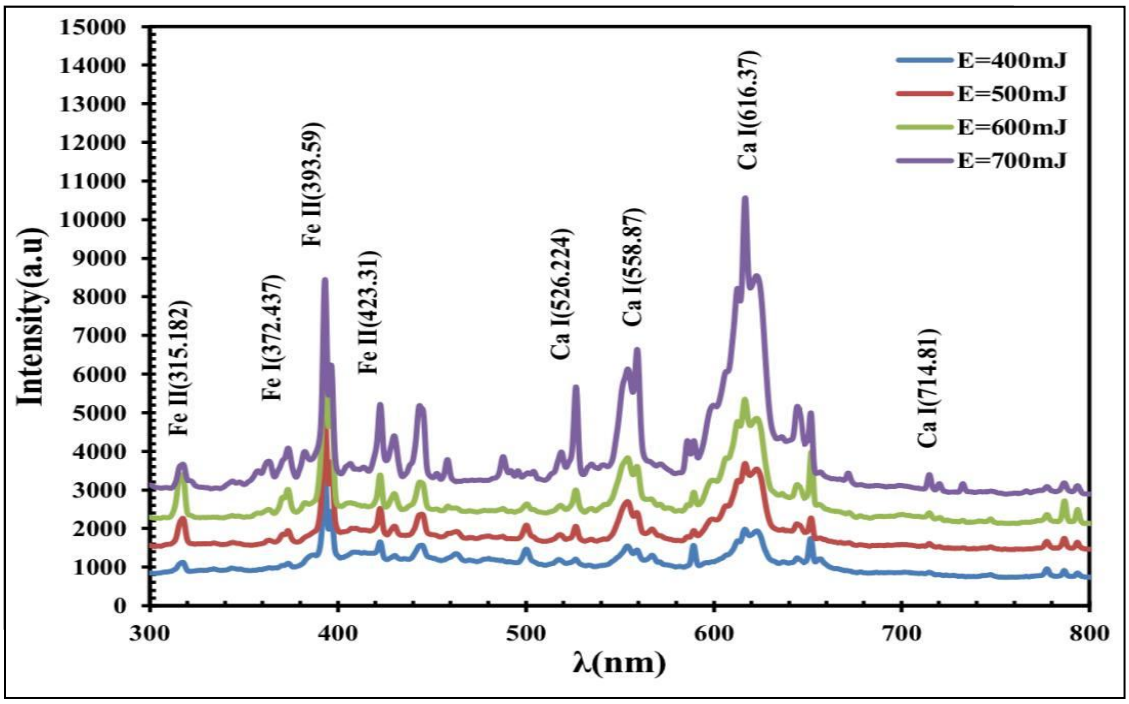


Figure 2: Spectral of Plasma Emission for CaFe Target at different Laser Energies

The impact of the laser's energy on the level of brightness of the spectral line is seen in Figure 2. It was discovered that the power of the laser has a direct correlation to the degree to which the intensity of the spectral line emission changes. This is because the plasma absorbs photons from the laser, but at the same time, the plasma is relatively transparent to the laser beam, which results in an increase in the amount of target ablation.Increased targeted ablation leads to increased plasma emissions.

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 CaFe plasma.

3. Electron Temperature

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

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

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 CaFe, 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 Fig. (3), was used to calculate the electron temperature; A straight line has an equal slope $(-1/k_B T)$.

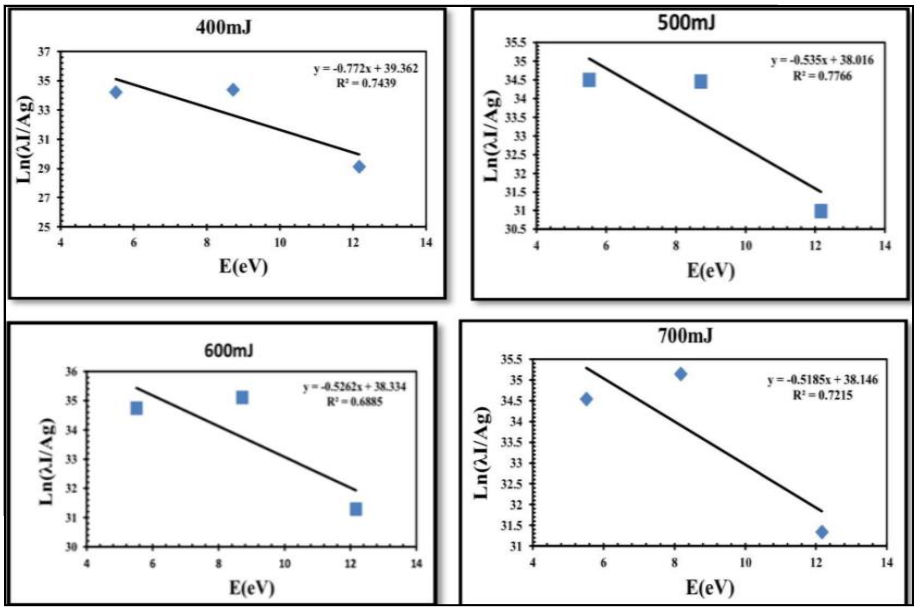


Figure 3: Boltzmann Plot of CaFe Plasma was Measured Using different laser Energies

The temperature of the CaFe plasma is calculated depending on the laser energy starting from 400 to 700 mJ. The value of the T_e range is (1.295-1.929) 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 Energie

E(mJ)	R^2	Slope	T_e (eV)
400	0.743	-0.772	1.295
500	0.776	-0.535	1.870
600	0.688	-0.526	1.900
700	0.721	-0.518	1.929

4. Electron Density

The laser-induced CaFe 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 connection, the electron density can be determined using the width of the spectral lines (2)[10]:

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

For different laser energies, the electron density was calculated using FeII spectral lines at 393.59nm. As shown in table (2), the electron density ranged from 2.25 to 3× $10^{18} cm^{-3}$.

5. Determination and Characterization of other Plasma Parameters

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

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

We can find the plasma frequency through the following equation [11].

$$f_p = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2} \qquad (4)$$

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 decreases. On the other hand, f_p rises when the laser energy goes up.

Table 2: Characteristics of the CaFe 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 (Hz) $\times 10^{12}$	$\lambda_D \times 10^{-5}$(cm)
400	1.295	2.25	13.470	0.664
500	1.870	2.55	14.340	0.636
600	1.900	2.78	14.959	0.615
700	1.929	3.00	15.554	0.596

Electron temperature and electron density (n_e) are highly dependent on laser energy. can be photographed for It is expected in Figure 3. Note that the electron temperature (T_e) increases with increasing laser peak power and its values in the range 1.295 to 1.929 eV. Electron density also increases with increasing laser power, values range from 2.25 $\times 10^{18}$ to 3 $\times 10^{18}$ cm^{-3}, the reason is that the increase in the laser peak energy has a strong and fundamental effect on the intensity of the emission line in all metals, and the peak energy becomes nearly stable as the plasma becomes opaque with the laser beam that protects the target. The plasma is shielded when the plasma itself occurs, this reduces the transmission of the laser peak energy along the beam path[12].

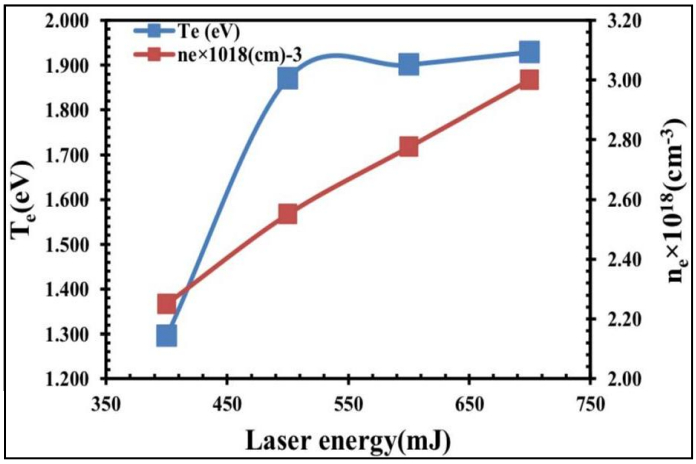


Figure 4: Difference between Te and n_e Versus Laser Power for CaFe at different Energy Values

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 13.47 to 15.554 $\times 10^{12}$Hz, and according to equation (4), 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 0.664 to 0.596 $\times 10^{-5}$ (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].

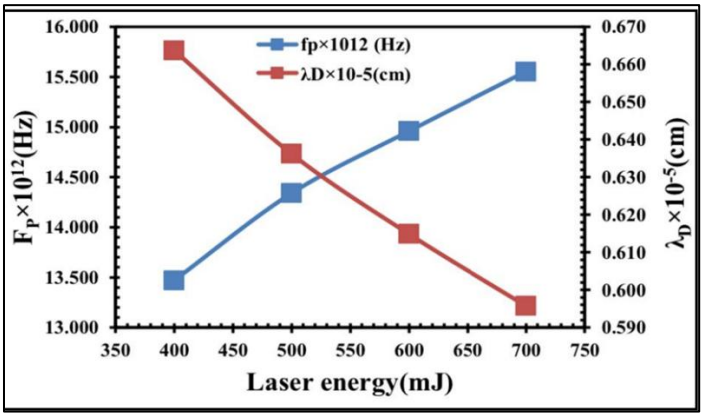


Figure 5: Difference between f_p and λ_D Versus Laser Power for CaFe at different Energy Values

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 CaFe 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 in the atmosphere, the values of T_e, n_e and f_p increase, while the values of λ_D decrease.

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