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Spectroscopic Diagnostic of Laser-Induced Zn Plasma

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Abstract

The sample's physical characteristics and laser parameters impact the generation and characterization of Laser-Induced Plasma (LIP), which is a relevant phenomenon in many applications. We investigated the effect of laser energy on laser-induced Zn plasma characterization in this study. A Zn plasma with a repeating frequency of 5 Hz, a first laser wavelength of 1064 nm, a pulse duration of 9 ns, and a laser energy range of 300 mJ to 500 mJ was created using a Q-switched ND: YAG laser. The basic plasma properties, such as electron temperature and density, were estimated using optical emission spectroscopy (OES). The electrons temperature was measured by the Boltzmann plot method, and the electrons temperature ranged from 1.6 eV to 2.051 eV in the laser energy range (300-500) mJ. In electron density value estimation using the Stark broadening methods, the density value ranges from 12.75×10^{17} cm^{-3} to 19.50×10^{17} cm^{-3}, in the laser energy range (300-500) mJ. In addition, various plasma characteristics such as plasma frequency (f_p), the number of particles in the Debye sphere (N_D), and Debye length (λ_D) were estimated. We found that laser energy affects every plasma parameter.

Keywords : Emission spectroscopy, Zn Plasma, Spectroscopic, ND: YAG laser.

1. Introduction

The term "laser-induced plasma spectroscopy" (abbreviated as "LIBS") refers to an application of atomic emission spectroscopy that utilizes high-energy laser pulses to excite optical materials (LIPS). Plasma is created when strong laser pulses strike a metal surface, and it is well recognized to be a source of incredibly pure metal spectra [1]. The production of plasma may be separated into many steps. In the initial step of the process, the laser light interacts with a solid, producing plasma products and rapid surface ionization in comparison to the pulse period. The second stage's plasma absorbs the laser light as it expands consistently and efficiently [2]. After step three, plasma is produced, which may occur as soon as the laser pulse energy heats the particular material (sample), causing the material's atoms to receive more energy and plasma to develop. For this, large samples of solids, liquids, and gases can be employed [3]. It is critical to understand that the generated plasma's spectral line emission intensity is determined by the characteristics of the plasma itself as well as the concentration of the element in the sample, which are determined by elements such as the physical and chemical properties of the sample under study, including density, the boiling point of the target, specific heat, and surface reflectance, laser parameters (pulse duration, energy, wavelength), as well as ambient conditions of the surrounding atmosphere in terms of electric field composition, pressure, and temperature [4, 5]. The temperature, density, and variety of emission types of electrons are the fundamental characteristics of plasma [6]. The importance of plasma temperature in plasma parameters is well established. Evaluating other plasma features, such as particle velocity dispersion and relative energy concentrations, depends on having a solid understanding of the plasma temperature [5, 6]. The spectrum of plasma light is detected using the spectrophotometer. Analyzing the plasma spectrum emissions, such as the target components, can yield quantitative and qualitative information. The breadth, forms, and transitions of emission lines can provide information on the temperature and density of electrons in the plasma [4]. It is also difficult to assess the influence of energy on its own. Increased laser energy usually increases the incised mass and ablation rate [7]. This work aims to utilize OES methods to analyze the influence of laser energy on Zn plasma properties.

Experimental Setup

The LIPS experiments, depicted in Fig. 1 as a schematic, were carried out at atmospheric pressure. Plasma was created using a sample of the element Zinc. A Q-switched ND; YAG nanosecond laser source with a pulse duration of 9 ns, a first wavelength of 1064 nm, a repeating frequency of 5 Hz, and laser energy of 300, 400, and 500 m J was used to create plasma. A spectrometer was used to collect and evaluate the light emission. The spectrometer is nearly 30 cm away from the laser target, at a 45^o angle from the laser beam path. An optical fiber with a core diameter of 50 m and a location of 1 cm was used to receive plasma light emissions induced by lasers from the surface of the Zn target. The optical emission line results were compared to NIST database software [8].

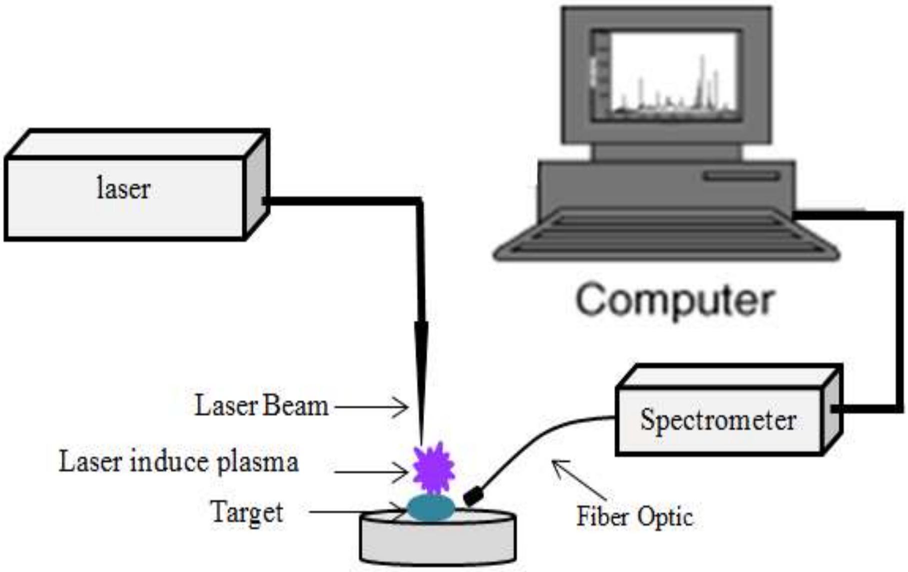

Figure 1. Schematic depiction of the experimental setup for laser-induced Zn plasma.

2. Results and discussion

2.1. Spectroscopy diagnostics of plasma optical emission (OES)

The composition of the material is determined by utilizing optical emission spectroscopy to simulate the decay of excited species in plasma. The investigation of optical emission by excited species helps in the identification of pure constituents in a substance. Throughout this method, assume that a bound electron relaxes from an excited state to a lower energy level, or ground level. In this case, a spectral line emission produces photons with a certain wavelength. The Zn plasma emission spectrum, which is restricted to the spectral region (300–700 nm) for distinct pulsed laser energies of 400, 500, and 300 mJ, is shown in Figure 2. This spectrum contains the emission of six spectral lines as a result of 1064 nm laser excitation at various laser energies. The spectral lines for Zn II are three ionic lines at 481.9, 491.1, and 636.2 nm, whereas for Zn I are three atomic lines at 328.2, 334.5, and 472.2 nm. Figure (2) shows that when laser energy rises, plasma absorbs more laser light, increasing both the ablation rate and the spectral lines' intensity [9].

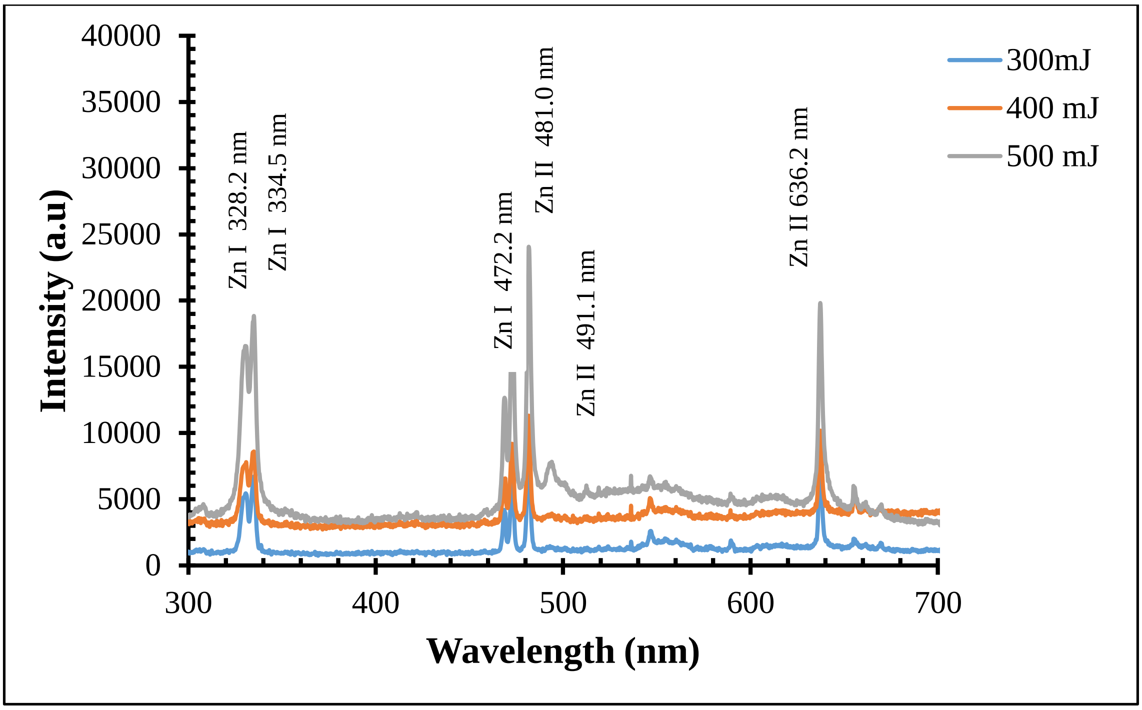

Figure 2. The spectra of the Zn plasma emission from a 1064 nm laser at different laser energies.

2.2. Characterization of laser induced Zn plasma

The electron temperature and density are two important plasma parameters inferred from emission characteristics unique to atomic and ionic species of Zn spectrum intensities and line width. The temperature and density of plasma electrons were then estimated as a function of laser energy.

Equation (1) [10] illustrates the Boltzmann plot technique for determining the electron temperature of the Zn plasma:

$$\ln\left(\frac{I_{ji}\,\lambda_{ji}}{g_j\,A_{ji}}\right) = -\frac{E_j}{k_B\,T_e} + \ln\left(\frac{hcN_j}{4\pi Q(T)}\right) \qquad (1)$$

Where, I_{ji} the light emitted intensity, λ_{ji} the emitted line wavelength, g_j is the statistical weight of the state concerned, A_{ji} is the transition probability, E_j the excited state energy, k_B is the Boltzmann constant, the number density is N_j (particle / cm^3), Q(T) is a plasma-temperature partition function for the emitting species of atoms that emit each species. Once the plasma temperature is known, the partition function for each element may be determined using spectroscopic data. By plotting $\ln\left(\frac{I_{ji}\,\lambda_{ji}}{g_j\,A_{ji}}\right)$ versus E_k, as appears in Figure (3). The straight line is used to measure the plasma temperature, which is equal to $-1/kT_e$.

According to Table (1), the values for the electrons' temperature (T_e) values were 12672.06, 15814.59, 19359.15, 19774.97, and 20874.57 K. The temperature of electrons at various laser intensities is depicted in Figure (4). According to Figure (3), the electron temperature rises as the energy of the laser pulse increases. In contrast to more collisions in other media, charged secondary particles originate from higher electron temperatures (Te), which are proportional to the top kinetic energy of free plasma electrons. This is because plasma may absorb laser photons while still enabling the laser beam to travel through it [11].

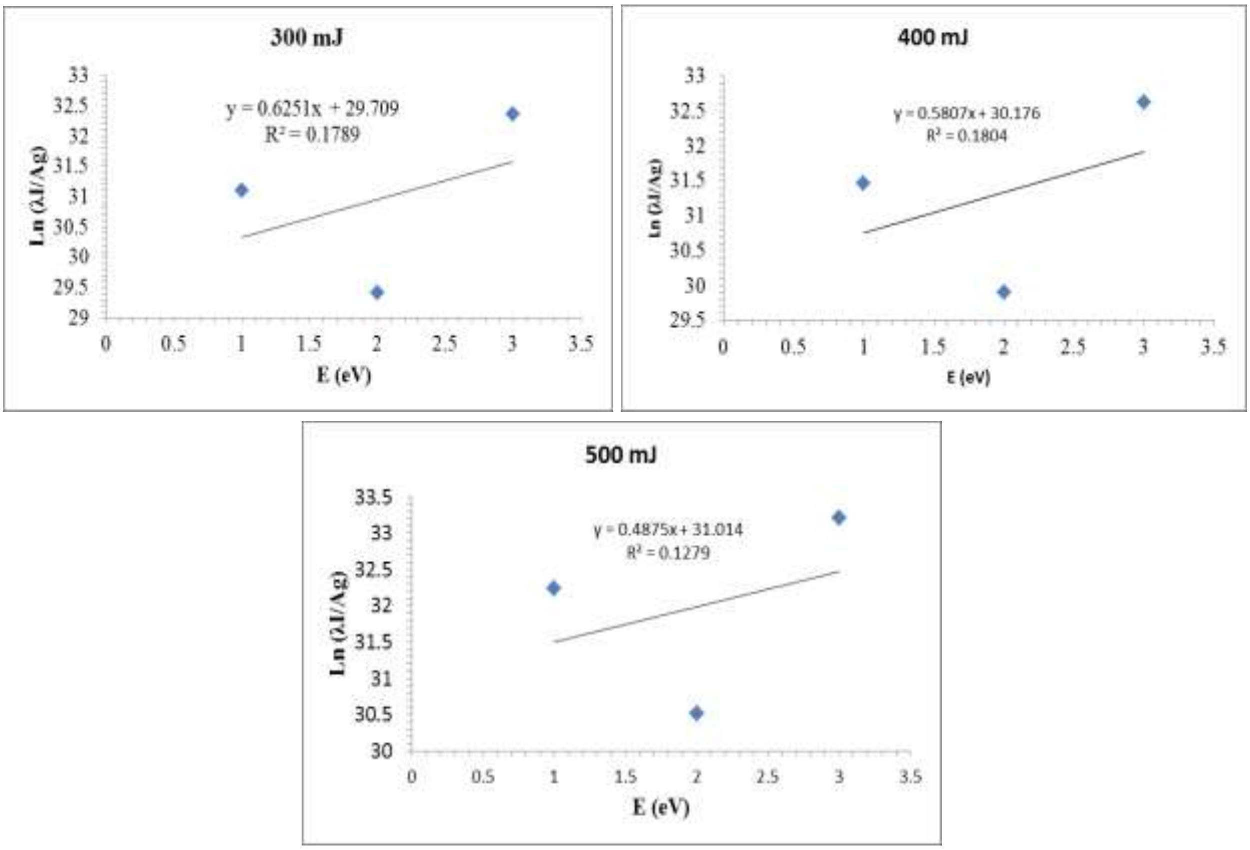

Figure 3. Boltzmann plot methods to measure electron temperature Zn plasma for different laser energy.

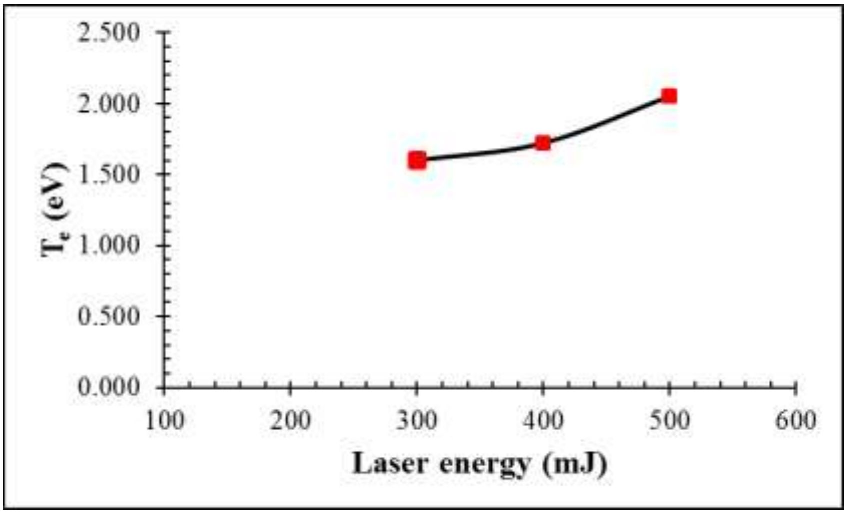

Figure 4. Zn plasma electron temperature for various laser energies.

When fast-moving electrons and relatively slow-moving ions combine to affect the ions or atoms in the plasma, electrical fields are formed. The electrical field's effect on atoms or ions to create energy shift levels results in a sharp expansion of plasma emission lines. The density of electrons caused by the line width-broadening of Stark's line emission spectrum might be the culprit. At half-maximum, the entire width of the Stark-broadened line is equal to the number of free electrons per unit volume, also known as an electron density (ne) (FWHM). Equation (2) contains a formula for calculating electron density [12]

$$\Delta\lambda_{\frac{1}{2}} = 2\omega\left(\frac{n_e}{10^{16}}\right) \qquad (2)$$

Where: $\Delta\lambda_{1/2}$ is the full-width at half-maximum (FHWM), n_e is the electron density, and ω is the electron impact parameter.

At wavelength 481 nm for spectral lines of Zn II, the electron density was calculated for various laser energies. The value range of electron density starts from 12.75×10^{17} to 19.50×10^{17} cm^{-3}, as reported in Table (1). As appears in Figure (5), as the laser energy increases, the electron density increases. The outcomes demonstrated that the electron density (n_e), a feature of the plasma shielding effect, fluctuates slowly (i.e., plasma reflection of laser light). The plasma shielding effect of the air decreases the ionization process and the laser energy's mass ablation efficiency since the experiment was carried out at atmospheric pressure [9].

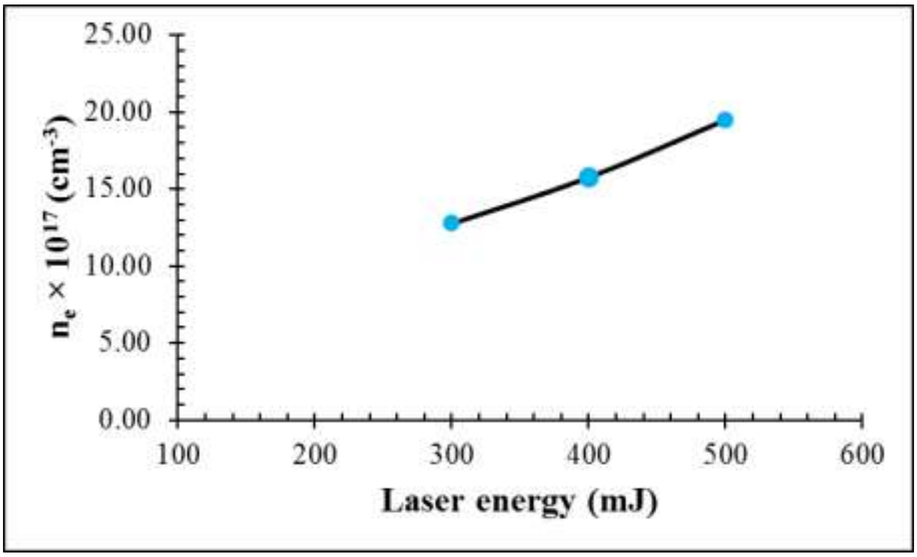

Figure 5. Zn plasma electron density at different laser intensity

The electron temperature (T_e) and density (n_e) were used to assess the impact of laser energy on other basic plasma properties, such as plasma frequency (fp), sphere (N_D), (λ_D), and particles in Debye length (λ_D) to characterize the Zn plasma better. Equations 3, 4, and 56 represent f_p, N_D, and λ_D, respectively [13].

$$f_p = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2} \quad \ldots..(3)$$

$$N_D = \frac{4\pi}{3}\lambda^3{}_D n_e \quad \ldots..(4)$$

$$\lambda_D = \left(\frac{\varepsilon_0 k_B T_e}{n_e e^2}\right)^{1/2} \quad \ldots\ldots(5)$$

Where: n_e: the density of the electron, ε_0: the permittivity, e: the charge of the electron, k_B : the Boltzmann constant, and m_e: the electron mass.

According to the findings and information in Table 1, it seems that the electron temperature and density affect the plasma frequency (f_p), Debye sphere (N_D), and Debye length (λ_D). With increasing laser energy, it was possible to observe changes in the plasma frequency (f_p), Debye length, and particle in the Debye's sphere (N_D), as seen in Figures (6), (7), and (8), respectively. Electron-ion collisions play a crucial part in this. Because of the rising electron density and rising plasma frequency in this case, the plasma is more able to absorb laser light. The troublesome zone becomes more prominent as the temperature rises because the Debye length grows, and the dependence λ_D on density $\lambda_D \propto n_e{}^{-1/2}$. It suggests that a greater quantity of shielding particles offers more efficient defense and minimizes the area of the troublesome zone.

Table 1: Plasma parameters of laser-induced Zn plasma at various laser energy.

Laser energy (mJ)	T_e (eV)	$n_e \times 10^{17}$ (cm^{-3})	λ_D (cm)	N_D (cm^{-3})	f_p (Hz)
300	1.600	12.75	0.366	2.621	10.140
400	1.722	15.75	0.293	1.664	11.270
500	2.051	19.50	0.266	1.535	12.540

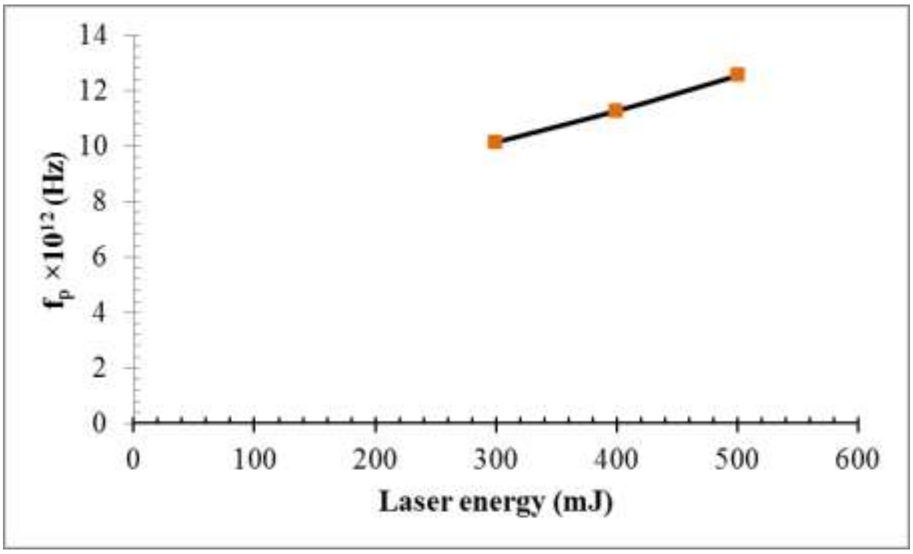

Figure 6. Zn plasma frequency at different laser energy

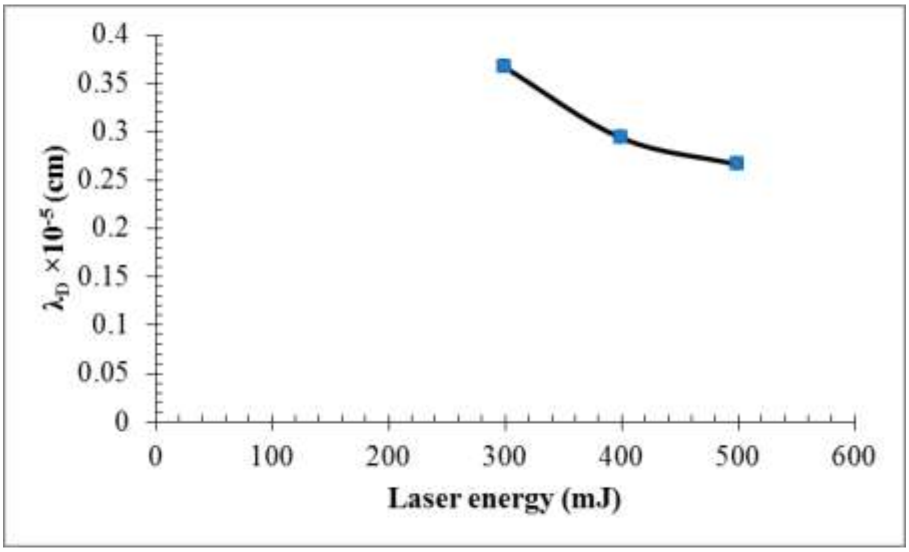

Figure 7. Debye length of Zn plasma at different laser energy

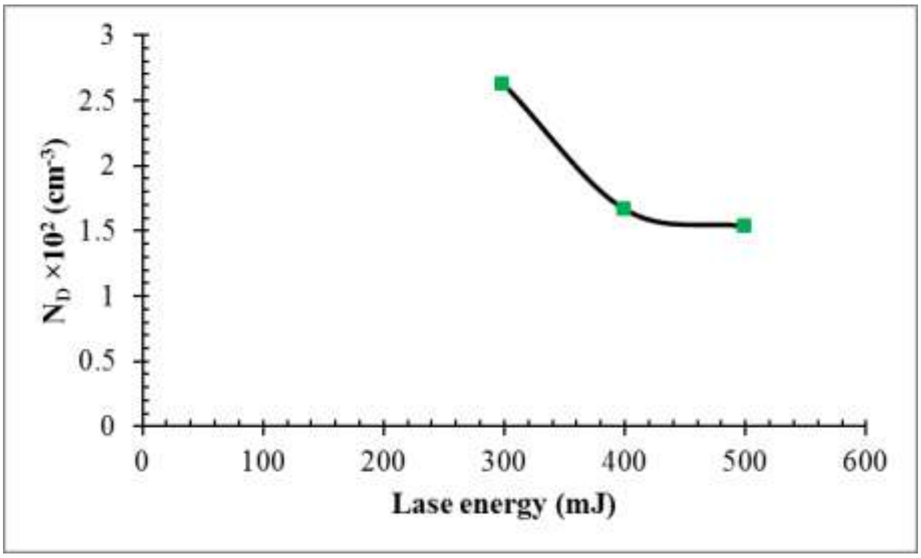

Figure 8. Debye number of Zn plasma at different laser energy

4. Conclusion

We have investigated how laser energy affects the characteristics of Zn plasma. Optically emitted spectra, electron temperature, electron density, and other fundamental plasma characteristics have been shown to be significantly impacted by changes in laser energy. With laser energy, the electron temperature of Zn plasma changes linearly. The Stark widening, which results from collisions between the liberated atom and charged particles, causes the spectral lines to widen and is inversely proportional to the electron density. All plasma characteristics, however, increase linearly with rising laser energy.

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