Spectroscopic Analysis of CdO: Fe Plasma Generated by Nd: YAG Laser

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Abstract

In this work, the optical emission spectrum technique was used to analyze the optical emission spectrum of (CdO: Fe) plasma produced by laser Nd: YAG with a wavelength of (532) nm, a period of 10 ns, and a focal length of 10 cm in the energy range of (200-500) mJ. The electron temperature (T_e) was determined using the method of line intensities ratio. Using the Saha-Boltzmann equation, the electron density (n_e) was determined. Other plasma parameters such as plasma frequency (f_p), Debye length (λ_D) and Debye number (N_D) were also measured. The CdO: Fe (at a mixing ratio of X= 0.5.) plasma spectrum was observed for different energies. As a function of the laser energies, the changes in electron temperature and densities were studied. The value of the electron temperature, at X=0.5, was (0.420 - 1.160) eV for laser energy (200-500) mJ, respectively.

Keywords: plasma parameters, optical emission spectrum, Laser-induced plasma spectroscopy.

التحليل الطيفي لـ بلازما CdO: Fe المولدة بواسطة ليزر النديميوم ياك

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الخلاصه

في هذا العمل تم استخدام تقنية الانبعاث البصري في عملية تحليل الطيف البصري. طيف بلازما (CdO: Fe) كان ناتج عن الليزرنيديميوم ياك بطول موجي (532) نانومتر و مقاسات 10 نانومتر وببعد بؤري بلغ 10 سم ضمن نطاق الطاقة (200−500) ميغا جول. تم حساب درجة حرارة الإلكترون (T_e) باستخدام طريقة النسبة بين الخطوط الطيفية . أما كثافة الإلكترون فقد تم استخدام معادلة ساها بولتزمان في حسابها. كما تم قياس معلمات البلازما الأخرى مثل تردد البلازما (f_p) وطول ديباي (λ_D) وعدد الذرات ضمن كرة ديباي(N_D) لوحظ طيف بلازما لل (:CdO Fe) للطاقات المختلفة عند نسب خلط 0.5 = X. بالاضافة الى ذلك تم دراسة درجة حرارة الالكترون وكثافتها كدالة لطاقات الليزر المختلفة. تراوحت نتيجة حساب درجة حرارة الإلكترون (1.160 − 0.420) الكترون فولت عند النسبة X=0.5 .

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1. Introduction

Laser-induced plasma spectroscopy (LIPS) is considered to be an established analytical technique used for the rapid determination of elemental composition of samples. LIPS can also be defined as a type of analytical technique of atomic emission spectroscopy with which any type of matter, whether in liquid, solid or gaseous state can be analyzed [1].Immediately after a laser beam hit a surface of a material, photons are released from the surface . In LIPS, when a laser beam interacts with a solid target, the laser excites and ionizes the target thus producing plasma. The identification of atomic and molecular species is achieved by studying their laser-induced plasma emission spectra [2,3]. The analytical efficiency of LIPS is highly influenced by the chosen experimental conditions such as duration of the observation time, pressure of the ambient gas, form and properties of the target and geometric configuration of optical instruments and by the laser parameters such as wavelength, pulse energy, length of the pulse. Atomic components emit distinctive light that is transmitted ,via optical fibers, to a spectrometer for analysis[4]. Recently, optical emission spectroscopy (OES) has gained a great deal of consideration for LIPS-dependent representation. For the optical emission spectrum, the ratio method(the ratio of the intensity of two spectral lines emitted from the same species) is one of the most common techniques. It is used in electron temperature measurements, although one of the best methods for measuring electron density is the Boltzmann plot method [5]. The ratio method was used in this experiment as a popular method for measuring the electron temperature at which it is possible to measure the strength of a pair of atomic or ion spectral lines at the same ionization stage.

The plasma temperature can be calculated (using the following equation) under the local thermodynamic equilibrium (LTE) [6]:

$$T = \frac{-(E_1 - E_2)}{k \ln\left(\frac{I_1 \lambda_1 A_2 g_2}{I_2 \lambda_2 A_1 g_2}\right)} \tag{1}$$

where I_1 and I_2 refer to the power, g_1 and g_2 are the statistical weight, A is the probability of the transition, λ_1 and λ_2 are the wavelength, E_1 and E_2 are the excited state energy values (eV), and k is the Boltzmann constant . The number of free electrons per unit volume represents the electron density. Saha-Boltzmann equation utilizes the same component and successive ionization stages of spectral lines. The Saha- Boltzmann equation is given as [7]:

$$n_e = \frac{I_1}{I_2*} 6.04 \times 10^{21} (T)^{3/2} e^{\frac{(E_1 - E_2 - X_Z)}{KT}} \tag{2}$$

Where:

$$I_{2*} = \frac{I_2 \lambda_2}{g_2 A_2} \tag{3}$$

Xz is the energy of ionization in eV, g_2 is the statistical transition weight from level (2) to level (1), λ_2 is the equivalent transition wavelength between level (2) and level (1), and A_2 is the probability of the transition from level (2) to level (1).

Whereas the frequency of the plasma from level (2) to level (1) is determined by the following equation[7]:

$$f_p = \sqrt{\frac{e^2 n_e}{m_e \varepsilon_o}} \tag{4}$$

f_p is the plasma frequency for electron (rad/sec), where ε_o is the permittivity of free space, m_e is the mass of an electron. It can be seen from this relation that the plasma frequency only depends on the plasma density. The frequency of plasma is one of the most important parameters of plasma [8].The duration of Debye is the fundamental characteristic of plasma action, as it describes the distance at which another charged particle is influenced by the individual particle, carrying a reverse charge within the plasma medium. Debye Length (D) is directly proportional to the square root of the temperature of the electron and inversely to square root of the density of the electron according to [9]:

$$\lambda_{D=}\sqrt{\frac{\varepsilon_O k_B T_C}{n_c q^2 c}} \cong 7430 * \left(\frac{T_e}{n_e}\right)^{1/2} \tag{5}$$

Depending on the electron density and the temperature of the electrons, the number of particles in the Debye sphere (N_D) is the second condition for the existence of the plasma when $N_D >>> 1$[10].

$$N_D = \frac{4}{3}\pi\lambda_D^3 n_e \tag{6}$$

The aim of this study is to analyse the optical emission spectrum of CdO: Fe nanoparticles and to the plasma parameters ($T_e, n_e, f_p, N_D, \lambda_D$).

2. Experimental Part

In this experiment, pulsed laser plasma was produced on solid target CdO: Fe. Figure 1 demonstrates the experimental set-up of laser induced plasma spectroscopy (LIPS).The laser beam was focused onto the target at an angle of 45 °. The laser beam evaporates the target material and ionizes it forming a plasma plume above its surface . For the determination of electron temperatures, densities, and plasma frequency, optical emission spectroscopy (OES) was used. Mathematically, the length of the numbers Debye and Debye was calculated. In every shot, the spectrometer that is used must be fast with the same response time.
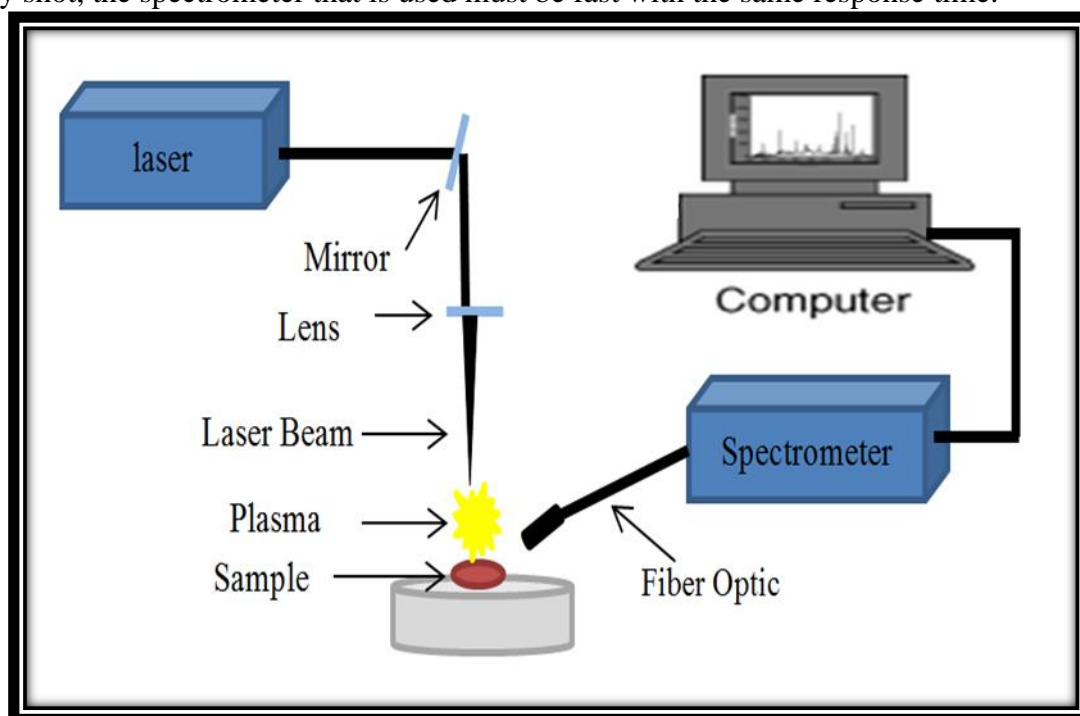

Figure 1-Schematic diagram of the experimental setup of LIPS

To generate the plasma, a Q-switched pulsed laser Nd: YAG with a wavelength of 532 nm, pulse energy of 200 to 500 mJ and a frequency of 6 Hz was used. The pulse laser energy was transferred using the streak light Q-switch delay through the laser controller and was measured by the energy meter. In the setup, a Surwit (S3000-UV-NIR) spectrometer, which has high efficiency objectives depending on the grinding used in it and responding to a wavelength of 200-900 nm, was used to evaluate the emission wavelengths. The spectrum of plasma with different values of energies was prepared by mixing CdO with Fe at a mixing ratio of X=0.5, . Each spectrum was obtained over a wavelength range of (300-700) nm. The findings were presented and compared with data from the National Institute of Standards and Technology (NIST database) [11].

3. Results and Discussion

Using the 532nm Nd-YAG laser optical emission spectroscopy technique, CdO: Fe plasma was analyzed. Figure 2 shows the emission spectra for (CdO: Fe) at X=0.5 induced by 532 nm
Laser of different energies(200-500 mJ). From these results, it is seen that the intensity of plasma increases with laser energy. This result agrees with that of Essa and Aadim[12].
Laser plasma, confined to air within the spectral range (300-700) nm with
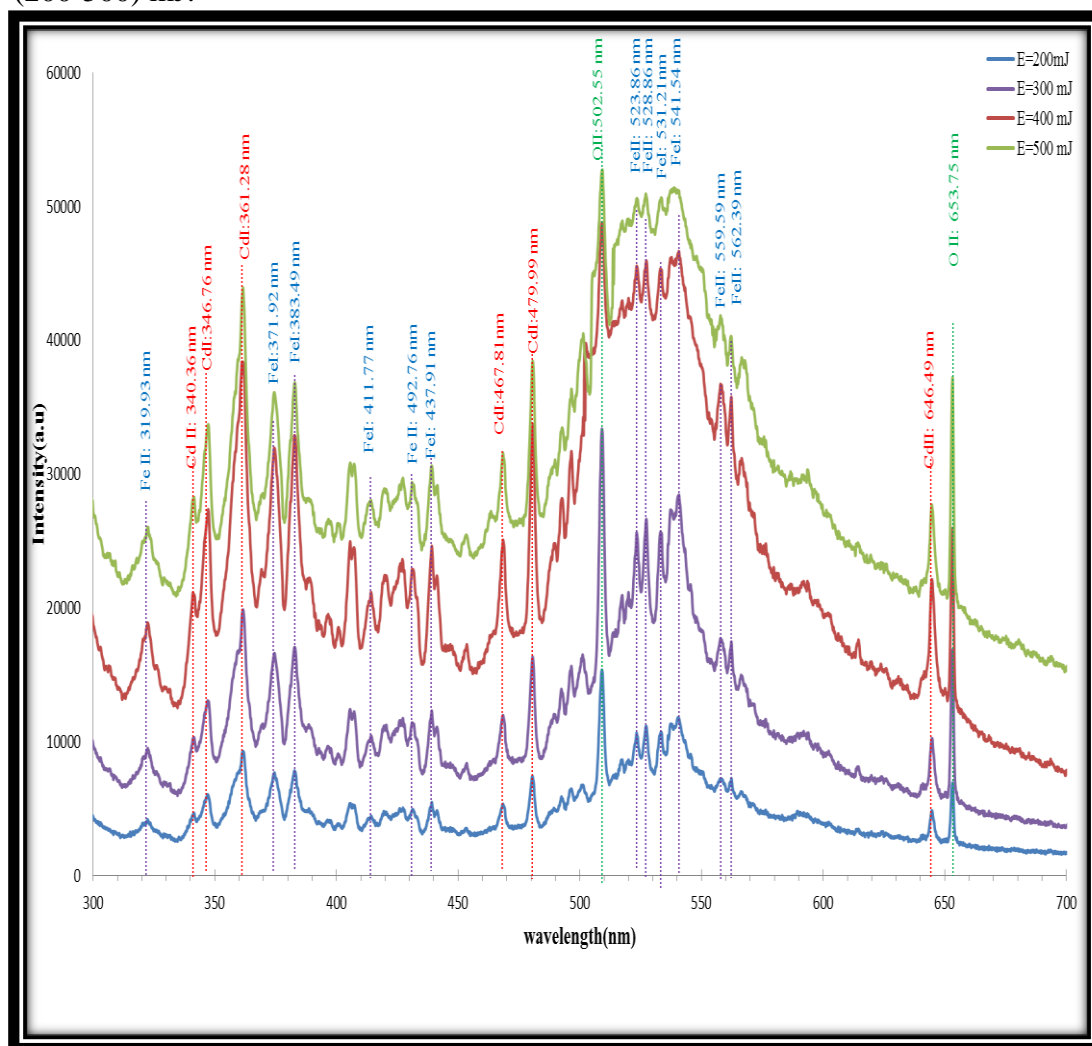 E = (200-500) mJ.

Figure 2-Emission spectra for (CdO: Fe) at X=0.5 in air.

induced by 532 nm laser, with different laser energies.

Table (1) shows the parameters for CdO: Fe plasma. The electron temperature of CdO: Fe plasma, calculated by Boltzmann plot using Eq (1) for laser energy E = (200-500) mJ, ranged from (0.420 to 1.160) eV, respectively. From this result, it is concluded that the electron temperature increases with increasing the laser energy. This result agrees with that of Khalaf and Hmood [13].

The electron density, calculated from by Saha- Boltzmann equation (Eq.2), ranged between 7.74 cm^{-3} and 8.26 cm^{-3} cm^{-3} for CdO: Fe plasma. It can be noticed ,From Figure 3, that electron density increases with the increase of the laser energy. This increase is due to the

increase of mass also ablation also the plasma frequency increase with laser energy . the values of the other plasma parameters such λ_D and N_D are listed in Table 1.

Table 1-CdO: Fe plasma parameters induced by 532 nm laser

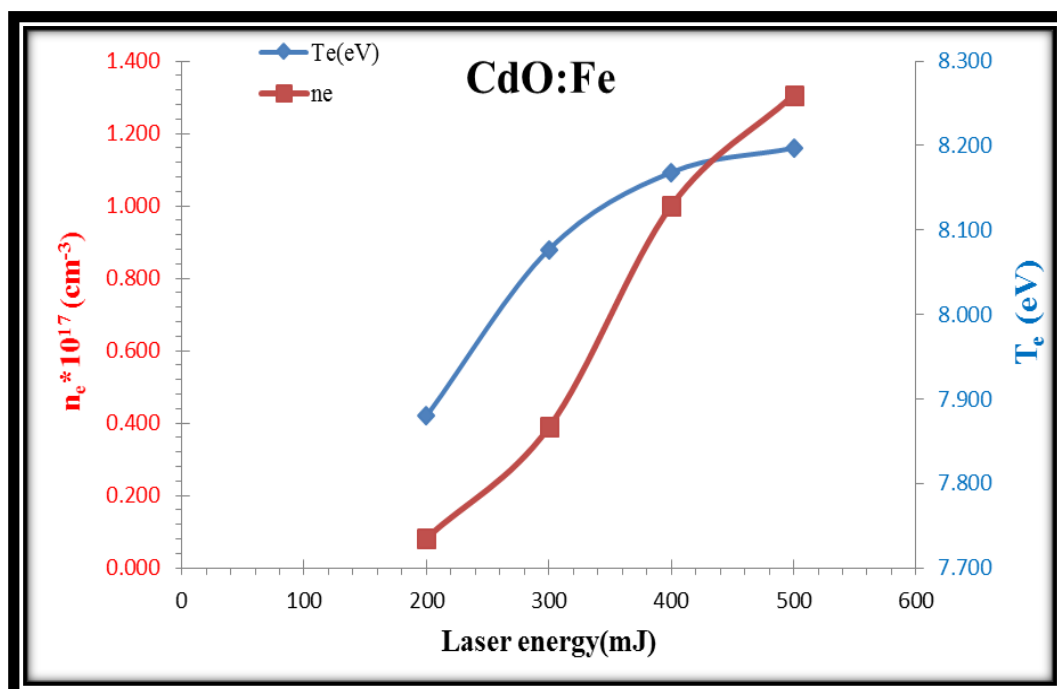| Laser energy (mJ)	T_e (eV)	$n_e \times 10^{17}$ (cm^{-3})	$f_p \times 10^{12}$ (Hz)	$\lambda_D \times 10^{-7}$ (cm)	$N_{D \times} 10^2$ (cm)
200	0.420	7.74	7.9	5.5	0.05
300	0.880	7.87	8.0	7.9	0.16
400	1.093	8.13	8.1	8.6	0.22
500	1.160	8.26	8.2	8.8	0.24

Figure 3- The electron temperature and electron density as a function of laser energy
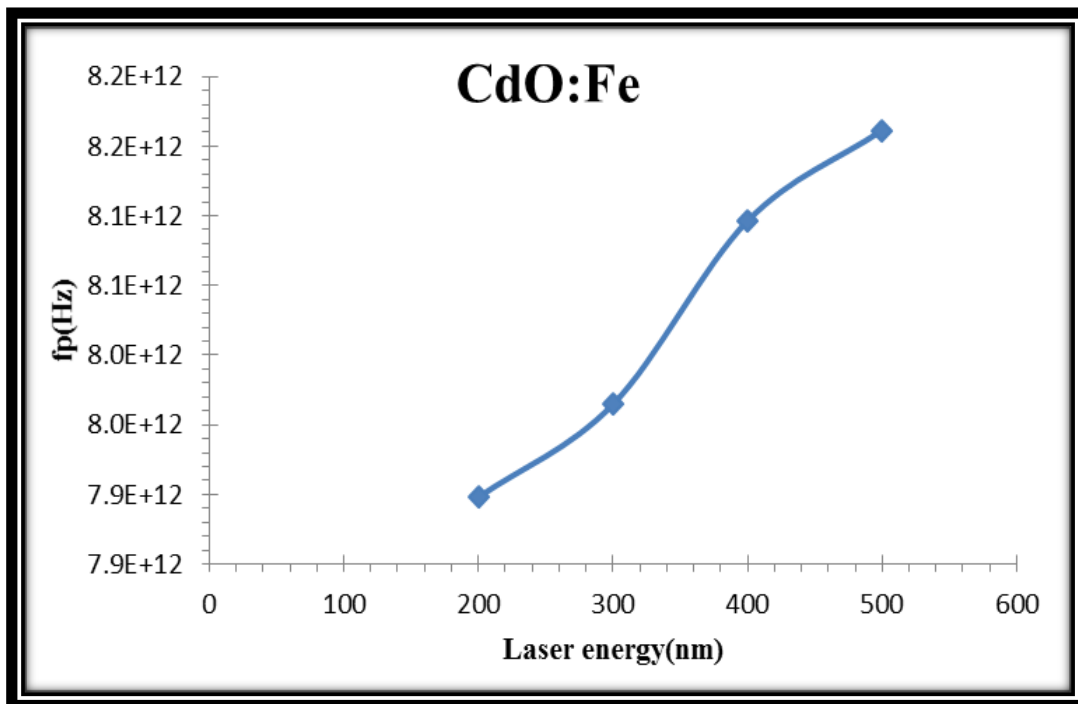
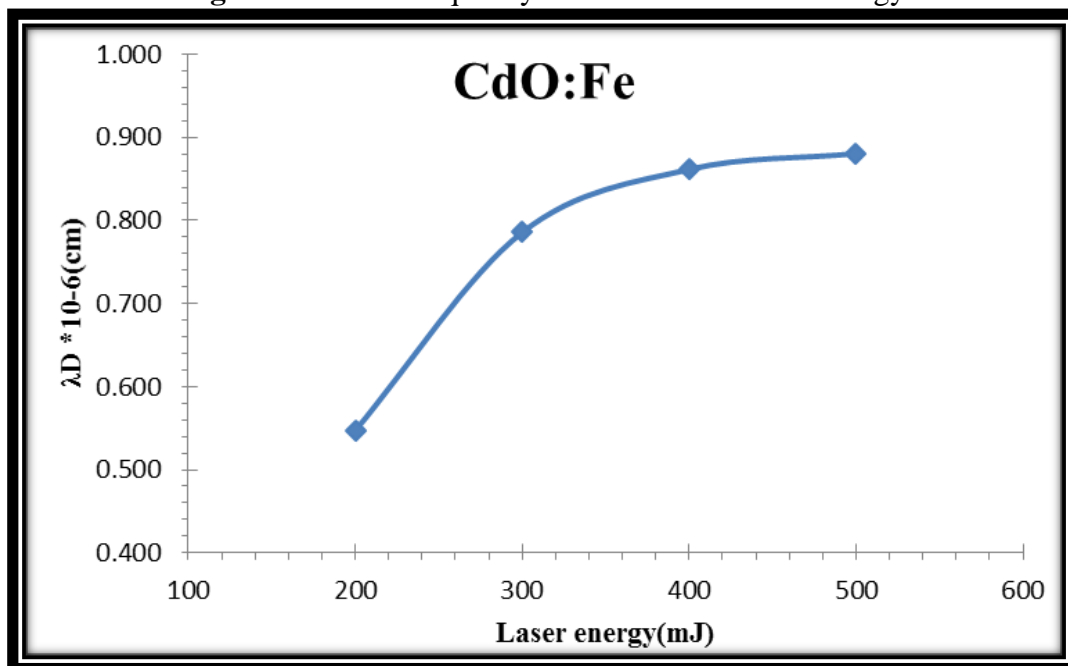**Figure 4-**Plasma frequency as a function of laser energy

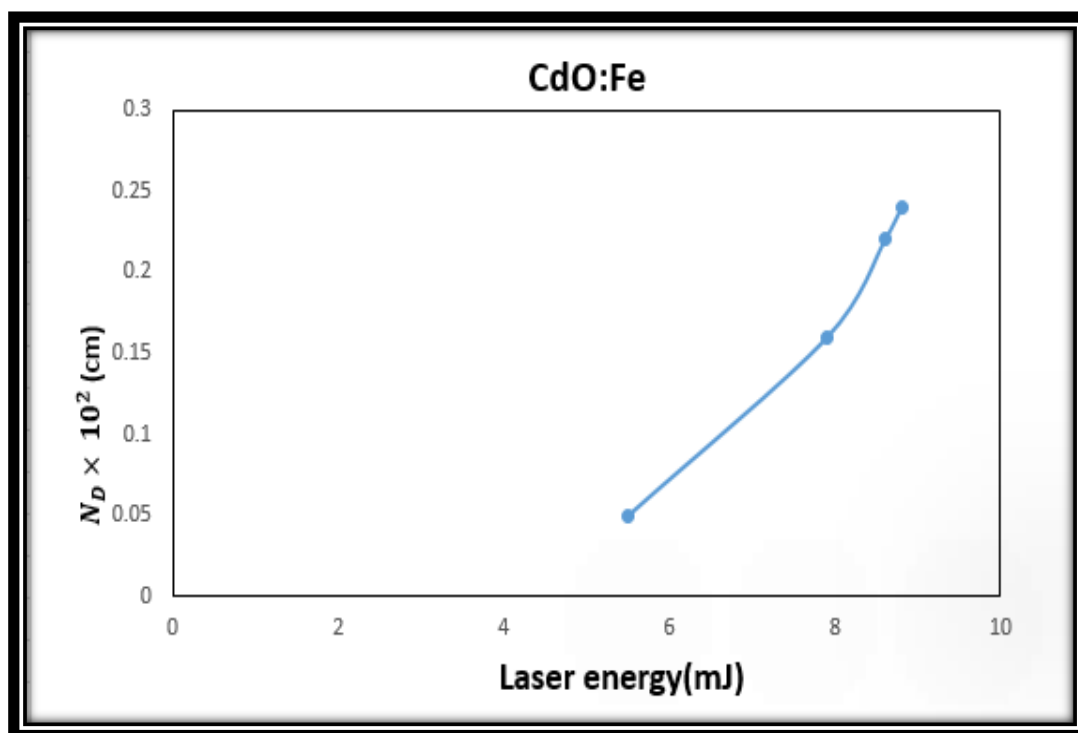**Figure 5-** Debye length as a function of laser energy

Figure 6- Debye number as a function of laser energy

4. Conclusions

   Plasma was produced using a Q-switched Nd: YAG laser at a wavelength of 532nm of different energies of (200-500) mJ. Optical emission spectral studies were conducted to determine the plasma parameter such as electron density and electron temperature. Plasma parameters ($T_e, n_e, f_p, N_D, \lambda_D$) have been estimated in terms of their laser energy dependence. The results indicated that all plasma parameter values increased with increasing atmospheric laser energy. It was found that all plasma parameters meet the plasma conditions.

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