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Characterization of Laser induced cadmium plasma in air

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Abstract

In this paper, the fundamental harmonic of a Nd:YAG laser (Q-switched 1064nm wavelength, 1 Hz repetition rate and 9 ns pulse duration) has been used for the ablation of cadmium samples in air at atmospheric pressure and the generation of the cadmium plasma. The experimentally observed lines of cadmium plasma emission have been used to calculate the plasma parameters such as (electron temperature (T_e), electron density (n_e), Debye length (λ_D) and plasma frequency (ω_p)). Line pair ratio of neutral species have been used for the electron temperature and electron density measurements. Plasma parameters were studied as a functions of laser pulse energy.

Keywords: cadmium plasma, electron density, Nd: YAG laser, plasma frequency, electron temperatural

خصائص بلازما الكادميوم المحتثة بالليزر في الهواء

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الخلاصة

في هذا البحث ، تم استخدام مواصفات الليزر نديميوم ياك ذ التردد الاساسي (مفتاح الكيو ذو طول موجي 1064 نانو متر، ومعدل التكرار وزمن النبضة 9 نانو) لاجتثاث او ترذيذ نماذج الكادميوم في الهواء والضغط الجوي لتوليد البلازما . ولوحظ عمليا خطوط انبعاث بلازما الكادميوم والتي استخدمت لحساب متغيرات البلازما مثلا (درجة حرارة الالكترون وكثافة الالكترون وطول ديباي وتردد البلازما). تم قياس درجة حرارة الالكترون وكثافة الالكترون من خلال خطين نسبة للمسافات الاعتيادية . وتم دراسة متغيرات البلازما كدالة لطاقة الليزر النبضي

Introduction

A powerful technique for qualitative and quantitative elemental analysis of gases, liquids and solid materials is Laser Induced Breakdown Spectroscopy (LIBS). Its principle is based on exciting matter to plasma state through irradiation by high laser pulses. The emitted radiation is influenced by the properties of the plasma so it gives a detailed picture of the basic structure elements and different processes in the plasma **[1,2]**. The diagnostics of the plasma can be done through the measurements of the electron temperature (T_e) and the plasma electron density (n_e). Optical emission spectroscopy has been used for years to determine the plasma parameters. A number of researchers have reported the measurements of the electron temperature by using the relative line ratio method **[3-5]**.

In this work, we have calculated the plasma parameters (plasma electron temperature (T_e), electron density (n_e), Debye length (λ_D) and plasma frequency (ω_p)) utilizing the Cadmium lines appeared

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during the interaction of the pulsed Nd:YAG (Q-switched) laser with solid Cadmium target. We also studied the dependence of the emission lines intensities of the cadmium plasma spectrum and the plasma parameters on the incident laser pulse.

Experimental setup

The experimental setup used in this work is described in figure -1. A Q-switched Nd:YAG laser (9 ns pulse duration and 1 Hz repetition rate) was used at the fundamental wavelength of 1064 nm. The pulse energy was varied from 200 to 600 mJ by the laser controller. The laser beam was focused through a 10 cm lens on the cadmium solid target and the target was manually rotated to provide a fresh area for the next laser shot. The light emission from the cadmium plasma was detected using an Ocean Optics (HR4000 CG-UV-NIR) spectrometer in the range (320-780 nm).The data acquired correspond to a single shot, averaged two times under the same conditions.

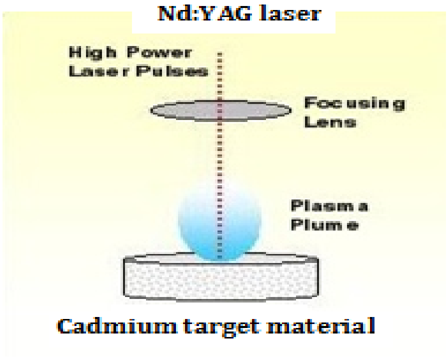

Figure 1- the experimental arrangement

Results and discussions

Plasma emission analysis:

Figure -2 shows a typical plot of the spectrum of the laser induced cadmium plasma plume at ambient air with a laser pulse energy of 500 mJ. The plasma spectrum consists of a number of neutral lines and the assignment of these lines was done using NIST database **[6].**

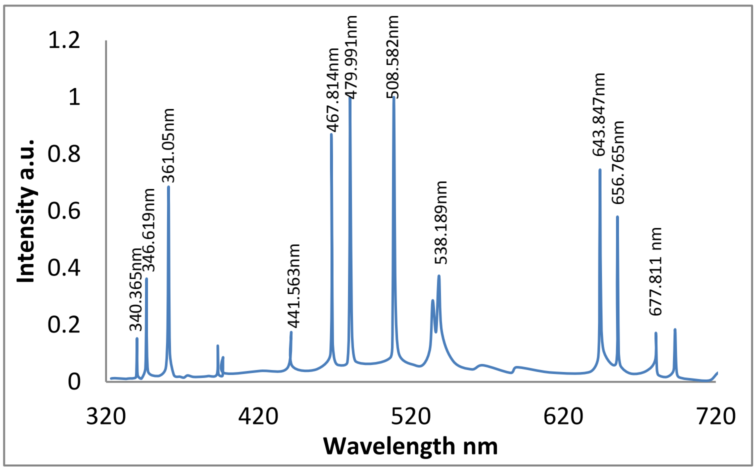

Figure 2- The emission spectrum generated by the 1064 nm laser with pulse energy of 500 mJ.

The highest intensity lines in the plasma spectrum are Cd I at 361.05 nm, 467.814 nm,479.99 nm, 508.582 nm, 643.847 nm and 656.765nm. some neutral cadmium lines at 340.365 nm, 346.619 nm, 441.563 nm, 538.189 nm and 677.811 nm have also been detected.

Figure -3 describes the variation of the cadmium lines intensities (at 340.365 nm, 346.619 nm, 398.193 nm and 643.847 nm) with laser pulse energy. From this figure, it is observed that the intensities of the emission lines increase slowly at (200 – 300 mJ) laser pulse, then it increased dramatically with increasing of the laser pulse energy. The increasing of the pulse energy means the increase of its absorption by the plasma leading to more ablation from the target and finally increasing of the emission line intensity.

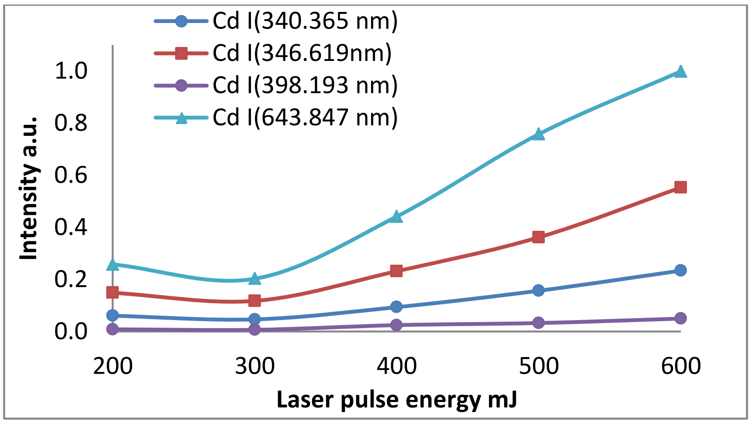

Figure 3- the variation of the emission line intensity with laser pulse energy.

Electron temperature diagnostics

The emission spectrum reveals noticeable lines which is useful for the estimation of plasma parameters such as electron temperature, electron number density, Debye length and plasma frequency. Under the assumption that the plasma is in local thermodynamic equilibrium (LTE), the measurement of the electron temperature can be done by the relative intensity of two lines emerging from the same kind of species and the same ionization stage **[7]**.

The electron temperature (T_e) can be determined from the following expression:[8]

$$T_e = \frac{E_1 - E_2}{K_B \ln\left(\frac{\lambda_2 I_2 g_1 A_1}{\lambda_1 I_1 g_2 A_2}\right)} \qquad (1)$$

where E, I, A ,g and λ are the upper level energy, line intensity, transition probability , the statistical weight for the upper level and wavelength respectively.

Figure 4- gives variation of the electron temperature of the laser induced cadmium plasma with respect to laser pulse energy. We noticed that as increasing the laser pulse energy from 200 mJ to 500 mJ, the electron temperature increases from 1.1 eV to 1.4 eV and saturates at higher laser pulse energies. This can be attributed to that the lines change from emission to absorption for spectra **[9]**.

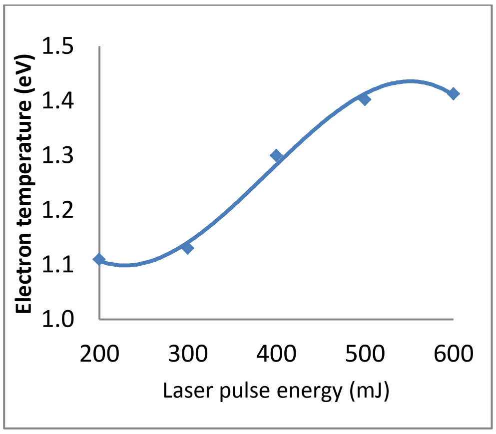

Figure 4-Electron temperature as a function of laser pulse energy.

Electron density diagnostics

When the plasma is sufficiently close to LTE conditions, the electron density (n_e) can be derived from the intensity ratio of two lines corresponding to different ionization stages of the same element (*Saha-Boltzmann method*)**.** The expression used for electron density calculation is:[8]

$$n_e = \frac{2(2\pi m_e k_B T_e)^{3/2}}{h^3} \frac{I^I_{mn} A_{ij} g^{II}_i}{I^{II}_{ij} A_{mn} g^I_m} e^{-\frac{E_{ion}+E^{II}_i-E^I_m}{k_B T_e}} \qquad (2)$$

Where m_e is the electron mass, k_B is Boltzmann constant, T_e is the electron temperature, h is Planck's constant, E_{ion} is the ionization potential of the neutral species in its ground state. Figure -5 describes the variation of the electron density with laser pulse energy .

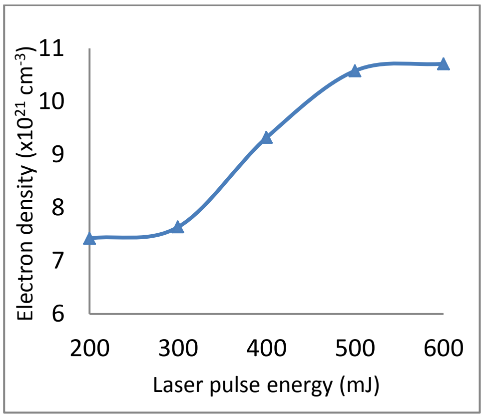

Figure 5- Electron density as a function of laser pulse energy.

From equation (1) and (2), we can see that the electron temperature and electron density are inter-dependent. Thus electron density increases gradually with the increasing of laser pulse energy.

Debye length calculation

Debye length of laser induced plasma is given as **[10]**:

$$\lambda_D = (\varepsilon_\circ k_B T_e / n_e e^2)^{1/2} \qquad (3)$$

where $\varepsilon_\circ$ is permittivity of free space, k_B the Boltzmann constant and e the electron charge. It can be showed that the Debye length varies with the term $(T_e/n_e)^{1/2}$ only. Figure -6 shows the variation of Debye length at different laser pulse energies. The amount of residual pulse energy which reaches the sample surface plays an important role in plasma expansion. It is dependent on the reduction of laser energy by the ablated matter and is called plasma shielding or Debye shielding. The process leading to the shielding is the absorption of laser energy by the electrons (inverse Bremsstrahlung) and multiphoton ionization.

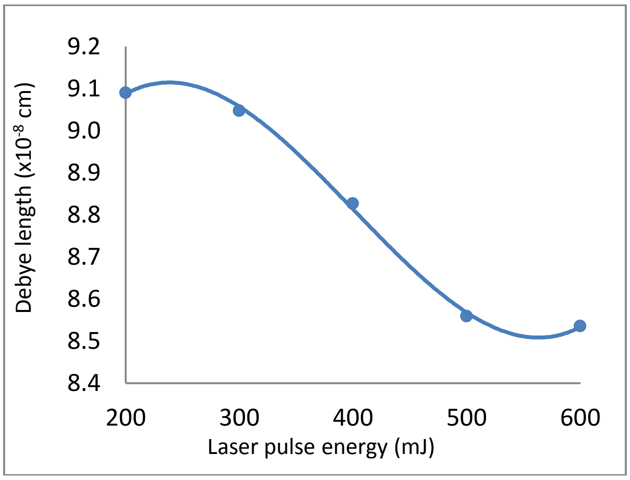

Figure6- the variation of Debye length as a function of laser pulse energy.

Plasma frequency calculation

Plasma frequency (ω_p) can be calculated as **[11]**:

$$\omega_p^2 = n_e e^2 / \varepsilon_\circ m_e \qquad (4)$$

Clearly, there is a different plasma frequency for each species. However, the relatively fast electron frequency is the most important. Figure-7 describes the frequency of laser induced cadmium plasma in air at a different laser pulse energies. one can observe that the plasma frequency increases with the increase of the laser pulse energy. The reason of this behavior is that the high laser pulse energy produces comparatively more plasma emission as a result of more material ablation. In this case, the plasma frequency increases as a result of increasing the electron density by increasing the absorption of laser in plasma through inverse Bremsstrahlung process.

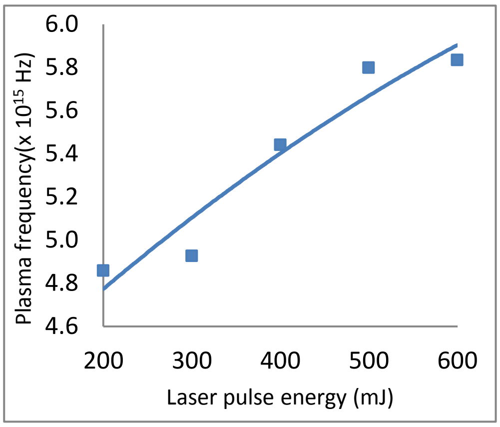

Figure7- the variation of plasma frequency as a function of laser pulse energy.

Conclusions

The optical emission spectroscopy method was used to analyze the emission spectrum of cadmium plasma generated via the interaction of Nd:YAG laser with a solid cadmium target in air at atmospheric pressure. One can observed that the intensity of neutral cadmium lines increased with increasing laser pulse energy. The plasma parameters (electron temperature (T_e), electron density (n_e), Debye length (λ_D) and plasma frequency (ω_p)) have been determined and found to be strongly dependent on the laser pulse energy

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