Influence of the Distance between Focusing Lens and Target Surface on the Characteristics of Laser-excited Lead Plasma

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Abstract:

The present work investigated the effect of distance from target surface on the parameters of lead plasma excited by 1064nm Q-switched Nd:YAG laser. The excitation was conducted in air, at atmospheric pressure, with pulse length of 5 ns, and at different pulse laser energies. Electron temperature was calculated by Boltzmann plot method based on the PbI emission spectral lines (369.03 nm, 416.98 nm, 523.48, and 561.94 nm). The PbI lines were recorded at different distances from the target surface at laser pulse energies of 260 and 280 mJ. The emission intensity of plasma increased with increasing the lens-to-target distance. The results also detected an increase in electron temperature with increasing the distance between the focal lens and the surface of the target in all laser energies under study. In addition, the electron number density was determined by using the Stark broadening method. The data illustrated that the electron number density was increased with increasing the distance from target surface, reaching the maximum at a distance of 11 cm for all pulse laser energy levels under study.

Keywords: LIBS, Plasma Temperature, Electron number Density, Stark Broadening, Boltzmann plot method.

تأثير المسافة بين الليزر والهدف على خصائص بلازما الرصاص المنتجة بالليزر

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الخلاصة

في العمل الحالي تم دراسة تأثير المسافة عن سطح هدف الرصاص على معلمات البلازما الرصاص المستحثة بالليزر Nd:YAG النبضي ذو طول موجي 1064nm وعرض نبضة 5ns في الهواء عند ضغط الجوي الاعتيادي وبطاق وبضة مختلفة. تم حساب درجة حرارة الالكترون بأستخدام طريقة Boltzmann plot للخطوط الانبعاث الطيفية PbI (369.03nm,416.98nm,523.48nm و561.94nm).حيث تم تسجيل خطوط الانبعاث PbI عند مسافات مختلفة عن سطح الهدف وعند طاقات الليزر 260mJ و 280 mJ. كشفت النتائج بأن درجة حرارة الالكترون تزداد مع زيادة المسافة بين عدسة التبئير وسطح الهدف ولجميع طاقات الليزر قيد الدراسة. بالاضافة الى ذلك, تم حساب الكثافة العددية للاكترون بأستخدام طريقة توسيع Stark. فقد بينت النتائج بأن الكثافة العددية للاكلتؤونات تزداد مع زيادة المسافة الفاصلة بين عدسة التبئير وسطح الهدف لتبلغ اعظم قيمة لها عند المسافة 11 cm لجميع طاقات الليزر.

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1. Introduction

In recent years, laser induced plasma spectroscopy (LIPS), or laser induced breakdown spectroscopy (LIBS), has been widely studied, as shown by many experimental and theoretical researches published on the topic [1-3]. LIBS has been increasingly involved in many research areas; for example, material production, biomedicine, military industry, pharmaceuticals, environmental monitoring, space applications, and diagnostic techniques [2,4,5]. The main activity of LIBS is the focusing of highly energetic laser pulses produced from a pulsed laser source on the target surface. Therefore, an approximately neutral plasma plume containing ions, electrons, atoms, or molecules is created on the surface of the target. The guided laser beam results in the evaporation, atomization, and ionization of the target's surface content, where the emitted radiation is used to detect the elemental composition of the samples [2,6]. This technique has several advantages over other traditional techniques of atomic emission spectroscopy; it is applicable to the study of conducting and non-conducting target samples and does not require sample preparation [4].

LIBS is used to calculate the temperature of the electrons and the number of plasma plume densities produced at the front of the target surface [2]. Most studies that were addressing LIBS temperature reported that the temperature of electrons appears to increase as laser wavelength, laser energy, pulse width, and ambient pressure increase [2].

Hongbing *et al*.[4] investigated laser-produced Mg plasma in the atmospheric air by a 1064 nm Nd:YAG laser. By employing Boltzmann plot method and the Stark expansion method, electron temperature and electron number density were calculated, respectively. They found that, along with the distance of the plasma expansion, electron temperature decreased with the increase in laser energy, whereas electron number density increased. Wang *et al*.[7] studied the effect of the distance between the target surface and the focusing lens on the temperature of Cu plasma caused by atmospheric Nd:YAG. They also applied Boltzmann plot method to calculate electron temperature. The results illustrated that, with the increase in lens-target distance, electron temperature firstly rose, and then dropped.

This work reports on the investigation of lead plasma generated by a 1064 nm Q-switched Nd:YAG laser in atmospheric air. We used Boltzmann plot method for determining electron temperature and Stark broadening method for determining electron number density of the produced Pb plasma. We report the effects of the distance between the focusing lens and target surface on these two parameters .

2. Materials and Methods

Figure 1 illustrates a schematic representation of the experimental arrangement of LIBS. The Pb plasma plume was created at atmospheric air from a lead target exposed to a pulse Nd:YAG laser with 1064 nm wavelength, 10 ns pulse duration, and two levels of pulsed laser energy (260, 280) mJ). A quartz lens with 15 cm focal length was utilized to focus the laser beam on the target surface to create a spot area of 1 mm^2. The lens was placed at a distance of 9, 10, 11, or 12 cm in order to understand plasma characteristics produced by different energies.

The Pb target's material purity was nearly 99.99%, which was previously well polished before being exposed to the laser beam.

The emitted spectra of the Pb plasma plume were collected by an optical fiber located at 45^0 of the laser light direction. The optical fiber was coupled to a THOR spectrometer. The experiment was performed under air and ambient pressure at room temperature.
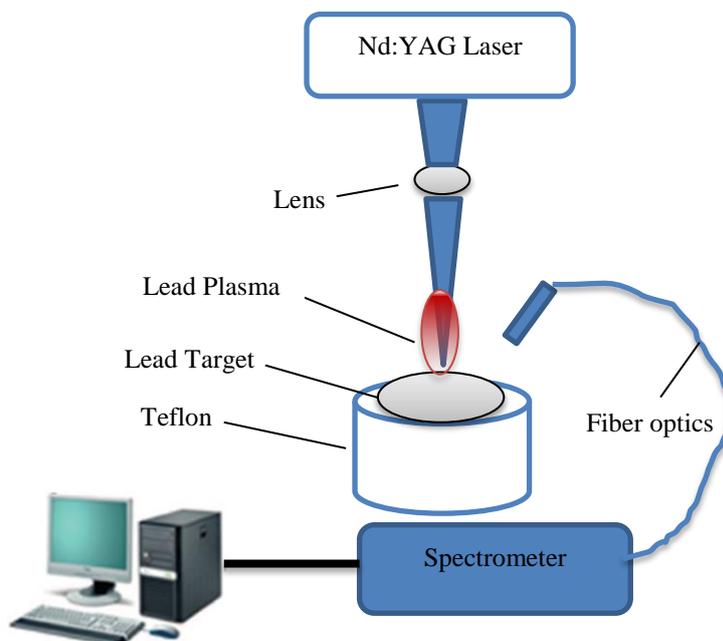
Figure 1-Schematic drawing of the experimental arrangement.

3.Results and Discussion
3.1 Emission Spectra of Lead Plasma

As a Q-switched Nd:YAG laser focuses at atmospheric pressure on a Pd target surface, emission intensity in the focal spot induces rapid local heating on the target surface of the Pb and creates a plasma that contains electrons, ions, atoms and molecules. Valuable references for improving the analysis techniques in the field of LIBS can be given by adjusting the distance between the focusing laser lens and the target surface. Two pulsed laser energies (260 and 280 mJ) at 9 cm to 12 cm with a rate of 1 cm were used to understand the effect of the distance between the focusing lens and target surface on the Pb plasma parameters. Figures 2, 3, 4, and 5 illustrate the influence of laser energy on the emission spectra of Pd plasma, recorded at different lens-to-target distances. The spectra detected in these figures show many peaks of neutral Pb (Pb I) at the wavelengths of 357.12, 363.47, 369.03, 371.89, 379.92, 395.86, 408.73, 416.98, 421.295, 511.08, 523.49, 539.52, 561.94, 573.66, 701.64, and 531.01 nm. The neutral emission lines of H I (at wavelength 434.04 nm) and the two peaks of H_2 I (at wavelengths 600.28 and 656.27 nm) also appear in these spectra. All levels of peak intensity increased with the increase in laser energy. The increase in absorbing energy of laser by the particles generated in front of the target was responsible for the increase in the line emission intensity. Consequently, these spectra indicate that the generated Pb plasma contained only atomic Pb emission lines, whereas no ionic emission of Pb appeared. This fact could be explained according to plasma generation processes, which occur within a very short time of less than one millisecond before atomization. Thus, the electrons extruded by atoms during the ionization are further arrested by ions through the recombination process. Therefore, the ions liberate their energy as photon emission due to recombination [8]. In addition, Pb atoms require high energy to be ionized (i.e. have high ionization energy)and thus the possibility of their ionization is low. Anyway, there are other features that can be noted from these figures. It is easy to note that the spectral line intensity increases to become maximum at the distance of 12 cm (below the focal length). The change of the lens-to-target distance is equal to the variation of the irradiance of the focused laser pulse beam. The effect of the variation of the distance between the focusing lens and surface target is similar to changing the spot size of focused laser beam in focusing geometry, where the longer distance is corresponding to smaller spot size, while the larger spot size occurs in the shorter distance

[7]. Therefore, the emission intensity of plasma spectra increases with increasing the lens-to-target distance.
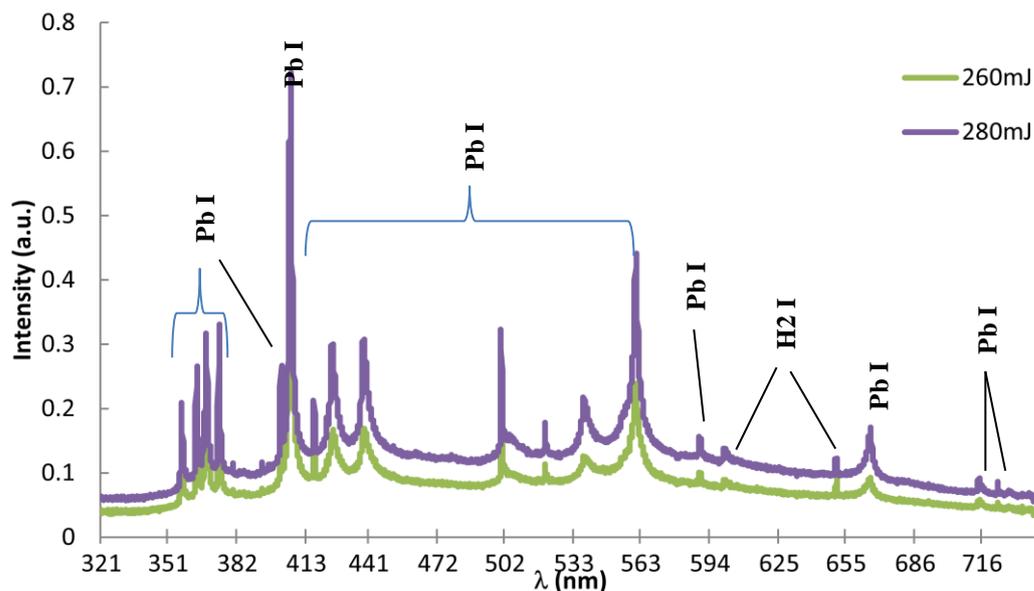
Figure 2: Emission spectrum of Lead plasma that detected for wavelength range 320-740nm at different laser energy and in distance 9cm between focusing lens and target surface.
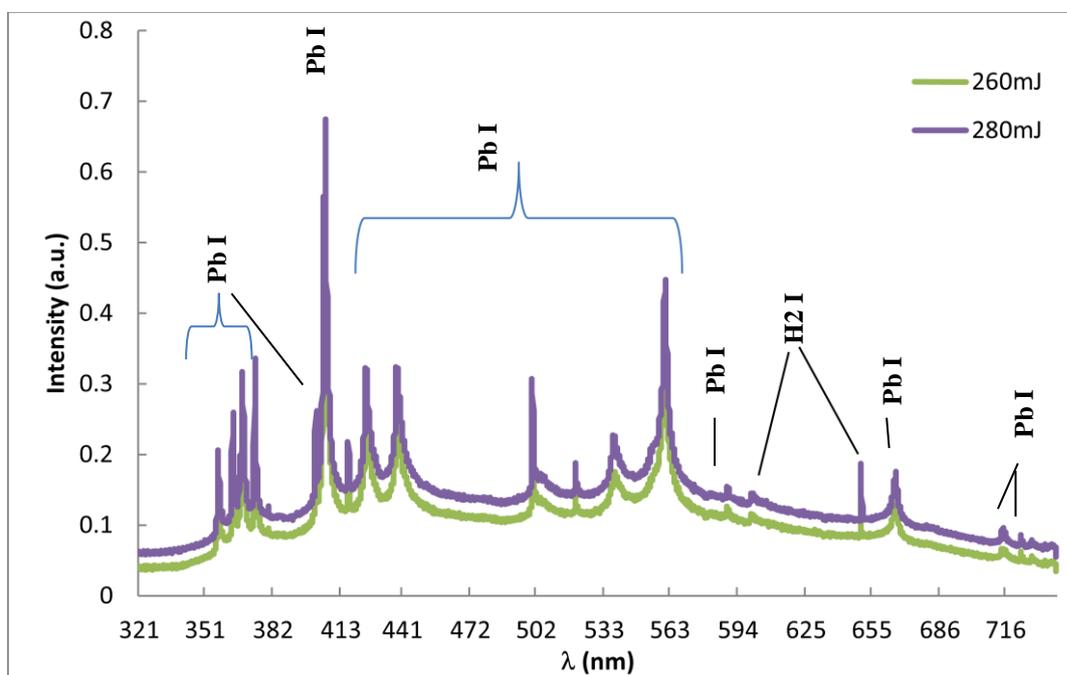
Figure 3: Emission spectrum of Lead plasma that detected for wavelength range 320-740nm at different laser energy and in distance 10 cm between focusing lens and target surface.
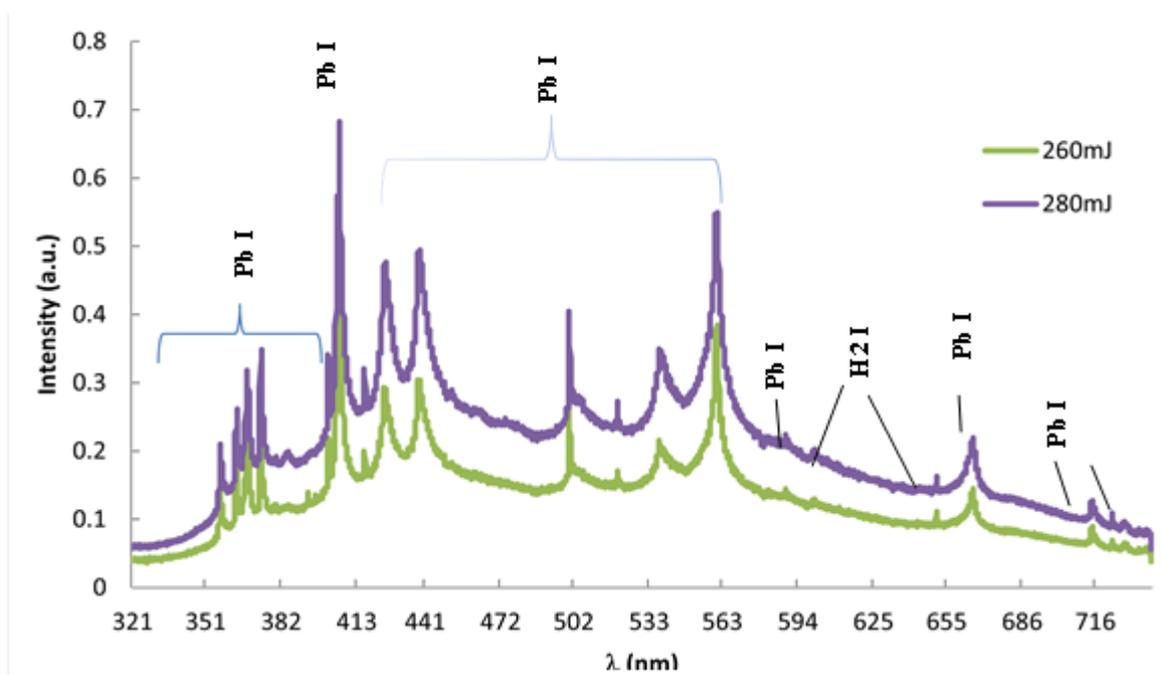
Figure (4): Emission spectrum of Lead plasma that detected for wavelength range 320-740nm at different laser energy and in 11 cm between focusing lens and target surface.
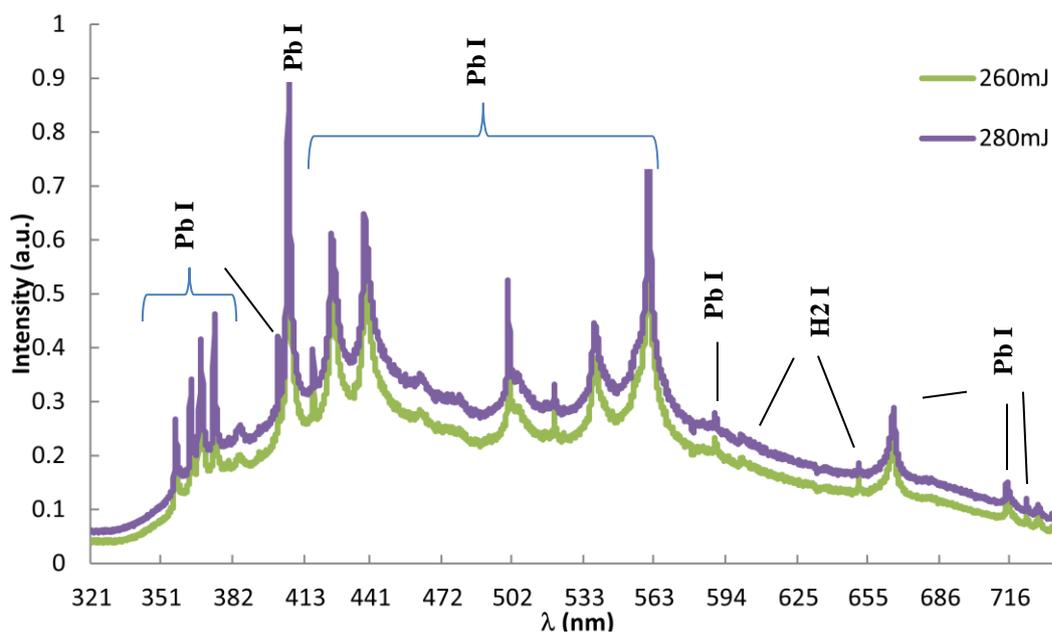
Figure 5: Emission spectrum of Lead plasma that detected for wavelength range 320-740nm at different laser energy and in distance 12 cm between focusing lens and target surface.

3.2. Measurement of Temperature and Number Density of Electrons

In the present work, emission spectral lines of lead were used to determine the electron temperature (T_e) and electron number density (n_e). These plasma characteristics are independent of each other, if one can consider that the local thermal equilibrium is satisfied. The most frequent method for calculating the T_e from relative intensities of the observed lines

is the Boltzmann plot, which is generally proportional to the population of the related upper levels, as follows [9-11]:

Table 1

Atom/ Ion	Wavelength (nm)	Ag (sec^{-1})	Lower Level Energy (eV)	Upper Level Energy (eV)
Pb I	369.034	2.24E+08	1.453	4.812
Pb I	416.984	6.00E+06	2.660	5.634
Pb I	523.486	3.52E+08	4.455	6.823
Pb I	561.944	2.54E+08	5.055	7.261

$$\ln\left(\frac{I_Z \lambda_{ki,Z}}{g_{k,Z} A_{ki,Z}}\right) = -\frac{1}{kT_e} E_{kZ} + \ln\left(\frac{hcL_{n,Z}}{4\pi p_z}\right) \tag{1}$$

Here, Z, h, k, c, L, $E_{k,z}$, and $g_{k,Z}$ refer to the ionization state of the species (where z=0 and 1 correspond to the neutral and singly ionized atoms, respectively), Planck constant, Boltzmann constant, speed of light, characteristic length of the plasma, the energy, and degeneracy of the upper energy level k, respectively. P_Z is the partition function of the species in the ionization stage Z. I_z is the integrated intensity of a spectral line occurring between the upper energy level k and the lower energy level i of the species in the ionization stage Z in the optically thin plasma. A plot of $\ln\left(\frac{I_Z \lambda_{ki,z}}{g_{k,z} A_{ki,z}}\right)$ versus E_k gives a straight line of slope $1/kT_e$. According to equation (1) and different spectroscopic parameters of identified lead emission lines, brought from the National Institute of Standards and Technology (NIST) database tabulated in table (1), the influence of laser pulse energy on the electron temperature was calculated in different focusing lens –target distance and plotted in figure (6).
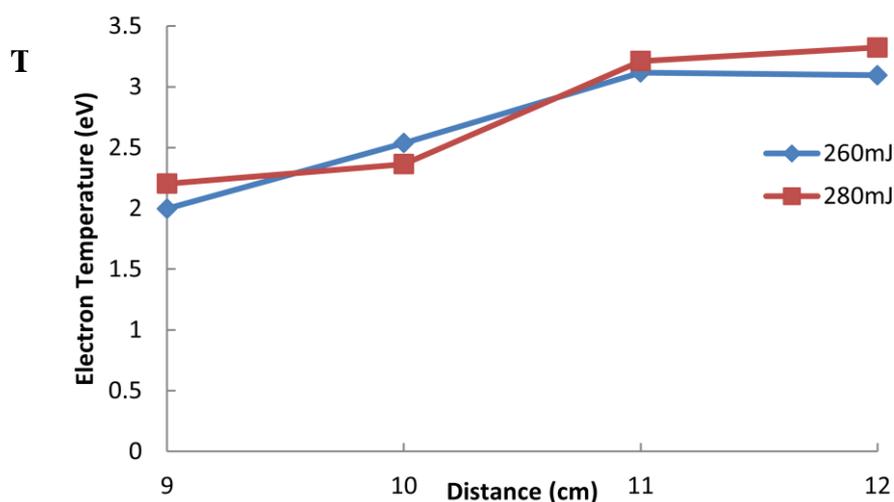
Figure 6- Variation of electron temperature with the distance from lead surface at variable laser energies.

It is observed from figure (6) that electron temperature has minimum value near the lead target and increases with increasing the distance of the focusing lens from the target surface. The temperature of the electron was increased from 1.99 to 3.1eV when the laser energy was 260 mJ and from 2.2 to 3.3 eV when the laser energy became 280 mJ. This result means that the thermal energy of electrons was rapidly converted into kinetic energy near the surface of the target. The increase of T_e with increasing the distance between the focusing lens and the target is strongly dependent on the spot size in the laser-induced plasma. When the lens-to-target distance is small (large spot size), the plasma spreads in the lateral and axial directions

due to the laser's greater cone angle, forming a spherical structure. When the gap is wide (small spot size), however, the plasma's vertical axis ratio decreases, resulting in a stream-like shape. The absorption of the tailing of the laser pulse energy is different since the entire plasma is heated to a higher temperature by the tailing of the laser pulse. The different lens-to-target distances produce the different shapes of the plasma. Furthermore, the majority of the energy from the laser pulse's tailing is absorbed by the plasma's front component, while a portion of the tailing pulse's energy is consumed to further ionize the plasma.

For the calculation of the number density of electron, we assume that the generation plasma must satisfy the local thermal equilibrium condition (LTE). Stark broadening represents the broadening of the spectral lines and the shift of the wavelength which occurs from the collision between the emitting atoms with the ions and electrons of plasma particles. This type of broadening is the most widely used to evaluate of n_e, as in the following equation [8, 12]:

$$n_e = \frac{(\Delta\lambda_{1/2} \times 10^{16})}{2W} \tag{2}$$

where $\Delta\lambda_{1/2}$ is the full width at half maximum (FWHM) of the emission line based on Stark broadening and W is the electron impact parameter, which was described in details by Griem [13]. According to equation (2), the electron number density is calculated versus the distance of the target from Pb surface for different laser energies. Widths and intensities of the observed Pb emission lines are directly linked with laser energy and both quantities are directly proportional to each other. Figure (7) demonstrates the variation in electron number density with the distance between the focusing lens and the target surface at different pulse laser energies.

One can depict that the number density of electrons varies with the distance from target surface of both laser energies. The electron number density first increased to a maximum value at the distance of 11 cm and then reduced far away from the laser target at both laser energies. The value of n_e increased sharply from 7.59×10^{16} cm^{-3} to 1.09×10^{17} cm^{-3} for 260 mJ and from 4.81×10^{16} cm^{-3} to 1.49×10^{17} cm^{-3} for 280 mJ. Then, it decreased from 1.09×1017 cm^{-3} to 9.25×10^{16}cm^{-3} for 260 mJ and from 1.49×10^{17} to 1.12×10^{17}cm^{-3} for 280 mJ. The increase of n_e is expected to occur due to the fact that plasma particles absorb laser photons through the inverse Bremsstrahlung process and then cause heat in the plasma plume, which causes the ionization of air around the target. This result agrees with the results reported earlier[14].
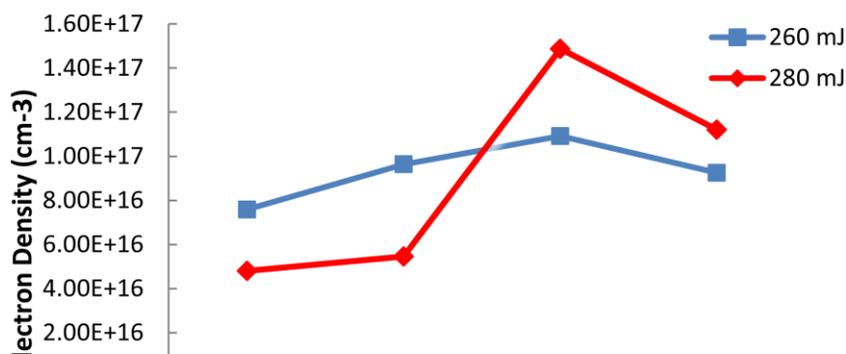
Figure 7-Variation of electron density with distance between focusing lens and target surface for different laser energies.

4. Conclusions

In this work, Pb plasma was induced by using Q-switched Nd:YAG laser at the fundamental wavelength with different energies resolved at different lens-target distances. The emission

spectrum of Pb plasma shows only transitions of neutral lead. Also, a weak peak of hydrogen molecule appears in this spectrum in all laser pulse energies and lens-to-target distances under study. The emission intensity of plasma spectra increases with the increase in the laser-target distance. The temperature of the electron, determined by the Boltzmann plot method, is raised far away from the target in all laser energies under study. Electron number density, calculated by Stark broadening parameter, increases to maximum at 11 cm distance from the target surface using both laser energies under study.

5. References

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