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The Electron Temperature and The Electron Density measurement by Optical Emission Spectroscopy in Laser Produced Aluminum Plasma in Air

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Abstract

In this work the Aluminum plasma in Air produced by Nd: YAG pulsed laser, ($\lambda = 1064$ nm, $\tau = 6$ ns) has been studied with a repletion rate of 10 Hz. The laser interaction in Al target (99.99%) under air atmosphere generates plasma, which is produced at room temperature; with variation in the energy laser from 600-900 mJ. The electron temperature and the electron density have been determined by optical emission spectroscopy and by assuming a local thermodynamic equilibrium (LTE) of the emitting species. Finally the electron temperature was calculated by the Boltzmann plot from the relative intensities of spectral lines and electron density was calculated by the Stark-broadening of emission line.

Keywords: Nd: YAG pulsed laser, Generation Aluminum Plasma, electron temperature and electron density, optical emission spectroscopy.

قياس درجة حرارة الالكترون والكثافة الالكترونية بواسطة تحليل طيف الانبعاث الضوئي لبلازما الالمنيوم المنتجة من الليزر النبضي في الهواء

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الخلاصة

في هذا العمل تمت دراسة بلازما الألومنيوم في الهواء الناتجه بواسطة الليزر النبضي : Nd –YAG (λ = 1064nm، τ = 6 ns) بمعدل 10 هرتز. تفاعل الليزر في منطقة الهدف Al (99.99٪) في الهواء الطلق يولد البلازما، التي يتم إنتاجها في درجة حرارة الغرفة. مع اختلاف في طاقة الليزر 600–900 ملي جول. وقد تم تحديد درجة حرارة الإلكترون وكثافة الإلكترون بواسطة طيف الانبعاث الضوئي وبافتراض نظرية التوازن الحراري الموضعي (LTE) لمناطق الانبعاث. وأخيرا تم حساب درجة حرارة الإلكترون من مخطط بولتزمان للخطوط الطيفية،وتم حساب كثافة الإلكترونات بواسطة نظرية توسيع ستارك لخط الانبعاث.

1. Introduction

The laser induced breakdown spectroscopy (LIBS) technique is one of the potentially growing applied techniques used in the field of elemental analysis, because of its simplicity and non-contact nature. Its basic principle is based on exciting matter (solid, liquid or gas) to plasma state through irradiation by high power laser pulses. The diagnostics of the plasma can be done through the measurements of electron density (n_e) and electron temperature (T_e). The plasma can be diagnosed by the optical emission spectroscopy (OES). The measurement of the electron density through Stark broadening effect requires a line which is free from self absorption. Self absorption occurs in general in any kind of system capable of emitting radiation, such as plasma. Moreover, the formation of the plasma in air shows, in general, a strong gradient of temperature due to the cooling effect of the surrounding air [1]. The electron number density is an important plasma parameter, crucial to the

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understanding of plasma characteristics and establishing equilibrium status [2].Aluminum nitride AlN is of interest in the industry because of its excellent electronic, optical, acoustic, thermal, and mechanical properties [3].The irradiation of focused, high-power femtosecond laser on a gas or solid medium can form laser-induced plasma. This plasma can be used in various applications, such as elemental analysis based on plasma emission, which is called laser spark spectroscopy or laser-induced breakdown spectroscopy (LIBS). Compared with other diagnostic techniques that detect various transient processes. Phenomena, the optical emission spectroscopy (OES) of the laser-induced plasma technique with high temporal and spatial resolution has considerable advantages to obtain information about the formed species, as well as to study the physical dynamics of the plasma expansion [4]. The laser beam intensity at the surface for Al processing is often high enough for plasma to form. This plasma consists of vaporized material and ionized ambient gas. One of the interesting side effect of the plasma is the enhanced or reduced coupling, which can be taken place when flux in the order of 108 Wcm^{-2} or greater is achieved [5]. Laser-induced breakdown spectroscopy (LIBS) is a popular technique because of its speed, simplicity, and usually inexpensive hardware. Additionally, LIBS requires little or no sample preparation and can provide simultaneous multi-element analysis Thus, it is not surprising that LIBS has been used for a wide variety of applications, such as material analysis, environmental monitoring, forensics, biological identification even characterization of fossils and works of art. Typically, these applications occur under standard Earth atmospheric conditions (i.e., 760 Torr). However, interest in LIBS under other atmospheric conditions has been a growing area of study for both fundamental knowledge and challenging applications [6]. The calculation of T_e was carried out under the assumption that the plasma is in LTE. In a transient system, such as the plasma formed by a pulsed laser beam, LTE is said to exist if the time between collisions of the particles in the plasma is small compared with the duration over which the plasma undergoes any significant change. When electron collisions are the major processes of de-excitation, the system is said to be LTE. It is clear that LTE will be approached only at sufficiently large particle densities [7]. Plasma temperature and electron density are two key parameters of the plasma. Moreover, the temporal evolution of plasma temperature and electron density under different ambient pressures are of prime importance, due to the fact that many kinetic reaction rates depend directly or indirectly on these two parameters. Under the assumption of the local thermodynamic equilibrium (LTE) model, the plasma temperature can be estimated by using relative intensities of the emission lines from the same atomic or ionic species. In LTE plasma, if level populations are distributed according to the Boltzmann law, the relative intensity of the emission line is expressed by [4,8]:

$$ln\left(\frac{\lambda I}{A_{ki} g_k}\right) = C - \frac{E_k}{kT_e} \qquad (1)$$

where I, λ, A_{ki}, g_k, E_k, k and T_e are relative intensity, wavelength, transition probability coefficient, statistical weight for level k, energy of the upper level, Boltzmann constant and electron temperature, respectively. C is a constant in our experiment. In Eq. (1), all of the temperatures are assumed to be equal, i.e., $T_e = T_{ion} = T_{plasma}$. With the measured relative intensities of several emission lines, a plot of the logarithmic term of several emission lines in the equation versus E_k can be obtained. It is a straight line with a slope equal to $1/kT_e$. Then, T_e can be obtained readily. The emission species (atoms or ions) in the plasma are influenced by the electric fields produced by the fast moving electrons and relatively slowly moving ions. This perturbing electric field acts on atoms or ions and induces a shift on their energy levels, which causes a broadening of the plasma emission lines, which is called Stark broadening. Electron density can be extracted from the spectral line width of the Stark-broadening of emission line. In our case, the spectral line width is dominated by the Stark-broadening effect, rather than Doppler and collisional broadening or the instrumental broadening. The electron density is related to the full-width at half-maximum (FWHM) of the Stark-broadened line, which is given by [4,8]:

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

where n_e is the electron density (cm^{-3}), ω is the electron impact width parameter. The impact factor is taken from Ref. [9].

2. Experimental Setup

The used experimental setup is shown in Figure-1. Nd-YAG laser was used at the emission wavelength of 1064 nm. The energy per pulse at the target surface was fixed at 600, 700, 800 and 900 mJ. The power-meter was used to An absolutely calibrated Nd-YAG laser. The laser focused on the target by a quartz lens of focal length of 10 cm. An aluminum slab of 2mm thickness was used as the target and the laser beam from pulsed Q-switch Nd-YAG pulse laser was focused into the air at atmospheric pressure. The laser emitted at the wavelength of 532 nm and pulses had duration of 6 ns. The emission from the induced spark was registered by the Thorlabs OSA spectrometer.

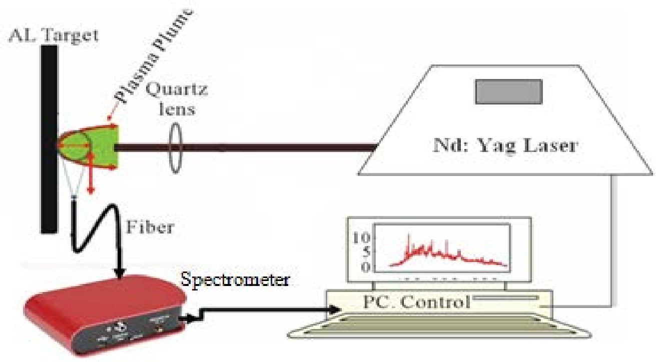

Figure 1- A schematic illustration of the experimental setup

3. Results and Discussions

The emission spectra of the plasma produced at the Al surface were recorded from 600 to 900 mJ, where generated by Q-switched Nd:YAG laser irradiance.

The recorded spectrum at different energy at duration time 6 ns is shown in Figure-2a and Figure-2b. The intensity peaks for Al II are rising as the energy is increased. The existence of the Al II ionic lines can be in the short wavelength region. Six Al II lines at (364.92, 624.336, 683.714, 704.208, 358.7 and 327.5) nm were considered for measuring the electron temperature and electron density, as a function of the laser energy.

In order to evaluate the electron temperature we have used the spectral radiances from the Al II ionic lines at 364.92 nm, 624.336 nm, 683.714 nm, 704.208 nm, 358.7 nm and 327.5 nm to construct the Boltzmann line with the result as shown in Figure-3. From equation (1), C in LTE model is very small therefore, the existence of the points on the straight line with slope indicating the electron temperature. We have determined the electron temperature (T_e) for different values of the laser energy by using mode of the Nd: YAG laser at 1064. We have observed that the intensities and the widths of the spectral lines increase with the increase in the laser energy. The electron temperature has also been determined by varying the energy of the laser from 600 to 900 mJ, for the fundamental (1064 nm) harmonic. The temperature increases from 1.7281 eV to 3.1174 eV as shown in the Figure-4.

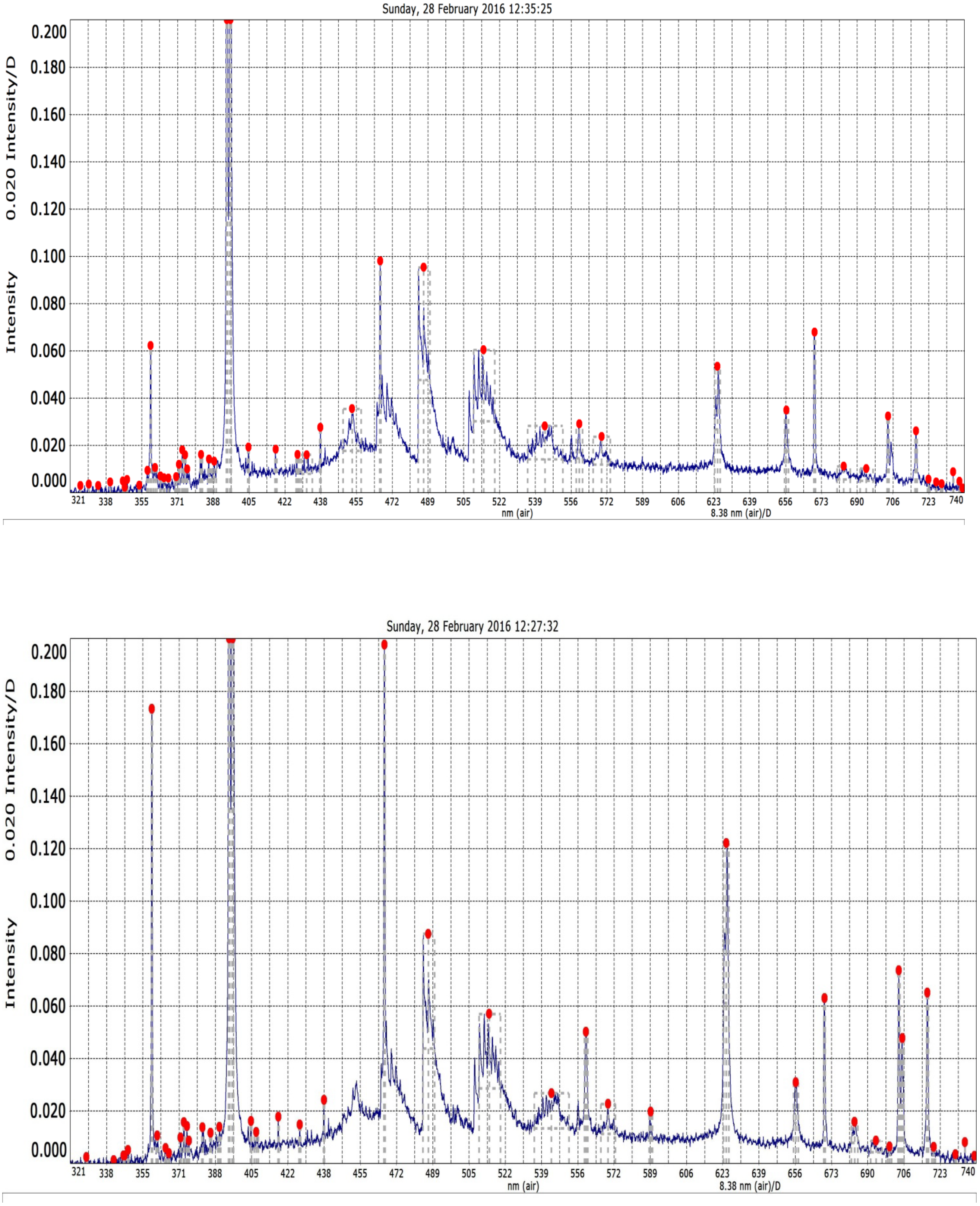

Figure 2a- The emission spectra for Al plasma at different energy 600 and 700 mJ.

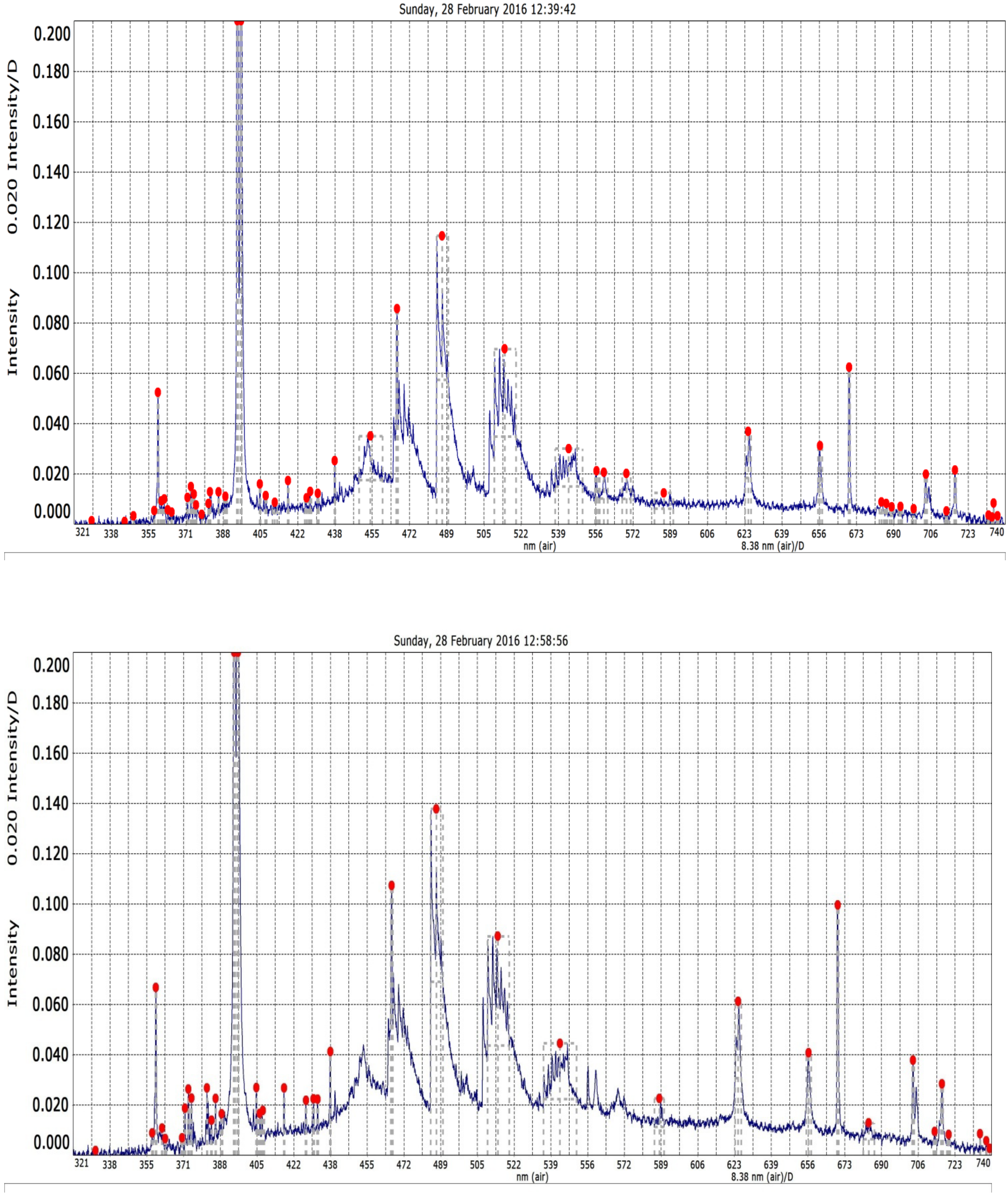

Figure 2b- The emission spectra for Al plasma at different energy 800 and 900 mJ.

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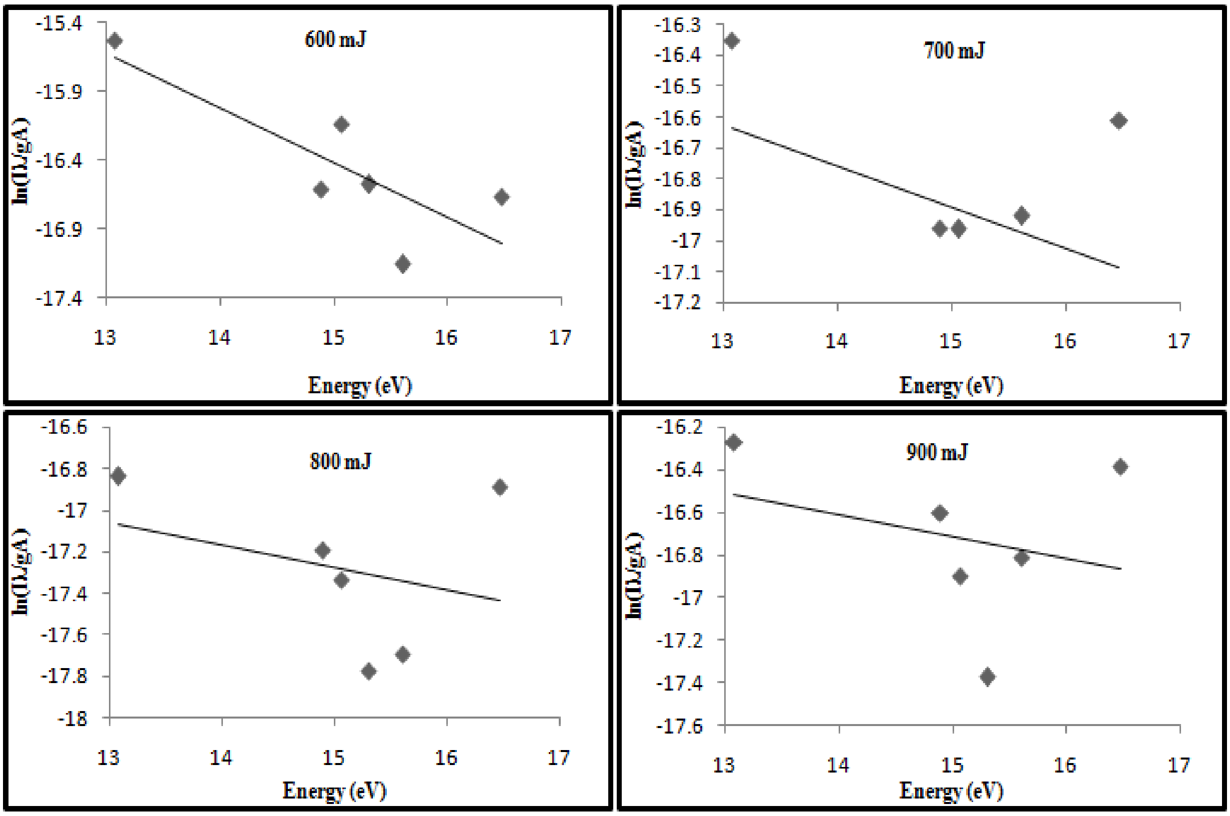

Figure 3- The Boltzmann plot utilizing the Al II ionic lines (364.92 nm, 624.336 nm, 683.714 nm, 704.208 nm, 358.7 nm and 327.5 nm) at different laser energy.

The electron density was calculated from Al II at the 358.7 nm line, according to Equation (2).
In the Figure-5, the variation in the electron number density can be as a function of the laser energy. In fundamental harmonic (1064 nm) of the laser, with the variation of laser energy from 600 to 900 mJ, the corresponding electron number densities varies from 7.21×10^{15} to 9.69×10^{15} cm^{-3}. The observed increase in n_e and T_e by the increase of the laser energy is due to the absorption or reflection of the laser photon by the plasma, which depends upon the plasma frequency.

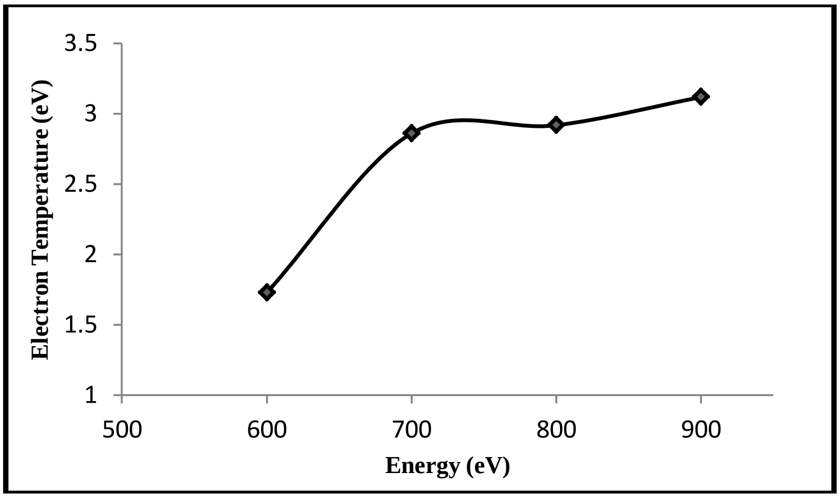

Figure 4- Variation of the electron temperature (Te) with the laser energy.

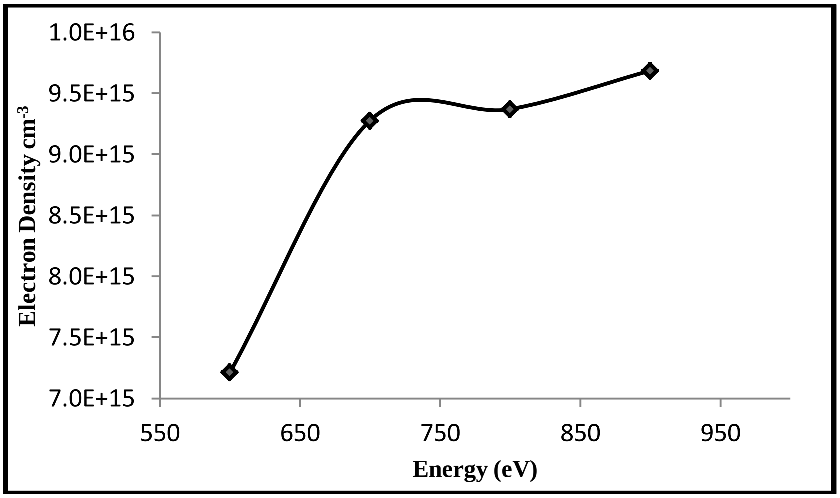

Figure 5- Variation of the electron number density with the laser energy using the fundamental harmonic (1064 nm) of the Nd: YAG laser.

4. Conclusions

We have used a Q-switched Nd: YAG laser to study the laser produced Aluminum plasma. The electron temperature and the electron number density can be determined using OES technique. The results indicate that both electron temperature and electron number density increases along the direction of propagation of the plasma. The results demonstrated that temperature and electron density depend strongly on the laser energy.

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