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Spectral and electrical characterization of an aluminum plasma laser between the flat plates of a capacitor

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Abstract. The spectral and electrical diagnostics of plasmas generated by laser were performed by using the LIBS technique accompanied with simultaneous measurements of the electrical signal in the perturbations of an aluminum plasma laser, submerged in electric fields transverse to the direction of the beam laser produced by a parallel flat plates capacitor. In this paper, we show that temperature and electron density in the formed plasmas are directly proportional to the energy deposited by the beam laser on the sample. Depending on the separation of the plates, the analysis of the electrical signal shows that it decays approximately with the inverse of the squared distance and it also decays with the number of laser pulses for plasmas produced on the same region of the solid sample.

1. Introduction

The technique of laser-induced rupture spectroscopy (LIBS) is based on the appropriate generation, the spectral and temporal analysis of the plasma produced by focusing the radiation of a laser pulse on a sample, whether solid, liquid or gas. The result of spectral analysis provides information on sample composition and, by using adequate calibration, the quantitative analysis is possible [1,2]. Furthermore, the spectral information of the LIBS spectra can be used as a powerful tool for the diagnostic of plasmas, determining electron and ionic temperature and density [3,4]. Optical Spectroscopy measurements -used as a noninvasive plasma diagnostic technique- are usually applied to determine such plasma parameters.

Previous work carried out by different researchers has demonstrated the potential of the LIBS technique for the detection and elemental determination of aluminum and alloys targets [5-7]. Likewise, aluminum plasmas-laser parameters, i. e. temperature and electron density, have been calculated for plasmas produced under different working and application conditions of the spectroscopic methods [8], [9,10].

In a previous paper [10], we reported the analysis of electrical, optical and spectral measurements of plasmas produced by laser in air, under the influence of electric fields generated by a parallel flat plates capacitor. The study included the analysis of the electrical signal in terms of the energy deposited by the beam on the sample, the voltage applied at the capacitor plates and the separation between the plates.

The plasma-laser of the different samples, under the effect of electric fields, has been subject of various studies to investigate their behavior caused by the perturbations of the electric fields. An early research paper [11] analyzed the influence of a transverse electric field on the gas breakdown formation at different intensities of the applied electric field. Recently, Bredice et-al [12,13] proposed a method for the characterization of plasmas-laser in air, combining optical and spectral signals from plasma with measurements of electrical signals of the plasma perturbations caused by electric fields. By using a

parallel flat plate capacitor, they showed that the electrical signal is directly proportional to the energy deposited by the laser beam on the sample. They concluded that the best deposition occurs when short focal distance lenses are used. On the same way, they showed that the peak of the electric signal measured in the resistor connected to a plate of the capacitor is uniquely related to the temporal evolution of the Stark broadening of the Hα line present in air or Cu plasmas; they propose that an electrical signal peak can be used to measure the temporal evolution of the electron density of plasmas produced by laser in real-time [13].

In other similar works, Robledo-Martínez et-al [14,15], investigated the formation, expansion, and size of plasmas-laser in air and its dependence with the application of transverse and parallel external electric fields to the laser beam. As a result of their research, they found that the laser power threshold required to initiate the breakdown increases when the applied external electric field is transverse to the laser beam, while the effect is not observed when the electric field is parallel to the laser beam. In addition, they concluded that an air plasma, under the effect of an uniform external electric field, presents a dipolar structure which dipolar moment aligns with the bias field; while the polarizability of plasma does not depend on the magnitude of the voltage applied to the capacitor plates or the direction of the field, but it does depend on the focal length and the energy deposited by the laser beam [15].

In a more recent work, Elhassan et-al [16], studied the effect of applying a static electric field with different polarities on the physical parameters and dynamics of plasma induced by laser radiation on samples of aluminum, placed on a plate of the capacitor. In particular, they investigated the effects of external electric fields on the electron density and the plasma temperature using LIBS signals, while the plasma plume dynamics was monitored by shock waves. Their work showed a pronounced increase or decrease of the signal-to-noise (S/N) ratio of different spectral lines of aluminum (Al I and Al II), depending on voltage polarity to the capacitor plates: they found that an intensification occurs if the target is connected to the negative plate and the positive electrode; while the emission line intensities deteriorate when polarity is reversed. Furthermore, they showed that plasma temperature remains constant in average with the increasing electric field applied in both directions.

2. Experimental description

In this paper, we use the LIBS technique to generate and study plasmas-laser on an aluminum sample placed between and at the center of a parallel flat plates circular capacitor. The plasmas were produced with a Nd:YAG laser operating at 532 nm, with a pulse duration of 3-5 ns and ~90 mJ per pulse energy. One of the plates was connected to an adjustable high voltage DC source and the other plate was connected to ground through a 4.7 kΩ resistor. The capacitor plates voltage was varied from 2 kV to 12 kV while the separation of the plates was varied from 20 mm to 80 mm. The Figure 1 is a schematic layout of the experimental arrangement used to generate plasma and the application of the electric fields. The laser light was focused on the aluminum sample using a plane-convex lens of 10 cm of focal length. The energy of the laser was set to its maximum value and the energy deposited on the sample was varied using an optical attenuator. The plasma light was conducted through an optical fiber to a 0.25 m focal length spectrograph equipped with a diffraction grating of 1200 grooves/mm that produces a 0.25 nm spectral resolution. In order to ensure the reproducibility of the data, the sample was placed on a stepper motor positioning system to move the sample away or closer with a 0.005 mm precision from the lens focus point and/or rotate it with a 0.6° resolution. The behavior of plasma size within the electric field was also observed with a 512 x 760 pixels CCD optical camera adjusted to a cooling temperature of 10°C and an integration time of 0.5 s.

Rapid plasma formation creates an electric pulse that can be measured as a potential difference across the resistor connected to the capacitor from ground. The electric pulse was studied with a dual channel digital oscilloscope with 300 MHz bandwidth and scanning memory. In order to characterize the electric pulse, an experimental assembly was implemented (see Figure 2). The assembly was used to study the pulse according to the amount of energy deposited by the laser beam on the sample, the capacitor plate separation, the potential of the plates, and the numbers of pulses at the same point in the sample.
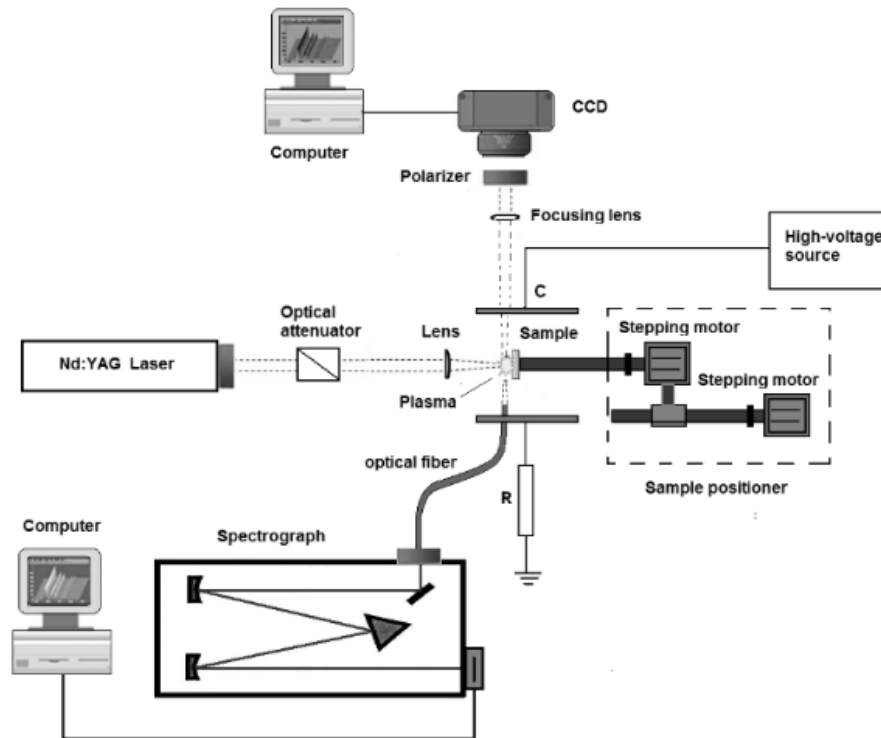
Figure 1. Experimental scheme used to observe the behavior of the plasma-laser of aluminum in the presence of the electric field, C: Capacitor, R: resistor.
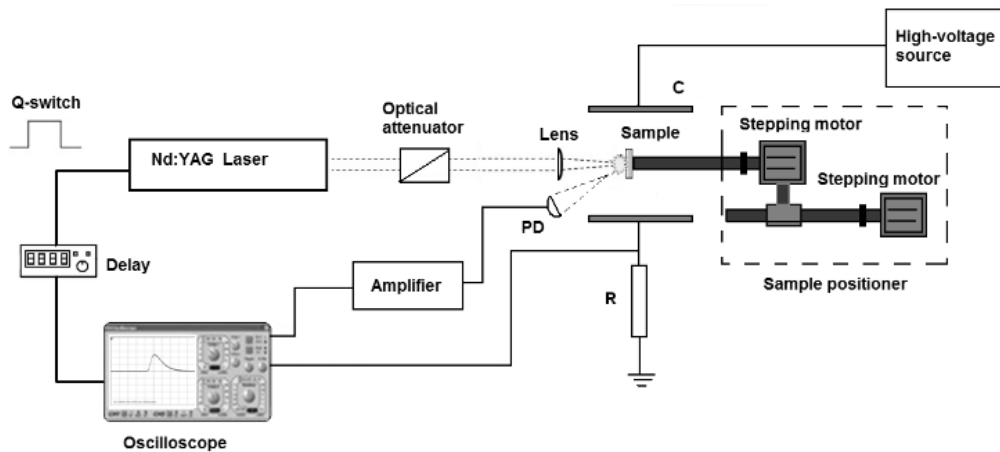

Figure 2. Scheme of the experimental setup used for the simultaneous acquisition of the electric pulse and luminous pulse of the plasmas-laser. C: Capacitor, R: resistor, PD: photodiode.

3. Results and discussion

Typical form of the electrical signal is shown in the Figure 3. To start, we characterized the electric pulse resulting of the resistor potential difference when connected to ground in different parameters, such as a) the separation of the capacitor plates whose behavior is shown in Figure 4, b) laser pulse energy deposited on the sample whose results are shown in Figure 5, and c) the voltage applied on the plates whose signal is shown in Figure 6.

From the graphics we can observe that the measurements of the electrical pulses can be taken as a signal of electrical characterization of the plasmas-lasers due to the well-defined and stable correlation of the data with the variation of the aforementioned parameters. Data adjustment led us to the conclusion that electric pulse intensity, in terms of the energy deposited by the laser and in terms of the voltage applied on the plates, holds a linear dependence, While the electrical signal in terms of plate separation has a dependence that decays approximately with the inverse of the square of the distance (d^2), in contrast to previous reports of [3] which find that the signal decays with the inverse as the cubic of the distance (d^3) for a plasma-laser in the air. Such a difference in the results we attribute precisely to the type of sample used. In this work, we used a metallic target of aluminium in the production of the plasmas-laser under the influence of electric fields transverse to the direction of the laser beam, which changes the physical conditions inside the capacitor plates, compared to plasma produced in the air.
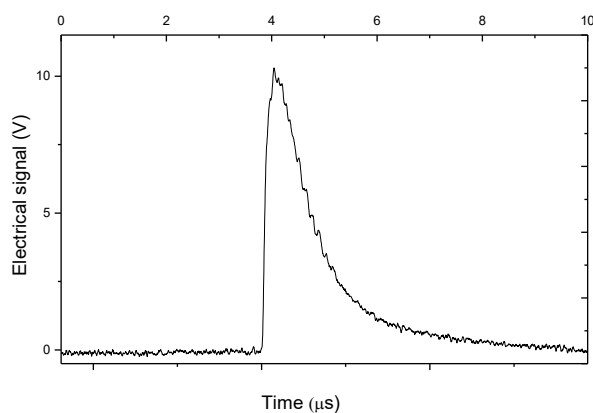

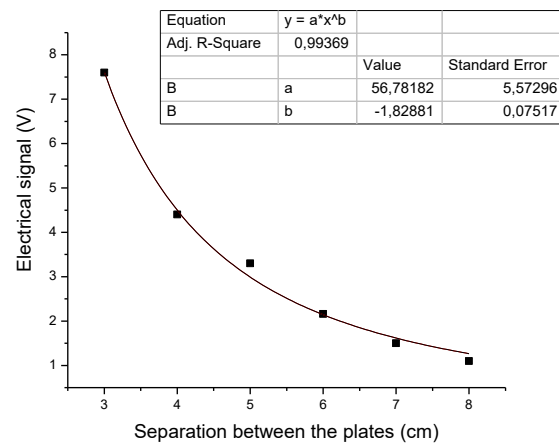**Figure 3.** Typical electric pulse obtained on the resistor connected to a ground capacitor.

Equation	y = a*x^b		
Adj. R-Square	0,99369		
		Value	Standard Error
B	a	56,78182	5,57296
B	b	-1,82881	0,07517

Figure 4. Behavior of the electrical signal in function of capacitor's plates separation.

Equation	y = a + b*		
Adj. R-Squar	0,98979		
		Value	Standard Erro
B	Intercept	-4,1816	0,47195
B	Slope	0,34209	0,01157
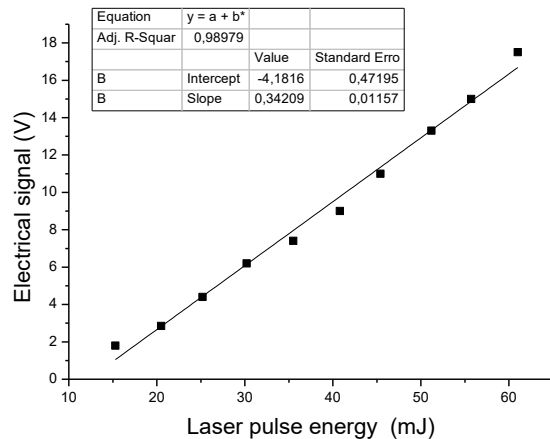
Figure 5. Behavior of the electrical signal in function of the laser pulse energy.

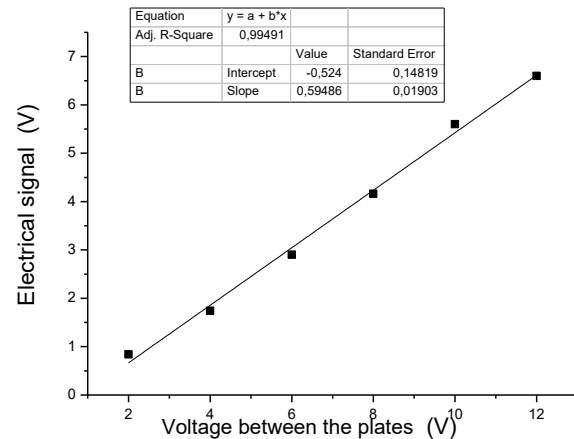| Equation	y = a + b*x		
Adj. R-Square	0,99491		
		Value	Standard Error
B	Intercept	-0,524	0,14819
B	Slope	0,59486	0,01903

Figure 6. Behavior of the electrical signal in function of the voltage applied on the capacitor plates.

For spectral characterization of aluminum plasma-laser, we registered the spectra in the optical region between 250 and 800 nm. Figure 7 shows the sector centered at 300 nm, where we see how the intensities of the spectral lines vary with the energy deposited by the laser beam in the sample. The maximum laser output energy decreased with the use of the optic attenuator that allowed to reduce the fluctuations that take place when lower values are chosen at the power supply source of the lamp flash to excite the laser. The energy deposited by each laser pulse on the sample was monitored with a

pyroelectric sensor, whose measures were registered between 15 mJ and 75 mJ. In this sector of the spectrum, we observe how the spectral lines decay as the energy deposited by the laser beam in the sample decreases.
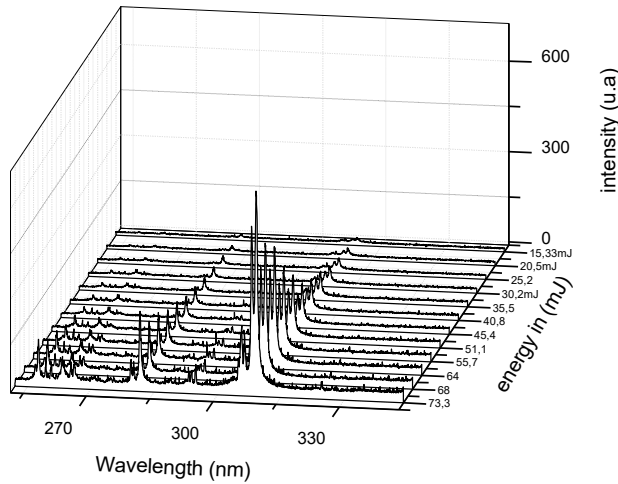

Figure 7. Sector of plasma-laser spectrum of aluminum in 300 nm as a function of the laser energy.

Figure 8 shows the spectral lines of Al I in the sector of 300 nm used to determine the electron temperature of plasma-laser. For the estimation of such a parameter in function of the laser energy, Boltzmann plot graphs were made by using the wavelengths measures and the reported spectral data [17] in Table 1.
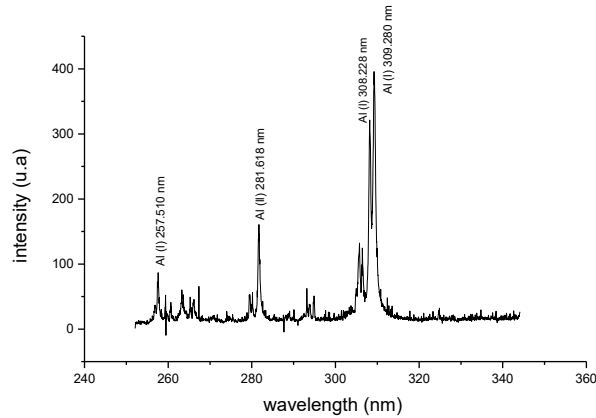

Figure 8. Sector of plasma-laser spectrum of aluminum centered in 300 nm.

Table 1. Spectral parameters reported [21] of the observed lines, used to measure the electron temperature.

$\lambda(nm)$	$g_k A_{ki}$ $(10^8\,s^{-1})$	E_k (cm^{-1})
309.280	4.4	32 436.796
308.228	2.5	32 435.453
257.510	1.7	38 933.968

Table 2 shows the electron temperatures obtained in the plasma-laser for the measured energies of the laser pulses. The electron density of the plasma-laser used in the Equation (1) was calculated with the obtained temperature values and the result of the Al I electron-impact broadening parameter calculation reported by Griem [18].

$$\Delta\lambda_{1/2} = 2w\left(\frac{N_e}{10^6}\right) + 3.5A\left(\frac{N_e}{10^6}\right)^{1/4}\left[1 - 1.2N_D^{-1/3}\right]\cdot w\left(\frac{N_e}{10^6}\right), \tag{1}$$

where $\Delta\lambda_{1/2}$ is the FWHM, N_e is the electron density in cm^{-3}, A is the ionic-impact broadening parameter, w is the electron-impact broadening parameter, and N_D is the number of particles in a Debye sphere. If we do not take into account the contribution of the broadening given by the ions, the electron density can be calculated with the Equation (2):

$$\Delta\lambda_{1/2} = 2w\left(\frac{N_e}{10^6}\right) \qquad (2)$$

The obtained results for the electron densities are shown in Table 3; Figure 9 and Figure 10 show the graphs with the electron temperature and electron density behaviors, respectively, in terms of the energy given by the laser pulse.

Table 2. Electron temperature in terms of laser energy.

Energy pulse (mJ)	Plasma temperature (K)
25	3048
35	3045
45	5915
55	6894

Table 3. Electron density in terms of laser energy.

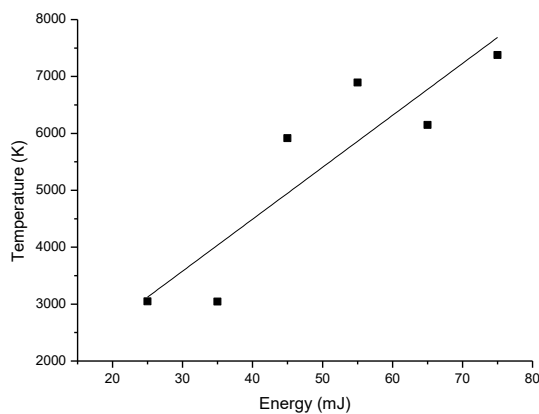| Energy laser (mJ)	Electron density (cm^{-3})
25	9.600x10^{16}
35	1.012x10^{17}
45	1.038x10^{17}
55	1.355x10^{17}
65	1.400x10^{17}
75	1.476x10^{17}

Figure 9. Electron temperature of plasma-laser aluminum as a function of the laser pulse energy deposited on the sample.
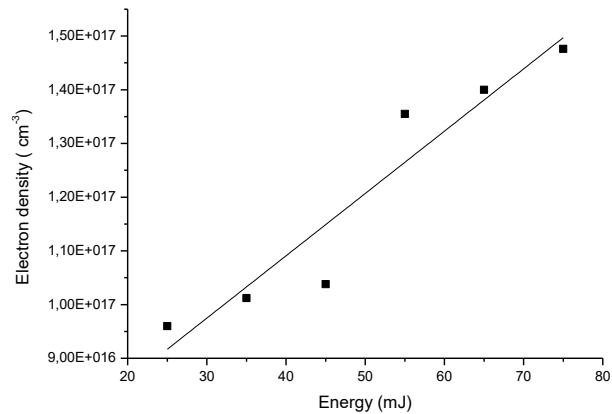

Figure 10. Electron density of plasma-laser aluminum as a function of the laser pulse energy deposited on the sample.

We can see in the figures that electron temperature as well as the electron density increase as the laser pulse energy increases. We also observed that the electric pulse signal increases linearly as the pulse energy of the laser increases (Figure 5); therefore, we are able to conclude that, for a fixed plate separation to a potential difference, it is possible to obtain the measurements of the electron density in real time starting with the measurements of the electron pulse in accordance with [13].

4. Conclusions

In this work, we carry out the spectral and electrical characterization of laser produced plasma, LPP, on an aluminum target under the influence of transverse electric fields to the laser beam, produced by a parallel flat plates capacitor. The experimental procedure of the LIBS technique accompanied with simultaneous measuring of plasma electric signal is an easy-to-implement non-perturbative method, that allows to obtain complementary measurements for optimization of the LIBS technique.

Our spectral and plasma electric signal analysis results show that electron temperature and density of produced plasma are directly proportional to the energy deposited by the laser beam on the sample. In addition, the electric signal in function of the separation of the plates shows a dependence that decays approximately with the inverse of square of the distance (d-2), for plasmas-laser formed on metallic target.

In addition, we note the decrease of the peak of the electrical signal to plasmas-laser formed on the same region of the solid sample of aluminum (fixed), Depending on the number of incidents of laser pulses (shots), which demonstrates the importance of constantly rotating or changing the target solids, it is possible for them to suffer erosion or to maintain the same conditions for the acquisition and reproducibility of data for the implementation of the LIBS technique for analytical purposes.

Acknowledgments

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