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Study on the influence of laser pulse duration in the long nanosecond regime on the laser induced plasma spectroscopy

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A R T I C L E I N F O

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A B S T R A C T

By using a high power pulsed fiber laser, this study reports the experimental investigation of the laser-induced plasma characteristics for the laser pulse duration range extended from 40 ns to 200 ns. The experiments were performed with keeping the laser fluence constant at 64 J/cm^2. The measurements show that, for the early phase of plasma formation, the spectral line intensities and the continuum emissions as well as the plasma characteristics decay to a certain extent with the increase of the pulse duration. On the other hand, as the plasma evolves in post laser pulse regime, the electron density and the degree of ionization increase slightly for the longer pulses, while the plume temperature is more or less independent from the pulse duration. Furthermore, the ablation characteristics, such as the ablation rate, coincide with the results of plasma characteristics for the different pulse durations. Eventually, with keeping the laser fluence constant at 64 J/cm^2, the analytical performance of Laser-Induced Plasma Spectroscopy (LIPS) for the corresponding pulse duration range is examined by using a temporal gating and non-gating analyses. The measurements show that, in the case of gating analysis, all pulse durations yield almost the same range of limits of detections LODs. On the other hand, for non-gating analysis, the longer pulse durations provide lower LODs (better) than the shorter ones by orders of magnitude. Moreover, the calculated absolute limit of detection (LOD_{Abs}) for the longest pulse duration (i.e. 200 ns) is lower by approximately factor 2 than that of the shortest one (i.e. 40 ns).

1. Introduction

It is well known that, the characteristics of the laser-induced plasma and consequently the analytical performance of the Laser-Induced Plasma Spectroscopy (LIPS) technique depend strongly on a large number of irradiation parameters such as wavelength, pulse energy, pulse duration, laser fluence, irradiance, burst of pulses and beam profile; These parameters have been studied experimentally and theoretically in order to achieve a great control of the sample ablation and the plasma formation processes [1–6]. Indeed, the avenue that can be followed for providing better understanding of the laser-matter interaction mechanism is studying the photo-ablation dynamics and the subsequent laser-induced plasma characteristics for the different laser pulse durations [7–15]. Up to date, many experimental studies and theoretical models have already been performed to investigate this key parameter. Yet, most of the previous works refer to the interaction of femtosecond, picosecond or <30 ns laser pulse widths [16–19]. By way of contrast, most of these previous investigations, with few exceptions, didn't provide the complete picture or derived a trend behavior for the potentially interesting range of laser pulse durations in nanosecond regime (i.e. in the range of few tens to few hundred nanoseconds) in which the laser irradiance will be in the typical values that are used for the LIPS and Pulsed Laser Ablation (PLA) applications (i.e. 10^8 W/cm^2–10^{10} W/cm^2) [20–22]. Moreover, the works that have already been done to study the laser-induced plasma characteristics for this interesting nanosecond pulse duration range were relied either on using two or more lasers having different pulse durations [as an example see ref. 23] or using a single laser incorporated the Q-switching technique for tuning the pulse duration where the laser pulse duration increases when the pulse repetition rate is increased and this accompanied with the lowering in the stored energy of the gain medium. Therefore, the operation near the lasing threshold gives longer pulse duration than the operation under a higher population inversion ratio [24–27]. This technique is characterized by definite limitation in the providing pulsed performance with sustained high peak power over a broad range of repetition rates. To clarify, with the Q-switched laser design, increasing in the pulse repetition above a certain rate (in order for producing long laser pulses) progressively leads to pulse collapse or dropout. Besides; pulse widths increase substantially as peak powers fall off dramatically [28]. A probable reason for this limitation was related to lack in developing the key technique for laser pulse amplification to generate high peak power with effective control of the pulse parameters aside from ruin the original beam's desirable qualities.

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Most recently, new pulsed fiber-laser-modules that offer an excellent combination of beam quality ($M^2 < 2$) and controllable pulse repetition rate, peak power, and pulse energy are introduced to the market. These pulsed fiber lasers integrate pulse-shaping technology called "Pulse-Tune" that is combined with the architecture design using a master-oscillator power amplifier (MOPA) for high-gain pulse amplification [28,29]. The key innovation with the Pulse-Tune approach is allowing pulse width and peak power to be programmed independently of the repetition rate. The pulse duration is controlled by using a range of preset waveforms (32 pre-programmed states) that can be chosen from laser control interface. Each of these waveforms is optimized based on the peak power for a specific frequency called "Switching Frequency" [28]. In general, operating at frequencies below the optimized level for any waveform (i.e. below Switching Frequency) will result in the same specific pulse conditions of peak power, energy and duration, but with lower average power as a result of fewer pulses. On the other hand, operation at repetition rates higher than the optimal frequency maintains the average power, but the peak power and FWHM of pulse duration can decrease dramatically while pulse energy decreases linearly as a function of pulse frequency [28–30].

However, by using this type of fiber laser, the present work devotes to provide an investigation of the influence of laser pulse duration in the long nanosecond regime (i.e. in the range from 40 ns to 200 ns) on the characteristics of the laser induced plasma. This investigation is performed by (i) the spectroscopic analysis of the plasma emissions which allowed the calculation of the plasma thermodynamic parameters (such as plasma temperatures and electron density) and (ii) the qualitative and quantitative inspection of the produced craters for different pulse durations which allowed the calculation of the ablated mass. With respect to this pulse duration range, the effect of varying the laser irradiance (in the range from 3.2×10^8 to 1.6×10^9 W/cm^2) during the early phase of the plasma formation is also examined. Subsequently, the role of this laser pulse duration range in the framework of LIPS performance is examined and discussed to demonstrate to what extent for a given fluence it could be significantly improved by the suitable choice of laser pulse duration. In order to achieve this goal, by using a temporal gating and non-gating analyses, the relative limits of detections (LOD_{Rel}) in the low μg g^{-1} range for minor elements in aluminium alloy samples are calculated and compared for the different pulse durations. Moreover, the corresponding absolute limits of detection (LOD_{Abs}) for the different pulse durations are also calculated.

2. Experimental setup

2.1. Laser module characteristics

The experiments are carried out by using a G3 SP-20P-HS series Pulsed Fiber MOPA laser (SPI Lasers, Southampton, UK), which delivers a high peak power up to 11 kW with 20 W average output power. The laser operated at its fundamental wavelength ($\lambda = 1064$ nm) with an emission band width $\Delta\lambda$ (FWHM) < 10 nm. The output of the fiber laser was coupled to a Beam Expander Telescope (BET) model PT-P00399 (SPI Lasers) with magnification of 8.7×. This laser system provides: (i) a wide range of laser pulse waveforms covering the pulse energy range from 40 μJ up to 800 μJ per pulse, (ii) output peak power in the range of 2–11 kW, (iii) repetition rate from 1 to 500 kHz and (iv) pulse widths (FWHM) in the 10–200 ns range. Conversely, for the present experiments, five representative pulse durations (τ) were selected in this range (namely: 40, 80, 120, 160, 200 ns). The maximum laser energy used in our conditions was set to 200 μJ per pulse with 5 W average output power and at a repetition rate of 25 kHz.

The laser beam was focused on the sample surface by means of a plano-convex lens (PLCX-25.4-38.6-C-1064 CVI Melles Griot, New Mexico, USA) with focal length $f = 75$ mm. Owing to the high beam quality achieved with this laser ($M^2 \approx 1.95$), the ablation laser spot on the surface of the sample was circular and its diameter was estimated for the different pulse durations to be about ≈20 μm, resulting in a laser fluence of ≈64 J/cm^2. The variation in the pulse duration leads to irradiance ranging from a 'low' $\approx 3.2 \times 10^8$ W/cm^2 at $\tau = 200$ ns to 'moderate' $\approx 1.6 \times 10^9$ W/cm^2 at $\tau = 40$ ns. An overview of used waveforms and their pulse durations is reported in Table 1. The temporal shape for the different laser pulses is presented in Fig. 1 and it was measured by using a fast photodiode coupled to a digital oscilloscope (Tektronix TDS 684A).

2.2. Materials

For studying the influence of laser pulse duration on the laser induced plasma characteristics, two disc-shaped aluminium standard samples provided by Alcan were used. An alloy plate (AL a380.2) that contains 0.028% of Mg was used for the emission lines and electron density characterizations and another alloy plate (AL 3003) that contains <0.7% of Fe was used for the plasma temperature characterization. Furthermore, the ablation behavior evaluation experiment was carried out on polished aluminium tooling plate. On the other hand, for studying the LIPS performance of the different pulse durations, 9 disc-shaped aluminium standard samples provided by Alcan were used.

In order to provide a fresh surface for each laser shot, the target was moved continuously across the laser propagation axis using a motorized translation stage model UTM-100CC1HL (Newport, Irvine, CA, USA), controlled by a universal motion controller model ESP300 (Newport).

2.3. Collection and detection systems

A schematic diagram of the experimental setups that have been used with two different spectrometer types is shown in Fig. 2. As can be seen, throughout the measurements, two different commercial combinations of spectrometer/detector were used. The first one (a) is a bench-top Czerny–Turner spectrometer coupled with ICCD. The other one (b) is a compact spectrometer incorporated linear array CCD.

Generally, light emitted from the laser induced plasma is imaged onto the optical fiber bundle by using a corrected triplet lens (diam. = 25.4 mm, $f = 45$ mm, Edmund Optics, New Jersey, USA), located at 70 mm from the target and at 18° off the normal to the target surface.

Light dispersion and detection for studying the influence of the laser pulse duration on the laser induced plasma characteristics was done by using a bench-top Czerny-Turner spectrometer. While throughout the experiments for evaluating the analytical performance of LIPS, both spectrometers were used where the bench-top Czerny-Turner spectrometer was used for gating analysis and the compact spectrometer was used for non-gating analysis.

For the benchtop spectrometer setup, the collection fiber is composed of an assembly of 25 optical fibers of 120 mm core diameter in the configuration round (input) to line (output), placed at ~13 cm behind the collecting lens. The position and the angle of the optical fiber were determined by the optimization of the signal to include all the plasma emissions, so the integrated emission from all the regions of the plasma could be acquired. The spectrometer is Czerny-Turner type (VM 504, Acton Research Co). Its focal length is 0.39 m while its effective aperture is f / 5.4. The spectrometer was equipped with a plane grating of 1200 lines/mm (blazed at 150 nm). The corresponding

Table 1
The reference table for waveforms at constant fluence of 64 J/cm^2.

Waveform number	Pulse duration (ns)	Irradiance (Φ) (W/cm^2)
11	200	$\approx 3.2 \times 10^8$
15	160	$\approx 4 \times 10^8$
19	120	$\approx 5.3 \times 10^8$
23	80	$\approx 8 \times 10^8$
27	40	$\approx 1.6 \times 10^9$