Optical and electrical investigations of transient plasmas generated by femtosecond laser ablation

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Fundamental investigations of laser produced plasma have been focused on understanding the formation and the expansion of such plasmas in various temporal regimes. Transient plasmas produced by pulsed lasers present complex spatial and temporal evolution, thus the usage of space- and time- resolved optical and electrical investigation methods are required. Here we present some preliminary results on the dynamics of transient plasmas generated by femtosecond laser ablation, investigated by means of fast camera imaging, space- and time-resolved optical emission spectroscopy and Langmuir probe. The measurements were performed on plasma plumes produced on various metallic targets, in different experimental conditions. The aim of our work is to find a link between the physical properties of the target and plasma parameters.

1. Introduction

The basic short and ultra-short laser pulses - surface interaction mechanisms are a challenge to scientists when relating to fundamental studies and have received a growing interest due to their impressive number of applications [1, 2]. Subsequently a significant number of studies have been carried out regarding the dynamics of the plume [3, 4]. Several studies showcased that femtosecond laser ablation might present some advantages in comparison to nanosecond or picosecond laser ablation regarding fundamental investigations. Generally the focus of fundamental studies is to completely investigate laser produced plasmas in terms of structure, life time and temperature or expansion velocity [5-7]. Although the influence of external parameters on the dynamics of the plasma plume is important and it has been intensely investigated [3-7], one of the main goals still remains to connect the target physical properties to the ones of the expanding plume.

Here we present preliminary result of fast ICCD camera imaging, space- and time-resolved optical emission spectroscopy and Langmuir probe measurements performed on laser - produced plasma on various metallic targets, in different experimental conditions.

2. Experimental Set-up

A schematic view of the experimental set-up [8-9] is given in Figure 1. The experiments have been performed in a stainless steel vacuum chamber at various background pressures. A Ti:Sa femtosecond laser beam (800 nm, 60 fs, 1.7 mJ/pulse, 100 Hz) has been focused at normal incidence by a f = 25 cm lens onto various metallic targets placed in a vacuum chamber. The estimated spot diameter at the impact point has been 160 μm, which leads to a laser fluence of 8.5 J/cm^2. Various targets were placed on a X-Y-Z micrometric stage and were electrically isolated.

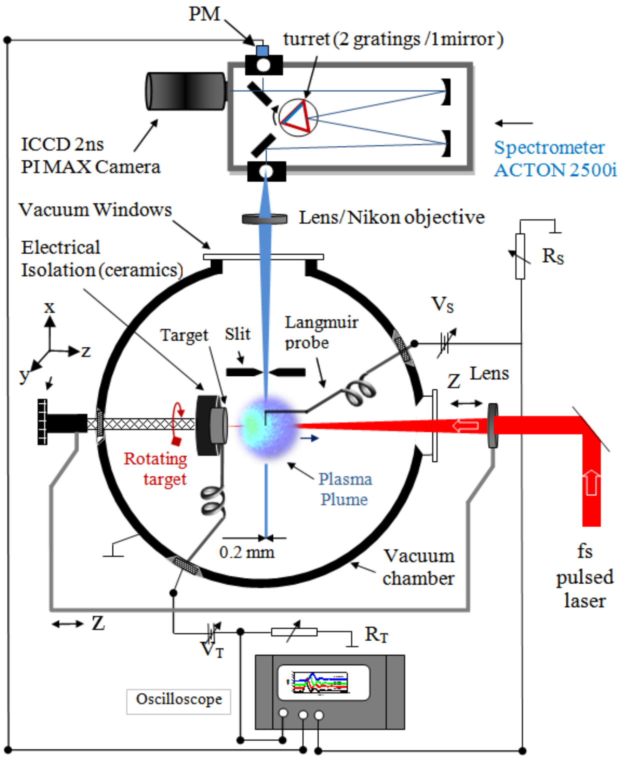

Figure 1. Experimental Set-up

The total ionic current extracted from the plasma plume was measured by a cylindrical Langmuir probe made of stainless steel (0.8 mm diameter, 5 mm length) has been placed perpendicular to the plasma plume expansion and could be moved at various positions from the target surface. The Langmuir probe was biased with stabilized dc power source. The transitory signals have been recorded by a digital LeCroy, Wave Surfer 620A oscilloscope (2 GS/s).

A Princeton Instruments ICCD camera (PIMAX2-91003-UNIGEN2, 1024 × 1024 pixels, minimum gating time 2 ns) has been used to record images of the plasma as a whole at various delays with respect to the laser pulse. The formation and the dynamics of the plasma plume have been also studied by means of high-resolution monochromator (Acton SP2500i) coupled with the ICCD camera. The monochromator is fitted with one mirror and two diffraction gratings (300 l/mm, blaze at 300 nm, and 2400 l/mm, blaze at 240 nm) mounted on the same three-position turret, which allows an easy switching between imaging, low-resolution, and high-resolution spectroscopy experiments. For the imaging experiments, a Nikon objective was used to form the image of the whole plasma plume on the ICCD array through the kinematic entrance slit of the spectrometer and with the turret fixed in the mirror position. The ICCD camera was triggered on the TTL Q-switch output of the ablation laser, and an internal routine was used to increment the delay between the laser pulse and the gate opening.

For space-resolved optical emission spectroscopy studies, a 1 mm ×5 mm slit was placed in the vacuum chamber, at 40 mm from the normal to the target. This slit defined 1 mm width plasma plume "slices" parallel to the target surface, which were further imaged (~1:10 magnification) by the cylindrical lens on the monochromator entrance slit.

3. Results and Discussions

3.1 Optical investigations

In Figure 2 we present a typical evolution of the whole plasma optical emission recorded by the ICCD camera gated (5 ns) at different delays with respect to the laser pulse. These images reveal a splitting of the plasma plume in two structures.

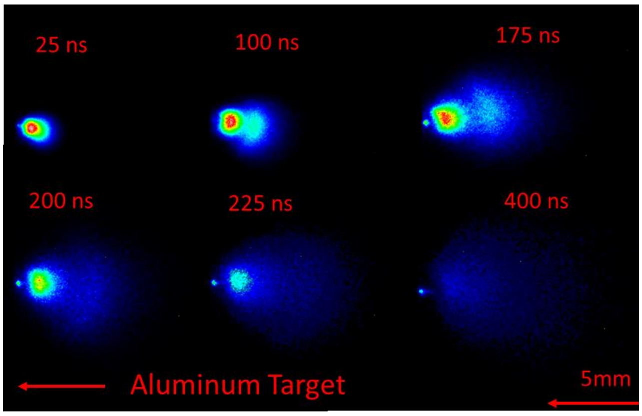

Figure 2. Temporal evolution of the Aluminum plasma plume emission recorded by the ICCD camera

The two structures exhibit distinct dynamics and velocities. The velocities were derived for the maximum emitting point of each plasma structure In this particular example for an Aluminum target, characteristic for a laser fluence of 8.5J/cm^2 and a pressure of 10^{-5} Torr we found velocities of 10^4 m/s for the first structure while for the second plasma structure the expansion velocity is about 10^3 m/s. The velocities are specific to each target and they present a dependence on the atomic mass.

In order to have a more complete view over the laser produced plasmas, we have performed a space- and time-resolved optical emission spectroscopy study [10]. In figure 3 we display an overview of the 300–600 nm spectral range recorded at 0.5 mm from the target and the assignment of the most intense spectral lines observed. It is noticed the presence of both neutral and ionic species in the spectrum. Moreover, in order to get some information regarding the internal energies of the species present in the plume, the excitation temperature can be calculated using the well-known Boltzmann plot method [11].

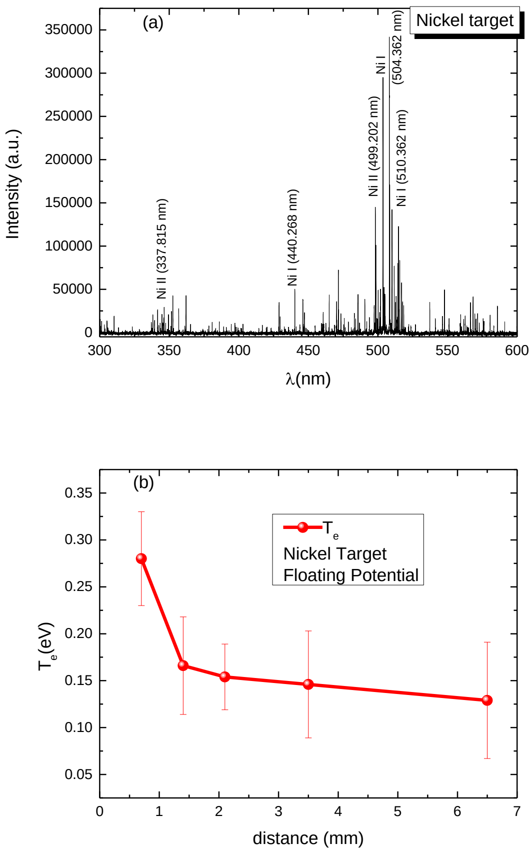

Figure 3. Emission Spectrum for a Ni laser produced plasma at 0.5 mm from the target (a) and the spatial evolution of the Nickel atoms excitation temperature (b).

We also studied the spatial evolution of the excitation temperature and observed that its value decreases, having the maximum close to the target surface. Although the spatial evolution is similar for all the investigated plasmas, the values are specific and depend on the physical parameters of the target (i.e. mass, electrical or thermal conductivity).

3.2 Electrical investigations

Although Langmuir probe method [12] is generally applied for isotropic homogeneous plasmas at thermodynamic equilibrium in which the charged particles are described by Maxwellian distribution function, for transient plasma [13] it has to be taken into account that all plasma parameters present complex space-time dependence. More specific for periodic or quasi-periodic plasmas the Volt-Ampère (I-V) characteristic is reconstructed at each evolution time.

The probe is biased with different potentials after which, for each value of the applied potential, the temporal traces are collected. Then, the I-V characteristics are reconstructed for specific values of the expansion time.

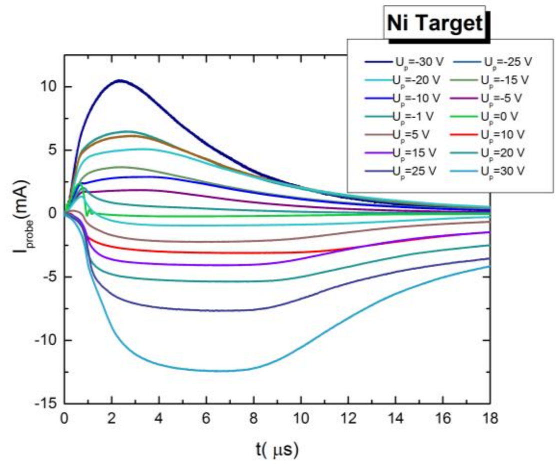

Figure 4. Transient ionic and electronic currents recorded by the Langmuir probe (placed at 6 mm, orthogonal on the plasma plume expansion direction) for different probe biases

The range of voltages chosen was -35V to +35V (with a voltage step of 1V). The specific TOF signals for Nickel laser-produced plasma are presented in Figure 4. The shape of the signal as well as the lifetime of the plume is characteristic to each material, being related to the inner properties of such materials.

Since this approach allows us the study the expanding plasma at different temporal points, we can apply the method presented in [12, 13] and determine a series of plasma parameters which describe the inner energy of the plume (plasma potential, electron temperature or thermal velocity) and others which give us insight over the intrinsic structure of the plasma (ion and electron or density Debye length).

In Figure 5 it is represented the evolution of thermal velocity, ionic concentration and Debye length with the atomic mass of the target.

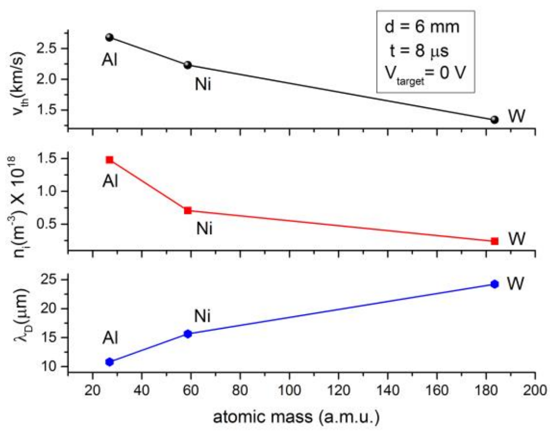

Figure 5. Plasma parameters evolution with the atomic mass

Moreover we found that not only mass influences the values and evolution of specific plasma parameters but the electrical and thermal conductivities are also highly influential physical properties. These properties may be directly linked to the material removal mechanisms.

3. Conclusions

The Langmuir probe measurements coupled with space-and time-resolved optical emission spectroscopy and fast camera imaging were performed in order to understand the behaviour of the laser produced transient plasmas under different experimental conditions. The plume dynamics and its intrinsic properties were found to be dependent on the physical properties of the target. Plasma parameters studied through optical and electrical investigations techniques, describing the internal energy of the transient plasma plume (plume velocity, excitation temperature, plasma potential, electron temperature and thermal velocity) are correlated presenting similar space-time dependence. All the preliminary results are showcasing the dependence of the expanding plasma dynamics on the physical parameters of the targets.

4. References

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