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INTENSE PLASMA GENERATED BY UV LASER IRRADIATION

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Abstract

In this work we present the experimental results concerning the study of the plasma produced by pulsed laser irradiation of a copper target. The analysis of the generated plasma plume was performed for three different laser spot sizes determining the threshold conditions of the ablation process. A diagnostic system with a Faraday cup was developed in order to detect the ion current along the propagation tube. Time-of-flight (TOF) measurements were performed, and an adjustable voltage electrostatic barrier was employed in order to analyse the kinetic energy of the produced ions. To study the plasma characteristics we evaluated the total etched material per pulse, $1.8x10^{16}$ atoms/cm^2, and the fractional ionisation, 36%. A modified Maxwell-Boltzmann distribution was applied to provide a consistent description of the velocity distributions in the plume. The ablated material was spatially monitored by optical transmission analysis of a deposited film.

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1. INTRODUCTION

A lot of new applications concerning ion beams, not only in research laboratories [1], but also in the fields of industry and hadrotherapy [2], have stimulated great interest in ion accelerators and, as a consequence, in multiple charged ion generation. The most widespread methods to produce ions are the electron beam ion sources (EBIS) [3] and the electron cyclotron resonance sources (ECR) [4] working with gases or evaporated materials. The development of high intense laser beams has allowed to improve the ion production by laser etching, acting directly on solid materials without preliminary evaporation. The Laser Ion Source (LIS) technique produces a high explosive plasma plume consisting in a high concentration of ionised matter which can generate short pulses of high current ion beams. Besides, since the eighties, due to technological progress achieved in the field of excimer lasers, new frontiers in the study of LIS by UV laser have been opened [5].

A laser beam incident on a solid target results in the evaporation of the material layer due to the absorbed energy which causes ion generation by electron-electron or by photon-electron interaction. The evaporating material interacts with the laser beam until its termination, obtaining an isothermal expansion of the plasma. In this stage soft X-ray are generated for a time approximately near to the laser pulse duration. The target surface can reach a temperature of 0.1-1 keV [6]. This value corresponds to an energy that is greater than that necessary to ionize the atoms of the target material. The interaction even produces atoms, molecules, clusters and ions. Experiments have evidenced the generation from many materials of multiple charge state ions having energies higher than 1000 keV [7]. With such an energy, it is clear that during the plasma expansion, the plume particles can enhance the ion production.

Experiments by long-wavelength lasers, such as commonly used CO_2 lasers [8], have produced low current and high charge state beams, while by short-wavelength lasers, such as excimer lasers, high ion currents of low charge states have been reached [9]. In this work, we present experimental results obtained with a short-wavelength excimer laser irradiating a Cu target. We studied the threshold conditions of the plasma generation for different laser spot sizes and monitored the plasma current along the propagation tube. We measured the ablation rate, the angular distribution and the fractional ionisation of the plume and, by means of an electrostatic barrier, we estimated the energy distribution of the ejected particles. At the end we applied an accelerating voltage and extracted the ion beam.

2. METHODOLOGY

We utilised a pulsed XeCl excimer laser (λ= 308 nm) having a 20 ns pulse width and a maximum energy on the target of about 100 mJ. The apparatus utilized in this experiment was very versatile and it could be arranged in different configurations. It is shown in Fig.1 and consists of a generating chamber, 30 cm long, and a drift tube, 120 cm long. In order to focus the laser beam onto the target, some different convergent lenses (L) were used, together with a set of neutral density filters, to vary both spot size and energy, respectively. The angle between the target surface and the laser beam was fixed at 70°. The target support was a stem mounted on the generating chamber by an insulator connector (I). This arrangement allowed to apply the extracting voltage directly to the target, keeping the chamber and the vacuum system to ground. The set-up was completed by a 18 cm long removable expansion chamber (E) connected to the target, which allowed the ions contained in the plasma to have an initial free propagation.

The diagnostic system consisted of a coaxial movable Faraday cup (C), 8 cm in diameter, closed on a 50 Ω load resistor by a transmission line and a 100 nF capacitor [10]. In this way we could polarize the cup in order to collect either the positive or negative plasma particles. The Faraday cup could be completed, if necessary, either with a suppressor electrode (S), in order to avoid secondary electron emission from the cup itself because of high energy impinging particles, or with an electrostatic barrier (B) for ion energy analysis.

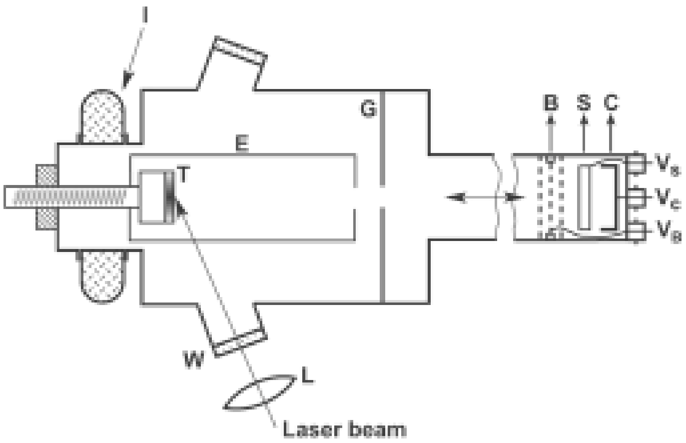

Figure 1: Experimental apparatus. T: target; I: insulator; C: Faraday cup; E: expansion chamber; V_C: cup pulse; V_T: target pulse; B: electrostatic barrier; G: ground electrode; S: suppressor electrode.

3. RESULTS

In order to study the etching process, we evaluated the ejected charge trend versus the laser fluence for different spot sizes. Three lenses of different focal length were used, producing three spots of 0.2, 0.3 and 0.5 mm^2 area. For each spot size, we integrated the ion current signal recorded by the cup at various laser fluence values. We observed that the total charge increased as the laser fluence increased (Fig. 2). Very surprising were the threshold results. Their values were dependent on the laser spot size on the target; that is with a larger spot the threshold value decreased. We explain this behaviour thinking that, being the laser pulse 20 ns wide, the core temperature decreases more slowly for larger spot dimensions, due to a lower diffusivity, so favouring the etching process. The lowest threshold value we obtained was 3.5 J/cm^2 with the 0.5 mm^2 spot.

At about 3 cm from the target we placed a glass substrate in order to evaluate the angular distribution of the ejected particles by the deposited material thickness. During the deposition the target was continuously rotated in order to avoid the plasma flux deviation owing to the progressive modification of the crater. The laser fluence was fixed at 10 J/cm^2 with 0.5 mm^2

laser spot. The film distribution was determined measuring the optical transmittance of the deposition by a HeNe laser as light source and a IR photodiode as detector.

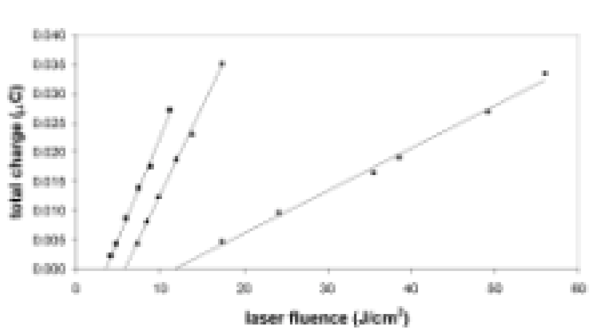

Figure 2: Measured charge for • 0.13, ▲ 0.35, and 0.56 mm^2 spot on the target as a function of the laser fluence.

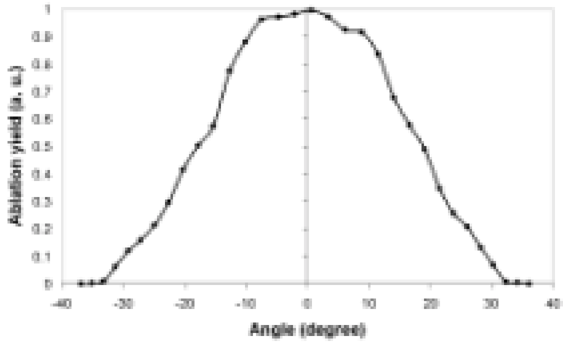

Figure 3. Angular distribution of the ablated laser ■ material.

The laser and the photodiode were fixed while the deposited film was translated. To assess the film distribution a 0.2 mm pinhole was placed in front the detector. The input (I_{in}) and output (I_{out}) intensities are linked by the well known relation

$$I_{out} = I_{in} e^{-\alpha x}$$

where x is the film thickness and α is the absorption coefficient of the deposited film at HeNe wavelength. The ablated material profile we obtained is shown in Fig. 3. As can be seen, the ejected material had a symmetric distribution and a narrow directionality (FWHM= ±18°) that is very interesting for the coupling between LIS and accelerators.

The ablated material quantity, containing both neutral and charged particles, was estimated measuring the mass of the target before and after the laser irradiation by a highly sensitive digital balance (Sartorius ME215S). Due to the low ejected material per pulse, the laser irradiation consisted of 1000 laser pulses at 10 J/cm^2. The ablation rate we found was 1.8x10^{16} atoms/cm^2 per pulse. Now, using the angular distribution of ejected particles, it was possible to obtain the total charge (1.1_10^{-3} C/cm^2) produced for each pulse; considering only single charged ions, it resulted an ion yield of 6.5x10^{15} ions/cm^2 per pulse and a fractional ionisation of about 36%. This is a very high percentage value that makes this apparatus very interesting.

In order to perform a preliminary ion energy analysis, we inserted in front of the cup an electrostatic barrier made of three meshes, 1cm apart from each other. We biased the central mesh of this barrier system to different positive voltages, while the two external ones were connected to ground, so that the stopping potential was only present in a gap very little with respect to the total drifting length. The effect of the stopping potential on the plasma signal is shown in Fig. 4 where two series of abrupt drops are evident for each barrier voltage value. We can ascribe this behaviour to the predominant concentration of Cu^{+1} and Cu^{+2} ions. In fact, increasing the barrier voltage the cut-off times get shorter due to the stopping of particles having velocity lower than

$$v_{th} = \sqrt{\frac{2ZeV_b}{m}}$$

where Z is the ion charge state, V_b is the barrier voltage, e is the electron charge and m is the ion mass. The dependence of experimental v_{th}^2 values versus V_b calculated from Fig. 4 for both two series of drops, confirms that they are due to $Z=+1$ and $Z=+2$ charge state ions.

The total number of ions, N, contained inside the plasma bunch is given by both the following integrals:

$$N = \int \frac{I_n(t)}{Ze} dt = \int f_n(E) dE$$

where $I_n(t)$ and $f_n(E)$ are the ion current distribution and the energy distribution related to $+n$ charged ions, respectively.

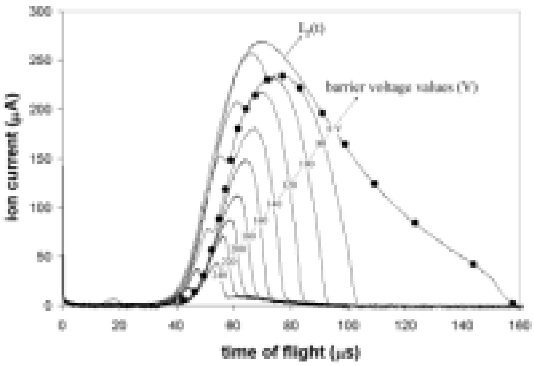

Figure 4: Ion current signals for different stopping voltages.

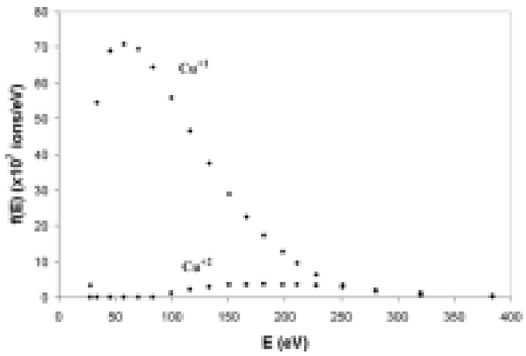

Figure 5: Energy distributions for Cu^{+1} and Cu^{+2} particles.

From such relation, it is possible to obtain $f_n(E)$, as follows [11]:

$$E = \frac{1}{2} m \frac{d^2}{t^2} \quad \text{and} \quad f_n(E) = \frac{I_n(t) t^3}{Zemd^2}$$

where d is the target-cup distance and t is the time of flight. The ion current distribution $I_1(t)$ for $Z=1$, can be obtained from Fig. 4 taking the tail of the total current curve, $I_T(t)$, and the segments between the cut-off times, see the black dots. The corresponding $I_2(t)$ for $Z=2$ is obtained as $I_T(t)$-$I_1(t)$. In Fig. 5 we show the most intense energy distribution functions, $f_1(E)$ for Cu^{+1} and $f_2(E)$ for Cu^{+2}. We observed that the most likely energies were 60 eV and 180 eV, for Cu^{+1} and Cu^{+2} ions, respectively.

It has been discussed elsewhere that, when a limited number of monolayers is expelled per pulse, the resulting one-dimension velocity distribution under Knudsen-layer (KL) formation is defined as[12, 13]:

$$f_K^{\pm} \propto v_x^4 \exp\left[-\frac{m(v_x - u_K)^2}{2kT_K} \right] \ ; \ -\infty < v_x < \infty$$

where $v_x = d/t$ is the ion velocity in the direction normal to the target, u is a sort of center-of-mass velocity, T is the temperature and the subscript K refers to the KL boundary. The above distribution fitted very well our experimental data as shown in Figs. 6, 7.

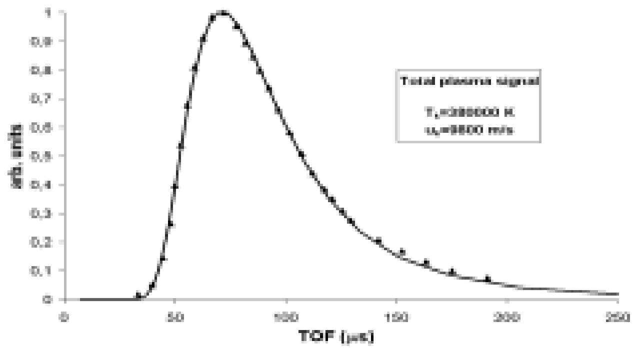

Figure 6: Total plasma measured signal (▲) fitted with the theoretical velocity distribution (solid line).

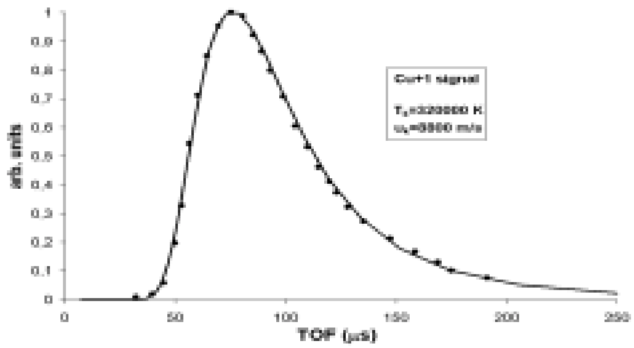

Figure 7: Cu^{+1} measured signal (•) fitted with the theoretical velocity distribution (solid line).

4. CONCLUSIONS

We analysed the characteristic of the plasma generated by a low energy UV laser beam on a Cu solid target. The analysis was performed by three different focal length lenses in order to study the dependence of the threshold conditions of the ablation process on the laser spot size. The time-of-flight (TOF) measurements were performed inserting in front of the cup an adjustable voltage electrostatic barrier that allowed us to get quantitative information about the ion flux and the kinetic energy of the produced ions. The experimental TOF curves were successfully fitted by a Maxwell-Boltzmann distribution with a flow velocity, which allowed to estimate the plume temperature ($\sim 10^5$ K). We evaluated the total etching material per pulse, 1.8×10^{16} atoms/cm^2, and the fractional ionisation, 36%. The ablated material direction was monitored by optical transmission analysis of a deposited film. Further work will include the study of the particle energy by a cylindrical electrostatic ion energy analyser (IEA) and of the percentage of neutral atomic component ejected from the laser by a mass quadrupole analyser (MQS).

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