DEVELOPMENT OF AN ION SOURCE VIA LASER ABLATION PLASMA*

F. Belloni, D. Doria, A. Lorusso#, V. Nassisi, Department of Physics of Lecce, LEAS, INFN of Lecce, Via per Arnesano, 73100 Lecce, Italy
L. Torrisi, INFN - Laboratori Nazionali del Sud (LNS), Via Santa Sofia, 95124 Catania, Italy

Abstract

Experimental results on the development of a laser ion source (LIS) are reported. A focused UV laser beam (0.1 – 1 GW/cm^2 power density) was used to produce a plasma plume from a Cu target. Several aspects were investigated: ion angular distribution, energy distribution, ion extraction and charge loss due to ion recombination. Diagnostics on free expanding plasma and extracted ions was carried out mainly by time-of-flight measurements, performed by means of Faraday cup and electrostatic spectrometer. At 18 kV acceleration voltage, the ion beam current resulted modulated on ion mass-to-charge ratio and its maximum value was 220 μA. A Cu^{+1} ion bunch of 4.2 nC charge was measured.

INTRODUCTION

The interaction of laser light with solid materials and the properties of plasma produced by laser ablation have been investigated for many years [1] and many problems are still open. Nevertheless, the generation of high density and high temperature plasmas by focusing high power laser radiation onto a solid target is interesting in basic science, engineering and material processing technology [2]. In particular, by impinging ultraviolet laser onto solid target, it is possible to obtain ablation plasma characterized by ions of low-charged states such as 1+ and 2+ and low temperature [3]. The advantages to obtain these kinds of ion beams consist to minimize the space charge effects for a fixed particle density of the beam. Moreover plasma of low temperature leads also to get beams of low emittance.

The common feature of all corpuscolar diagnostics is the fact that they give information about the plasma parameters at long distances from the target. In particular, time-of-flight (TOF) diagnostics is utilized in this work in order to record the signal of the ions carried by the drifting plasma. TOF diagnostics characterize the free plasma expansion in the vacuum as well as the stream obtained by the extraction of the ions from the plasma. It is noteworthy to study also the role of the recombination processes on the loss of charge carried by the plasma plume during its free expansion. The knowledge of the end of recombination processes is important when the extraction of ions from the plasma is required, in particular way on the laser ion source development.

EXPERIMENTAL APPARATUS AND RESULTS

A XeCl excimer laser (λ = 308 nm, 20 ns pulse duration) was utilised. The beam power density on a Cu target was 0.3 GW/cm^2. The apparatus utilized in this experiment was very versatile and it could be arranged in different configurations according to the measurements which have to be done. It is shown in Fig.1 and consisted of a plasma generation chamber (GC), and a drift tube (DT) along which a Faraday cup (FC) was collocated in order to perform TOF measurements of the plasma in free expansion.

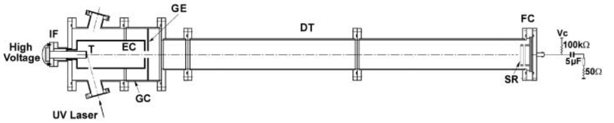


Figure 1: Experimental apparatus. GC: Generating Chamber; EC: Expansion Chamber; T: Target; IF: Insulting Flange; GE: Ground Electrode; DT: Drift Tube; FC: Faraday Cup; SR: Suppression Ring; V_c: FC bias voltage.

Before the ion extraction the characterization of the plasma plume was done by means of the electrostatic barrier (B) by which it is possible to estimate the charge states and the energy distribution of ions. The electrostatic barrier was composed by three polarized electrodes, 1 cm apart from each other, placed in front of the cup. The energy distribution can be found by putting the central mesh of this barrier system to a positive bias voltage, while the two external ones were connected to the ground. In this way the stopping potential was only present in a short gap, 1 cm, with respect to the total drift length.

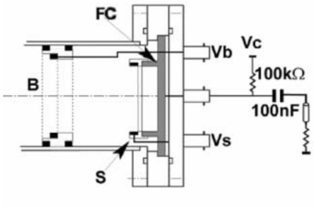


Figure 2: Sketch of the FC. Vc: Faraday cup polarization voltage; S: suppressor ring; Vs: suppressor ring polarization voltage; B: electrostatic barrier.

The effect of the stopping potential on the plasma signal is shown in Fig. 3 (a) where two series of abrupt drops are evident for each positive barrier voltage value. We can ascribe this behaviour to the predominant concentration of Cu^+ and Cu^{2+} ions. The low concentration of the higher

---

*Work supported by V Com. INFN
#antonella.lorusso@le.infn.it

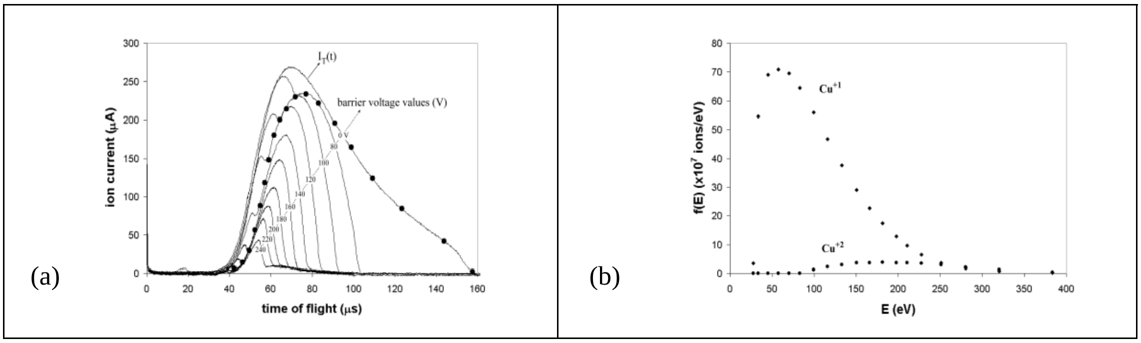


Figure 3: a): Cup current waveforms recorded under the influence of the barrier polarization. b): Energy distributions for Cu+1 and Cu+2 particles.

charge states did not allow to observe the correspondent abrupt drops. In fact, when the barrier voltage is increased, the cut-off times become shorter due to the stopping of particles having velocity lower than:

$$v_{th} = \sqrt{\frac{2ZeV_b}{m}} \qquad (1)$$

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

$$N = \int \frac{I_n(t)}{Ze} dt = \int f_n(E) dE \qquad (2)$$

where $I_n(t)$ and $f_n(E)$ are the ion current distribution and the energy distribution related to charge-states of ions, respectively. From Eq. (2), it is possible to obtain $f_n(E)$, as it follows:

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

where d is target-cup distance and t is the TOF.

The ion current distribution $I_1(t)$ (Z=1) can be obtained from Fig. 3(a) taking the tail of the total current curve, $I_T(t)$, and the segments between the cut-off times, corresponding to the black dots. The corresponding $I_2(t)$ (Z=2) can be obtained as difference $I_T(t)$- $I_1(t)$. In Fig. 3(b) the energy distribution functions, $f_1(E)$ for Cu^{+1} and $f_2(E)$ for Cu^{+2} are shown. The most likely energies are 60 and 180 eV for Cu^{+1} and Cu^{+2} ions, respectively, corresponding to peak velocities of 1.35×10^4 m/s for Cu^{+1} and to 2.34×10^4 m/s for Cu^{+2}.

In order to study the modification of the plasma charge during the plume expansion into the vacuum, the FC - target distance, L, was changed from 8 cm to 40 cm. It is quite difficult to record signals at distances lower than 8 cm due to the occurrence of plasma breakdown which produced short-circuits between the cup and ground.

For each distance, time-resolved current signals were integrated to measure the total charge, Q, carried by the ion beams. The dependence of Q on L is shown in Fig. 4.

The full squares and circles represent the measured charge at distances L < 20 cm and L ≥ 20cm, respectively. The solid line is a fit of the points at distances L ≥ 20 cm as the $Q \propto L^{-2}$ dependence, assuming that the detector area subtended a solid angle much smaller than the FWHM of the plasma angular distribution. In absence of the recombination processes the charge decreasing should be ascribed only to the plasma dilution.

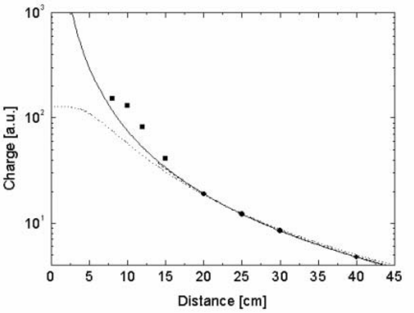


Figure 4: Collected ion charge vs. distance (squares and circles). The data were fitted by the function $Q \propto L^{-2}$ (continuos line), and by Eq. (5) (dot line) which including both the geometrical FC effect and the ion angular distribution effect on the FC response.

In a more realistic, forward-peaked, angular distribution of the plasma plume has to be taken into account. The particles emitted from the target which collide by themselves, were characterized by an angular distribution shape described by the law

$$h(\theta) \approx A \cos^p \theta \qquad (4)$$

where h is the number of ejected particles per solid angle unit, θ is the angle with respect to the target normal, A is the maximum amplitude and p is an empirical parameter. Regarding h as $dQ/d\Omega$ (where Ω indicates the solid angle), and integrating on the overall solid angle, we found the following relation for the total charge:

$$Q_p(L) = Q_{0,p} \cdot \left\{ 1 - \left[1 + \left(\frac{R}{L} \right)^2 \right]^{-\frac{1}{2}(p+1)} \right\} \qquad (5)$$

The dot line in Fig. 4 reproduces the curve obtained by fitting with Eq. (5) the experimental points at $L \geq 20$ cm only, with the value of p kept fixed ($p = 7$), as determined elsewhere [3]. Comparing the measured data and the dot curve, it was possible to estimate that the end of recombination processes ranging from 15 cm to 18 cm, because the measured charge at shorter distances is higher than the one predicted by the extrapolated fit in the same distance. The practical consequence of the knowledge of the end of the recombination processes can be essential for the extraction of ions from the laser-produced plasma.

To performing the extraction of Cu ions from the laser-produced plasma, the extraction voltage was applied directly to the target, keeping the chamber and the vacuum system to the ground.

The experimental setup was completed by a removable expansion chamber (EC) mechanically and electrically connected to the target stem, which allowed the ions contained in the plasma to get an initial free expansion. A ground electrode (GE) in front to the EC allowed to generate an intense electric field which was able to extract the charged particles (see Fig. 1). Many attempts were done in order to extract plasma particles without the EC, but arcs were present. As a consequence, the extraction voltage value decreased, provoking a power supply extra-current.

Measurements of extracted ions were performed positioning the FC at 147 cm from the target. In this position the cup had an acceptance angle of $3 \cdot 10^{-3}$ sr, indicating that only a small part of the initial particles could be collected. Furthermore, the FC was equipped with a suitably biased suppressor electrode for stopping the secondary electron current.

Applying high voltages to the target stem, an electric field was present in the extraction gap. The cup signal varied with the extraction voltage. Fig. 5 (a) shows three waveforms at 10, 14 and 18 kV. The output signals resulted modulated by small peaks at fast time and a large peak at slow time. We ascribe the "fast" peaks to light ions of H, C and O like compounds adsorbed in the target. Next, the extracted "slow" Cu ion bunch was revealed.

The peak current increased with the extraction voltage, as shown in Fig. 5 (b), respectively. The highest current was recorded at the highest extraction voltage, 18 kV, and resulted 312 μA. The bunch charge was 6 nC. These values were obtained without any bias voltage on the SR. Applying a -100 V polarization value on the SR, the output current decreased by a factor of 30%. Taking into account that the cup acceptance is only $3 \cdot 10^{-3}$ sr, a higher output current could be recorded. Considering that the relative abundance of Cu^{+2} ions was negligible with respect to the Cu^{+1} one, we estimated that the extracted bunch consisted of about $2.6 \cdot 10^{10}$ ions, while the total ion yield was of about $3.1 \cdot 10^{13}$ particles [4].

Our experimental results confirm that LISs are interesting tools to obtain easily ion bunches with high peak current even at low values of DC extraction voltage. Our apparatus, just in minimal setup, results to be very versatile and particularly suitable to get ion implantation and modification of the morphological aspect of substrates at tens keV energy.

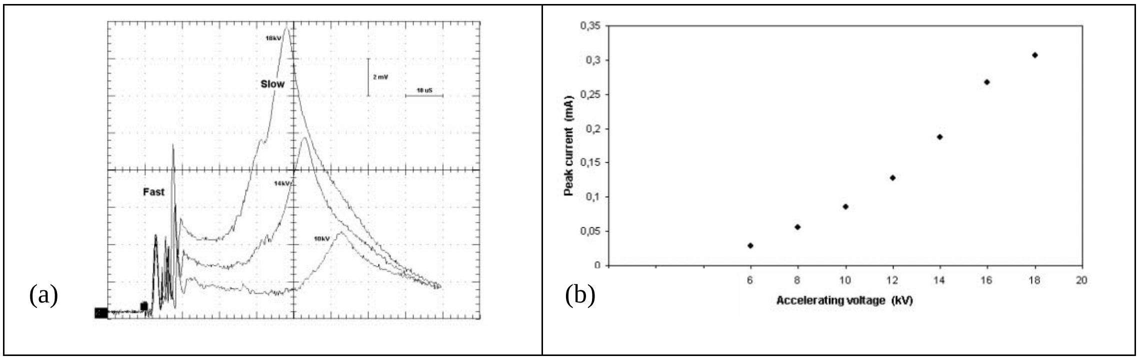
REFERENCES

[1] E. T. Kennedy, *Contemp. Phys.* **25**, 31 (1984)

[2] M. Von Allmen and A. Blatter, *Laser Beam Interaction with Materials: Physical Principles and Applications*, Berlin: Springer (1995).

[3] D. Doria, A. Lorusso, F. Belloni, V. Nassisi, L. Torrisi and S. Gammino, Laser Part. Beam 22, 461 (2004)

[4] D. Doria, A. Lorusso, F. Belloni and V. Nassisi, *Rev. Sci. Instrum.* **75,** 387 (2004)



(a) (b)

Figure 5: a) Waveforms of the extracted beam current at three different extraction voltages. Bunches of "fast" and "slow" ions can be distinguished. b) Extracted beam peak current as a function of the extraction voltage with SR not polarized.