Study of particle acceleration of Cu plasma

F. Belloni, D. Doria, A. Lorusso, and V. Nassisi

University of Lecce, Department of Physics, INFN of Lecce, Laboratorio di Elettronica Applicata e Strumentazione (LEAS), 73100 Lecce - I, Italy

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The experimental results of particle acceleration by plasma generated using a XeCl laser are described. The laser ion source developed is able to accelerate specific particles and to overcome the plasma effects which occur specially during the application of the accelerating voltage. In order to successfully execute this experiment, plasma expansion was highly necessary before the accelerating voltage application. For this goal an almost hermetic expanding chamber with a hole at its end, used as extraction electrode, was made. In this way arcs were eliminated and specific particles propagate in the drift tube. Time-of-flight and current intensity measurements of the ion beam have been done. The output signal, measured at 147 cm from the target, resulted modulated on ion mass-to-charge ratio and its maximum current was 220 μA at 18 kV accelerating voltage. Under the same accelerating value the bunch charge was estimated to be 4.2 nC. © 2004 American Institute of Physics. [DOI: 10.1063/1.1809285]

I. INTRODUCTION

Our INFN program consists in the development of techniques of particle acceleration by the generation of highly concentrated laser-plasma. To get the capability to accelerate ions of different mass without changing devices, is very interesting for many existing and future applications, both scientific and industrial. Machines of such potentiality can be realized by applying the pulsed laser ablation (PLA) technique which recently is growing just due to its multiple applications. In this way, only small changes (e.g., laser target) are necessary to get beams of different elements. Laser ion source (LIS) has also the potential to fulfill the requirement of high current ion beams.1

Complex ion beams are particularly useful for nano-structure construction,2 in realizing accelerators for ion implantation,3 for cultural heritage analysis,4 for biophysics and medicine applications.5

Laser-plasma is produced easily by focusing laser beams on solid targets. The plasma plume, consisting in a high concentration of ionised matter, evolves fairly perpendicularly to the target surface advantaging the beam propagation direction. Moreover, in these experiments, exploding plasma plume reaches temperatures of few hundred-thousands Kelvin,6 energy spread measurements of plasma particles have recorded energies up to about 1 keV with the present device,7 and up to thousands of keV by a photodissociation iodine laser system, PERUM.8

Preliminary studies have demonstrated that the overall degree of ionisation is about 16% near the target, due to the absorbed energy via inverse bremsstrahlung. Following the plasma expansion, recombination of the ions with electrons to form neutral particles takes place, emitting free-bound radiation. Therefore, to get a reliable device, it is necessary to construct large experimental chambers in order to allow the plasma expansion and to avoid short-circuits. Moreover, to get an efficient device, the accelerating voltage might be applied to the plasma before the substantial decrease in the ion percentage.

In this work we present the particle characteristics obtained by a short-wavelength excimer laser of relatively low intensity and the experimental results of the ion acceleration under the influence of low values of accelerating voltages, using an expanding chamber of moderate dimensions.

II. EXPERIMENTAL SETUP

The laser used in this experiment generated an ultraviolet beam by a XeCl mix. Its wavelength and time duration were 308 nm and 20 ns, respectively. A 70 mJ energy per pulse was centered onto a Cu target having a purity of 99.99% by a 15 cm focal length lens. The angle between the normal to the target surface and the laser beam was 70°. The laser spot was approximately 0.01 cm² and as a consequence the average fluence value resulted of about 7 J/cm² with a maximum value of 20 J/cm² only in the spot central part.

The accelerating apparatus utilized in this experiment was quite versatile and could be arranged in different configurations. It consisted of a generating chamber (GC) 26.5 cm long and a drift tube (DT) 124.3 cm long, see Fig. 1. The GC had an insulating flange (IF) where the target support was fixed. The target support was a 2 cm in diameter stem, with the Cu target on its end. An expanding chamber (EC) was mounted on the stem. In this experiment its task was very important.

Many attempts were done in order to accelerate plasma particles without the expanding chamber, but arcs were present in almost all experiments. The arcs short-circuited the target support to the ground and the accelerating voltage value decreased provoking a power supply extra-current. Therefore the EC developed in this experiment, was an almost hermetic cylinder, having only the hole necessary for the beam acceleration, operated on the electrode surface. The
EC length was about 18.5 cm. On its lateral surface an optics hole was bored, as the laser inlet port, and closed by a thin quartz window. The EC diameter was 9 cm and the distance between its pierced electrode and the target was 16.8 cm.

The ground electrode (GE) was an Al pierced disc fixed at 1.3 cm from the perforated EC electrode. It formed the accelerating gap together with the EC electrode surface. The accelerating zone area was 0.78 cm². A Faraday cup (FC) placed at the end of the DT, 147 cm from the target and 128 cm from accelerating gap, was utilized as a diagnostic system. In this position the cup had an acceptance angle of 3·10⁻⁶ sr showing that only a small part of the initial particles could be collected. The FC had got a suppressing ring (SR) that avoided the recording of the current due to secondary electron emission by charging the SR to a negative bias potential.

To stabilize the accelerating voltage, particularly during the accelerating process, a set of four buffer capacitors was connected between the target and ground. Each capacitor was 1 nF, 18 kV. So, the stored charge was much higher than the accelerated one maintaining constant the accelerating voltage value.

The interaction chamber was pumped by two independent turbomolecular pumps with a base vacuum of the 10⁻¹⁰ Torr.

III. EXPERIMENTAL RESULTS

Before the acceleration of the particles, we characterized the plasma by an electrostatic barrier (EB) (Ref. 9) and by an ion energy analyzer (IEA). The former was composed by three polarized electrodes placed in front of the cup, while the latter was composed by two bent electrodes charged to equal and opposite voltages V₀ and −V₀. Both systems were utilized to analyze the energy of the plasma particles. The EB method allowed us to determine the charged species energy by modifying the waveform of the free expanding plasma by the action of the suppressor electrode voltage. Namely, utilizing the ion current I₂(t) for z charge state ions obtained by the filtering action of the EB, one can get the ion energy distribution f₂(E) because the EB did not alter the time of flight:

\[ f₂(E) = \frac{I₂(t)^3}{zemd^2} \quad \text{and} \quad E = \frac{1}{2} \frac{m}{I} \frac{d^2}{L^2} , \]

where d is the target-cup distance, e and m are the electron charge and ion mass, respectively. With this technique only ions of energy up to about 350 eV were recorded.

The IEA method is more sensitive. It is able to detect particles that satisfy the following relations:

\[ \text{TOF} = L \sqrt{\frac{mze}{2\gamma V₀}} \quad \text{and} \quad E = \gamma zeV₀ , \]

where L is the distance between the target and the IEA (L =2 m) and \( \gamma \) is a constant depending on the system geometry (\( \gamma = 20 \)). Such a method allowed us to reveal ions of energy up to about 800 eV. This energy value was higher than the previous one but it was just due to the higher sensitivity of the IEA.

However, as we have seen above, the particles generated by PLA get a very low energy which is insufficient for many applications. Such a value of energy can be responsible for the chemical of the films produced by pulsed laser deposition (PLD). So, to accelerate particles means to increase further their energy. We could reach this goal applying high voltages to the insulated target support. The diagnostics of the extracted beam was performed by the Faraday cup normally closed on 50 W. By this configuration the cup waveform represented the real-time evolution of the ion pulse.

Before the acceleration of the particles, we characterized the plasma particles. To collect positive plasma flux, without any accelerating voltage, the FC was negatively polarized with a bias voltage up to −200 V. In this configuration the current recorded was independent of the SR polarization. The signal was a positive pulse starting at about 30 μs after the laser action. When the cup bias voltage was null, the cup recorded a negative pulse roughly equal and opposite to the positive one. Figure 2 shows the positive and negative pulses above mentioned. Since we expect an almost neutral plasma, these results were amazing at the first moment. In practice, our plasma was a nonequilibrium plasma whose characteristics are modified near the cup collector as well as at the metallic walls of the chamber. Applying a −0.55 V bias voltage to the cup, its response was null. On the contrary, decreasing the applied voltage to −0.77 V, the cup response became positive like that obtained with −200 V. This behavior can be ascribed to the low ion mobility and their center of mass velocity that favour the ion collection just at low potential values. However, by these results we can conclude that the ion current was in saturation regime just after −0.77 V and that the maximum charge collected was 140 nC. Moreover, from the low bias cup voltage applied to get ions, we assert that the binding energy of plasma ions was less than 0.77 eV.

The cup negative signal in absence of any bias voltage was due to the thermal velocities of plasma particles. Since
the electrons moved much faster than ions, because of their small mass, the recorded pulse was negative. The negative pulse charge increased up to 450 nC by increasing the bias value. For the electron current, the saturation regime was got at 70 V. This higher bias voltage necessary to obtain the electron saturation current was due to the higher energy necessary to repel ions from the cup collector during the plasma bunch owing to its centre of mass velocity direction.

By the temperature measurements performed previously, 500 000 K, applying the well known thermodynamic relation, $\frac{3}{2}kT$, we expected a particle energy of about 65 eV.\textsuperscript{7,11} Instead, by our measurements we found a maximum energy value of 770 meV for the positive particles and 70 eV for negative ones. Neither values correspond with that expected. However, in this kind of experiments it is very difficult to determine, by direct measurements, the thermal energy of the particles. In fact, the cup output signal was the difference of potential between the cup collector and the chamber wall, this last connected to ground. The effect of the plasma interaction on both the cup collector and chamber wall must necessarily be the same, but the plasma resistance present was different as the cup bias polarity changed. This difference provoked a lower saturation voltage value for the ions which represented only part of their thermal energy.

To further explain the plasma behaviour we have performed experiments closing the cup signal on 1 MW load resistance without any bias polarization. In this case we observed a positive signal coincident with the laser onset time.
Since the cup-target distance was 147 cm, the signal could not be ascribed to plasma particles, but to a photoelectric emission processes. Namely, by photoelectric effect the electrons escaped from the cup because the soft x rays energy was sufficiently higher than the work function of the collector metal. As a consequence the FC collector became positively charged. Figure 3 shows the cup signal waveform under the above conditions at different laser energies. For time higher than 30 µs, at 70 mJ laser energy, the cup was struck also by the plasma bunch, composed by electrons and ions. Due to the higher electron velocity, the cup response became negative until the tail of the plasma signal. In this case the response signals were higher than the corresponding ones recorded with the cup closed on 50 W and therefore it was possible to perform measurements even at lower laser energies. At laser energies higher than about 3 mJ, corresponding to waveforms 1–3 in Fig. 3, the cup signals present a positive pulse at fast time scale, induced by the photoemission process. At 3 mJ laser energy (waveform 4), in correspondence with the plasma bunch (at about 100 µs) a positive signal overcomes the negative one present at higher laser energy. In fact, at low laser energy the plasma concentration was very low and the electrons easily can escape from the plasma charging it positively (see Fig. 4).

The accelerating studies were performed with the cup closed on 50 Ω. Applying an acceleration voltage to the target stem, an electric field in the accelerating gap was present. Under the acceleration process the cup signal varied with accelerating voltage. In particular, the signal resulted modulated by small peaks at fast time and a large peak at slow time. We ascribe the fast peaks to suprathermal species and light ions of H, C, and O. The former escaped easily from the

![FIG. 4. Plasma current waveform recorded at 20 cm from the target. 1: Laser signal; 2: Faraday cup signal.](image)

![FIG. 5. Waveforms of the extracted beam current at three different accelerating voltages. Bunches of “fast” and “slow” ions can be distinguished.](image)
plasma edge as well as the light ones, so both reached the accelerating gap in a few microseconds and next the cup. Figure 5 shows the waveforms of the accelerated species at several accelerating voltages. Their FWHM, for all voltages applied, resulted higher than one of the plasma flux measured immediately beyond the accelerating gap (Fig. 4) which was of about 10 μs, in the absence of an accelerating voltage. In fact, due to the large spread of the initial energy of the particles, we expected an accelerated pulse having a FWHM higher than 10 μs, as one can see in Fig. 5. The peak current and the extracted charge increased with the accelerating voltage, as shown in Figs. 6 and 7, respectively. The maximum current was recorded at the maximum accelerating voltage, 18 kV, and resulted 312 μA with a charge bunch of 6 nC. These values were obtained without any bias voltage on the SR. Applying a −100 V polarization value on the SR the current output decreased of a factor of 30%. Taking into account that the cup acceptance is only 3 · 10^{-3} sr, a higher output current could be recorded.

IV. DISCUSSION

We have performed preliminary experiments on a laser ion source at relatively low incident energy. Before the acceleration of the particles, we characterized the free expanding plasma flux, revealing both ion and electron components by means of a Faraday cup and a bias voltage. When the extraction voltage was applied, what we concluded was the indispensability of a suitable expanding chamber in order to avoid arcs. The maximum accelerating voltage applied to the extraction gap was 18 kV, resulting in an ion bunch of 4.2 nC and a peak current of 220 μA, under a cup acceptance angle of 3 · 10^{-3} sr.

The accelerated charge was obtained by an accelerating gap of 1 cm in diameter. However, the output current could be higher increasing the gap diameter.

Taking into account that the relative abundance of Cu^{+2} ions was negligible with respect to the Cu^{+1} one, we estimated that the accelerated bunch consisted of about 2.6 · 10^{10} ions, while the total ion yield was of about 3.1 · 10^{13} particles. Considering that an initial laser energy of 70 mJ was spent in ions production, a specific energy amount of about 2.7 pJ/ion, equivalent to 17 MeV/ion, was estimated to be necessary in getting the extracted bunch. Referring to the overall ion yield, the specific energy resulted of about 2.3 fJ/ion, equivalent to 14 keV/ion.

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**FIG. 6.** Extracted beam peak current as a function of the accelerating voltage with SR not polarized. Current and accelerating voltage normalized to the lowest value (29 μA and 6 kV, respectively).

**FIG. 7.** Extracted charge as a function of the accelerating voltage with SR not polarized. Charge and accelerating voltage normalized to the lowest value (0.7 nC and 6 kV, respectively).
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