On the Emittance dependence on anode morphology of laser induced ion beams

L Velardi\textsuperscript{1}, D Delle Side and V Nassisi
LEAS Laboratorio, Dipartimento di Matematica e Fisica, INFN sezione di Lecce, Università del Salento, Italia

E-mail: luciano.velardi@le.infn.it

Abstract. In this work, we studied the characteristics of ion beams generated by PLATONE accelerator in different anode configurations. The accelerator is a laser ion source with two gaps which accelerate the ions in cascade. The laser is an excimer KrF able to work at irradiances of $10^8 - 10^{10}$ W/cm$^2$. The target ablated was disk of Cu. The accelerating voltage applied in this work was 60 kV. The emittance evaluation was performed by the pepper pot method utilising radio-chromic films, EBT Gafchromic, as sensible targets. The study was performed by varying the geometric configuration of the anode (the extracting electrode), modifying the hole morphology. A plane and curved grids were mounted in order to change the extraction configuration. The results were compared with the ones obtained with the extraction hole without any grid. For the normalized emittance the lowest value found was 0.20 π mm mrad.

1. Introduction

In the last decades, new techniques by interaction between high power femtosecond laser pulses and thin foils\cite{1} are employed to produce ion beams. In contrast with other techniques, these give the advantage to obtain highly collimated and energetic particle beams from the rear of the target surface. Two mechanisms are involved in the ion acceleration: target normal sheath acceleration (TNSA) \cite{2} and radiation pressure acceleration (RPA) \cite{3}. Despite of the high quality beams obtained through TNSA and RPA systems, older and well known techniques, such as pulsed laser ablation (PLA), still play a fundamental role for applications, since the former have extremely high total costs of ownership and require large space for its working.

The PLA technique works at intensities of the order of $10^8 - 10^{10}$ W/cm$^2$, producing hot plasmas\cite{4} from which it is possible to extract ion beams whose energy can be increased up to some tens of keV by applying post acceleration\cite{5,6}. Nowadays, ion beams of moderate energy have a wide range of applications, from scientific to industrial ones\cite{7-9}. Consequently many laboratories, as well as the LEAS, are involved to develop accelerators of very contained dimensions, easy to be installed in little laboratories and hospitals.

In this work, we characterize ion beams provided by a laser ion source (LIS) accelerator composed by two independent accelerating sectors, using an excimer KrF laser to get PLA from a pure Cu target. Using a pepper pot system and a Faraday cup, we characterized the geometric quality of the

\textsuperscript{1} To whom any correspondence should be addressed.
beams, evaluating the emittance and the extracted charge for different morphologic configurations of the extracting electrode, in order to understand how these changes influence the resulting beams. The emittance is an important parameter that characterizes charged particle beams. It is the measure for the average spread of particle coordinates in position and momentum phase space. So it is necessary to have low emittance to increase the quality of the particle beam, when it is required a paraxial beam with low divergence.

2. Experimental setup
The Platone accelerator is a LIS source with an electrostatic system to extract and accelerate the ions from the plasma plume. It consists of a KrF excimer laser operating in the UV range ($\lambda = 248$ nm, $\tau = 25$ ns) to get PLA from solid targets and a vacuum chamber device for the expansion of the plasma plume. The maximum output energy of the laser is 600 mJ. The angle formed by the laser beam with respect to the normal to the target surface is $70^\circ$. Focalizing the laser beam by a thin lens of 15 cm length, the spot area onto the target surface was $0.005 \, \text{cm}^2$, obtaining irradiances of the order of $10^8$-$10^9 \, \text{W/cm}^2$. The target was a pure disk (99.99%) of Cu.

![Figure 1. Schematic drawing of the LIS accelerator (T: Target support, EC: Expansion Chamber, GE: Ground Electrode, R: Radiochromic, TE: Third Electrode).](image)

The accelerating system consists of three parts, Fig. 1: i) an expansion chamber (EC) placed around the target support (T) at a positive high voltage (HV) of $+40 \, \text{kV}$; ii) a pierce ground electrode (GE) placed at 3 cm distance from EC; iii) a third electrode (TE, 30 mm diameter) placed at 2 cm from GE connected to a power supply of negative bias voltage of $20 \, \text{kV}$.

The EC and GE holes have both a 15 mm diameter. In this way, applying 40 kV at EC and 20 kV at TE, it is possible to generate an intense accelerating electric field in two gaps, between EC-GE and GE-TE, able to extract and accelerate the positive ion of the plasma plume. Four capacitors of 1 nF, between EC and ground, stabilize the accelerating voltage during the fast ion extraction.

TE is also utilized as Faraday cup collector. It is connected to the oscilloscope by a HV capacitor (2 nF) to separate the oscilloscope from the HV and a voltage attenuator, x20, to suit the electric signal to oscilloscope voltage. The value of the capacitors applied to stabilize the accelerating voltage (4 nF) and to separate the oscilloscope from the HV (2 nF) are calculated assuming a storage charge higher that the extracted one. Under this condition, the accelerating voltages during the charge extraction is constant as well as the oscilloscope is able to record the real signal.

TE is not able to support the suppressing electrode on the cup collector and therefore secondary electron emission, caused by high ion energy, is present leading to register more charge on FC. In order to compare the efficiency of the extraction and the geometric quality of the beams we
varied the configuration of the EC (the extracting electrode) by modifying the hole. We mounted grids (with an attenuation factor of 20%) and so we obtained three configurations (see Fig. 2). Figure 2 shows the photos of the anode: a) extraction hole without grid; b) extraction hole with a plane grid; c) extraction hole with an inward curved grid, radius 0.8 cm.

![Figure 2. Photos of the extraction hole without a grid (a), with a plane grid (b) and with an inward curved grid (c).](image)

Using TE as Faraday cup and a pepper pot system[10], we studied the geometric quality of the beams and the extracted charges. Figure 3 shows a sketch of the system used to evaluate[10] the emittance by pepper pot technique. The emittance is related to the area of the ellipse in the trace plane. The mask we used was made of aluminum, in order to evacuate the charges impinging on its surface. It has 5 holes of 1mm in diameter and it was fixed on the GE. One hole is in the centre of the mask and 4 holes are at 3.5mm from the centre. We used as photo-sensible screen radiochromic films (R) Gafchromic EBT, placed on TE.

![Figure 3. Sketch of the system used to measure the emittance value by pepper pot technique.](image)

Radiochromic detectors involve the direct impression of a material by the absorption of energetic radiation, without requiring latent chemical, optical, or thermal development or amplification. A radiochromic film changes its optical density as a function of the absorbed dose. This property and the relative ease of use, led to adopt these detectors as simple ion beam transverse properties diagnostic tools. So, the ion beam after the mask imprinted the radiochromic film and then it was possible to measure the divergence of all beamlets. The divergence values allowed to determine the beam area in the trace plane (TPx). For a z-axis beam propagation, the x-plane emittance $\epsilon_\alpha$ is $1/\pi$ times the area $A\alpha$ in the TPx occupied by the points representing the beam particles at a given value of $z$. 
3. Results

We applied 250 laser shots to imprint the radio-chromic films. We measured the emittance for the three different anode configurations. By radiochromic images we drew the ellipses in the trace plane and we calculated the area in the TPx. Moreover, by Liouville's theorem it is known that the area occupied by the particle beam in phase plane (PPx) is an invariant quantity and the normalized emittance is:

\[ \varepsilon_{nx} = \beta \gamma \varepsilon_s \]  

where \( \beta = v/c \) and \( \gamma \) is the Lorentz factor.

The results at the maximum accelerating voltage are shown in Fig. 4. In the figure it is inserted the table of the emittance values we measured. The results obtained show that the lowest emittance value, 435 mm mrad, is provided by the anode without any grid. Considering equation (1) we found the normalized emittance value, which resulted \( \varepsilon_{nx} = 0.20 \pi \) mm mrad.

![Trace Plane - Emittance](image)

**Figure 4.** Emittance diagram in the trace plane for different anode configurations.

The experimental results were confirmed by a simulation study, performed with Comsol Multiphysics v3.5 software [11]. In Fig. 5 it is shown the simulation of Cu\(^{1+}\) beams (black lines) under 40+20 kV of accelerating voltage. The gray lines represent the electric streamline distribution.

![Comsol simulations](image)

**Figure 5.** Comsol simulations of Cu\(^{1+}\) beams (black lines) under 60 kV of accelerating voltage for different anode configurations. The gray lines represent the electric streamline.
The simulations showed, in accordance with the results obtained experimentally, that: i) the hole without grid (a) focus the ion beam near the extraction hole and reduces its divergence and emittance; ii) the hole with the plane grid (b) enlarges the beam and forms a paraxial beam with a good emittance value, but larger than that obtained with configuration (a); iii) the behaviour of the hole with the curved grid (c) is similar a convergent lens which diverges the beam after the focus position, increasing its emittance.

The results presented in this work confirm and extend a finding presented in a previously published work[12], showing that the PLATONE setup is a very promising LIS that could be considered to feed large accelerators.

4. Conclusion
In this work we investigated how the morphology of the extraction anode in a LIS affects the beam qualities. We have shown that the presence of a grid on the extraction hole of EC modifies both the emittance and the total extracted charge. Increasing the voltage of the first accelerating gap, we increased substantially the efficiency of the extracted current due to the rise of the electric field and extracting volume inside the EC. We measured the geometric characteristics of the beam by means of the pepper pot technique and we found that the optimal configuration both for emittance and charge extraction is that without any grid. In this configuration, we obtained the lowest value for the normalized emittance, $\varepsilon_{\text{nx}} = 0.20 \pi \text{ mm mrad}$ and the maximum charge extracted, $1.1 \mu \text{C}$. Finally, the findings obtained in this work suggest that improvements on the quality of the beams could be obtained only by changes in the geometry of the apparatus.

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