Velocity distribution of ions in UV laser induced plasma plumes

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Abstract. Plasmas induced by UV laser ablation have been studied and analysed using time-of-flight measurements. A KrF laser beam of 23 ns FWHM time duration was focused into Si and Nb targets with a moderate laser fluence of 2 J/cm$^2$. A suitable theoretical expressions were derived for fitting the recorded ion current under the assumption of a “shifted” Maxwell-Boltzmann velocity distribution. The deconvolution of time resolved ion current signals, taking into account a multi-mode velocity distribution has revealed that the contribution of the different charge states of ions in the plasma induces electric field which accelerate the expanding plasma along the target normal.

1. Introduction
Interest in laser-produced particle beams is being stimulated by a series of applications during the last few years. In particular, the investigation of the characteristic of the ion component of the plasma plays a key role in understanding the processes on the basis of the laser-target interaction [1-3]. Furthermore, the ion energy distribution study is helpful to understand if the laser induced plasma is characterized by the presence of an ambipolar electric field known in literature as double layer (DL) [4, 5]. The DL is, in fact, formed as result of the spatial charge separation in the expanding plasma breaking the quasineutrality of the plasma. In the high power laser irradiance the presence of DL divides the expanding plasma into regions with thermal and accelerated ions resulting with a multipeak ion current signals [6, 7].

Nevertheless, the evidence of the ion energy distribution of the laser induced plasma at moderate laser fluence found also a possible explanation in the presence of an ambipolar electric field which is responsible of the ion acceleration. The presence of the DL in the laser induced plasma influences the
kinetics and the angular spread of ions which are fundamental parameters for pulsed laser deposition of thin solid films as well as for the development of laser ion sources.

This work presents a study of the time resolved ion current signals by the deconvolution method taking into account the contribution of the different charge states of ions. The study is useful to understand if the kinetic energy distribution of ions is influenced by a possible presence of DL.

2. Experiment

The measurements of the ion currents are performed in a vacuum chamber of $10^{-5}$ mbar by Faraday cups (FC) placed in front to the target as shown in the Fig. 1a.

![Figure 1. Sketches of the experimental apparatus: a) vacuum chamber; b) FC array placed in front to the target.](image)

The operating circuit of FC is well described elsewhere [8]. The laser plasma is induced by using a KrF excimer laser (Lambda Physics, Compex) of 248 nm laser wavelength and FWHM pulse duration of 23 ns. The laser beam is focused by a 150 mm focal length lens with a resulting spot area of about 1 mm$^2$ and a laser fluence of 2 J/cm$^2$.

An array of nine FC is placed in front to the target at a distance of 90 mm in order to diagnostic the plasma characteristics. On the point of view of the target, the cups, placed on the left side, are labeled as +4, +3, +2, +1; the cup along to the target normal is labeled as 0, while the cups placed on the right side are -4, -3, -2, -1.

The cups are 9 mm in diameter and 11.5 mm distant from each other (see Fig. 1b). All cups are inserted into the grounded flange, insulated among them and coaxially connected to a BNC of 50 Ω which is able to derive the ion current signal to the oscilloscope.

3. Results and discussions

Typical time of flight ion signals recorded by the 9 cups are shown in the Fig. 2a and 2b for the Si and Nb targets, respectively.
Figure 2. Time of flight ion current signals recorded by the different cups.

It is noteworthy to observe that the highest ion current signal is recorded by -1 cup and that the vast majority of ions are ejected within a small solid angle respect to the target normal while their abundance decreases along the oblique directions, e.g. +4 and +3 cups.

Furthermore, the cups in proximity of the target normal detect ion signals characterized by anticipated time of flight. Such a kind of ion acceleration could be justified in terms of ambipolar electric field formation. The formation of the DL is, in fact, associated with the generation of hot electrons ascribed to the absorption of the incident laser radiation due to inverse bremsstrahlung [9] and to three-body recombination processes [10]. The electrons escape mainly along the target normal inducing the formation of electric field with the ions of different charge states.

In order to confirm the above hypothesis, let deconvolute the ion current signals taking into account a multi-mode velocity distribution along the contribution of the different charge states of ions carried out by the plasma.

Due to the collisions among the ions in the initial phase of the plasma expansion, the Knudsen-layer formation is responsible of the velocity distribution of ions which is well described by a shifted Maxwell–Boltzmann distribution. As it has been demonstrated [2, 8], it is possible to derive the equation for the ion current based on the shifted Maxwell–Boltzmann distribution (MBD):

$$I(t) \propto t^{-3} \exp[-\beta^2(L-u t)^2 / t^2]$$  \hspace{1cm} (1)

where $\beta^2$ stands for $m/2kT$, with $m$ the atomic mass of the ion species, $k$ the Boltzmann constant, $T$ the Knudsen-layer temperature, $L$ the target-cups distance and $u$ the centre of mass velocity of ions.

The program Peakfit 4.12 version is utilized to perform the deconvolution analysis sharing the temperature parameter among the different charge states keeping the other parameters as free variables, e.g. the centre of mass velocity of the charge states, $u_i$.

An example of the deconvolution is reported in Fig. 3 concerning the Si ion signal recorded by -1 and +4 cups. The dash lines of different colors represent the contribution of the different charge states of ions while the red continues line represents the fit of the experimental data (dot points) obtained by the sum of the different charge state contribution. It is noteworthy the presence of Si$^{+4}$ for -1 cup signal as well as a much more abundance of the difference charge states.
| Charge state | Collected charge (nC) | Temperature (eV) | Centre of mass velocity (m/s) |
|--------------|-----------------------|-----------------|-----------------------------|
| 3            | 1.1                   | 2.3             | 21.7x10^3                   |
| 2            | 1.3                   | 2.3             | 16.8x10^3                   |
| 1            | 0.2                   | 2.3             | 12.1x10^3                   |

| Charge state | Collected charge (nC) | Temperature (eV) | Centre of mass velocity (m/s) |
|--------------|-----------------------|-----------------|-----------------------------|
| 4            | 2.6                   | 2.8             | 35x10^3                     |
| 3            | 3                     | 2.8             | 28.4x10^3                   |
| 2            | 3.4                   | 2.8             | 21.6x10^3                   |
| 1            | 5                     | 2.8             | 15.2x10^3                   |

**Figure 3.** Deconvolution of time of flight signals for laser induced Si plasma. The temperature and the centre of mass velocity values are obtained by fitting the experimental data by Eq. (1).

Beside, in Fig. 4 the values of $u_q$ are reported on the detector angle position for the different charge states. The enhancement of $u_q$ is present in proximity of the target normal with the evidence of an abrupt change of slope for Si$^{+4}$ and Nb$^{+4}$. Such result can be justified by the possible presence of DL in the expanded laser-induced plasma which much more influences the expansion of ions with higher charge state.

**Figure 4.** Dependence of the centre of mass velocity $u_q$ of the different charge states of ions on the detector angle position.
4. Conclusions

The time of flight spectrometry with cups placed at different angular position respect to the target normal is very useful to study the characteristics of the UV laser induced Si and Nb plasmas. In particular, the time resolved ion current signals reveal a decreasing of the time of flight when the signals are recorded in the proximity of the target normal.

The justification of the experimental results has to be found in the presence of an ambipolar electric field which accelerated the most energetic particles mainly along the target normal. The deconvolution of ion current signals is useful to give confirmation of our idea. The increasing of the centre of mass velocity on the different detector angle is ascribed, indeed, to the presence of an ambipolar electric field in the laser plasma.

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