# A LASER DRIVEN ACCELERATION METHOD*

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*Abstract*

Traditional ion accelerators use quite large buildings and complex/expensive instruments to produce mono-energetic ion beams with energies of the order of 100 keV/nucleon and current densities of the order of 1 mA/cm$^2$. Powerful pulsed lasers irradiating in vacuum solid targets produce hot and very dense non-equilibrium plasmas with high average charge state. A laser ion source (LIS) can be obtained with a pulsed laser at intensities of the order of $10^{10}$ W/cm$^2$ or upper, with pulse duration of the order of few ns and repetition rate of the order of 10 Hz. High directivity electric fields are generated inside the non equilibrium plasmas with intensities higher than 10 MV/cm. Ions are emitted from the plasma in the direction of the electric field with energies of the order of tens or hundreds eV/nucleon, depending on the laser intensity. Emitted ions have a Boltzmann ion energy distribution depending on the ion charge state. Ion post-acceleration and analysis by means of high electric and magnetic fields can be provided.

## INTRODUCTION

A laser-generated plasma is a non equilibrium plasma that produces high electric field pulses which accelerate directionally the ions. High kinetic energies, charge states and currents can be obtained. When Nd:Yag laser intensities of the order of $10^{10}$ W/cm$^2$ irradiate metallic targets it is possible to obtain heavy ions with kinetic energies up to about 10 keV, charge states up to about $10^+$ and current densities up to about 1 mA/cm$^2$ [1]. The ion emission is narrow around the normal to the target surface with an aperture of the order of ± 30° [2]. The ion emission can be repetitive and constant by using 30 Hz laser repetition rate and by irradiating a roto-translating target, so that the laser ablates a continuously fresh surface.

Three phenomena are responsible of the ion energy increase: the thermal interactions, the adiabatic expansion of the plasma in vacuum and the Coulomb interactions. The ion energy distribution follows a Boltzmann function which is shifted towards high energies, when increasing the charge state and the plasma temperature [1]. The ion energy and directivity can be increased by using a positive bias of the metallic target and a post-acceleration and focalization system. In this way it is possible to provide pulsed multi-energetic ion beams for ion implantation processes [3]. If the laser pulse intensity is increased, it is possible to obtain plasmas with higher temperature and densities and the ion energy may reach values of the order of MeV and charge states higher than $50^+$ [4]. However, in the case here described only single ion pulses have been obtained because the laser repetition rate was low.

## EXPERIMENTAL SETUP

Figure 1: Photo of the experimental set-up at INFN-LNS of Catania.

Fig. 1 shows a photo of the experimental set-up used at INFN-LNS of Catania. A Nd:Yag laser, 1064 nm fundamental wavelength, 9 ns pulse width, 900 mJ maximum energy, 30 Hz repetition rate and a focal spot of the order of 1 mm$^2$, is employed to irradiate metallic targets in high vacuum ($10^{-7}$ mbar).

Different diagnostics monitor the plasma properties. The time-of-flight (TOF) technique is used to measure the mean ion energy and to analyze the energy-to-charge ratio by means of an electrostatic deflection ion energy analyzer (IEA) system. The measurement of the ion energy distribution is possible by using a variable deflection bias and detecting different energy-to-charge ratios. The fit of the distribution with Boltzmann functions gives an indication of the equivalent temperature of the plasma core. A mass quadrupole spectrometer monitors the mass species emitted from the plasma. An optical spectrometer analyzes the characteristic lines from the neutral and ionized species in order to evaluate the coronal temperature and density of the plasma. A fast CCD image permits to measure the plasma plume volume and, in connection with the measurement of the crater volume on the target surface, it is possible to evaluate the atomic and electron plasma densities [5]. Different Faraday cups (IC) placed at different angles with respect to the normal to the irradiated targets permit to measure the angular distribution of emitted ions.

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## RESULTS

Fig. 2 (top) shows a typical IEA spectrum obtained by irradiating an Ag target at 9.3 J/cm$^2$ fluence, 280 mJ pulse energy and by detecting the ions along the normal direction ($f_{det}$ = 0°) with U = 60 V deflecting bias, corresponding to an energy filtering of E/z = 600 eV/charge state. The negative peaks indicate that six charge states, identifiable through the different TOFs, are produced in the expanding plasma. The same plot (bottom) shows the IC signal registered along the IEA direction. This spectrum permits to check the total ion yield entering in the IEA input, so that the detection angle can be improved and the ion signal optimized.

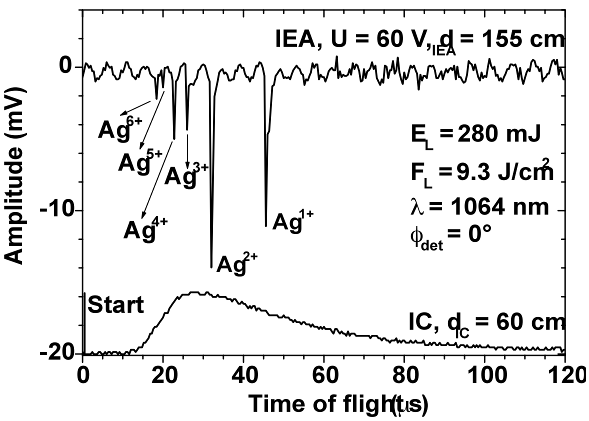


Figure 2: IEA spectrum of Ag ions (top) and IC spectrum of the total ion emission (bottom).

By changing U in the range 10÷180 V, different E/z ratio have been selected and different spectra have been collected. The analysis of these spectra permitted to plot the ion energy distributions for the different charge states, as reported in Fig. 3. Experimental data indicate that the ions have Boltzmann-like distribution depending on their charge state. Increasing the charge state the mean ion energy shifts towards higher values. This result is in agreement with the Boltzmann-Coulomb-shifted distribution (BCSD) [1, 6].

The ion energy distributions contain information regarding not only the ion temperature ($T_i$) but also the Coulomb interactions occurring in the non-equilibrium plasma. The total energy ($E$) of the ions detected through the IEA, in fact, is due to three different contributions: (i) thermal energy ($E_T = 3k_BT/2$), (ii) adiabatic expansion energy ($E_A = gk_BT/2$, where g is the adiabatic coefficient), (iii) Coulomb energy ($E_C$). We focused our attention on the latter contribution due to an acceleration potential generated by the local spatial separation effects occurring in the laser-generated plasma. The Coulomb energy can be expressed as $E_C = zeV_0$, where $ze$ is the ion charge and $V_0$ is the acceleration potential developed inside the non-equilibrium plasma. Finally, the experimental data can be fitted by using the BCSD:

$$f(E) = \frac{A}{\sqrt{m}}\sqrt{\frac{1}{(\pi k_B T)^3}}(E - E_A - E_C)\exp\left(-\frac{E - E_A - E_C}{k_B T}\right) \quad (1)$$

where A is a normalization constant and m the ion mass.

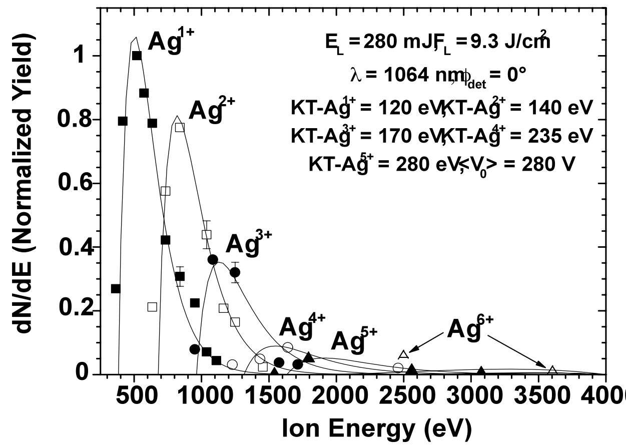


Figure 3: Ion energy distributions of the Ag plasma for different charge states.

The fitting parameters ($T$ and $E_C$) determine the equivalent ion temperature and the acceleration potential. The ion temperatures assume mean values of about 140 eV for Ag$^{1+,2+,3+}$ and 260 eV for Ag$^{4+,5+}$. The calculated acceleration potential is approximately constant for the five different fits and assumes a mean value of about 280 V. Moreover, this acceleration is not isotropic but strongly directed along the normal to the target surface, i.e. along the main direction of the expanding plasma plume.

The maximum electron temperature, $T_e$, and density, $n_e$, obtained at INFN-LNS laser regime are of the order of 100 eV and 10$^{17}$/cm$^3$, respectively. With such value, assuming the plasma to be in near local thermal equilibrium (LTE) conditions, the Debye length assumes a value of the order of:

$$\lambda_D = 743\,(T_e/n_e)^{1/2} = 0.24\ \mu m \quad (2)$$

Assuming the ion acceleration voltage $V_0$ to be applied to the Debye length, the corresponding electric field assumes the value:

$$E = V_0/\lambda_D = 11.7\ \text{MV/cm} \quad (3)$$

Measurements demonstrated that with the decrease of the laser spot dimension the laser intensity increases and, consequently, the equivalent temperature and the plasma density increases as well. This effect produces also a charge state enhancement, an electric field increase and finally an ion energy increase.

At the highest laser intensities the electric field can reach values of the order of tens GV/cm [7].

The post-acceleration by means of 50 kV voltage between the target (positive) and a cylindrical deflector placed in front of the target (ground), produces a separation between the ion energy distributions depending on their charge state. The ion beam so obtained has a total current of about 1 mA over six charge states with different intensities. Fig. 4 shows a simulation of the ion emission trajectories from the laser irradiated target, performed with Tosca Opera 3D code [8]. The insertion of a magnetic field between the target and the cylindrical deflector improves the ion focalization along the system axis, increasing the axial current. In the simulation Ta ions produced by 800 mJ laser pulse plasma feel a 50 KV post acceleration and 1T magnetic focalization.

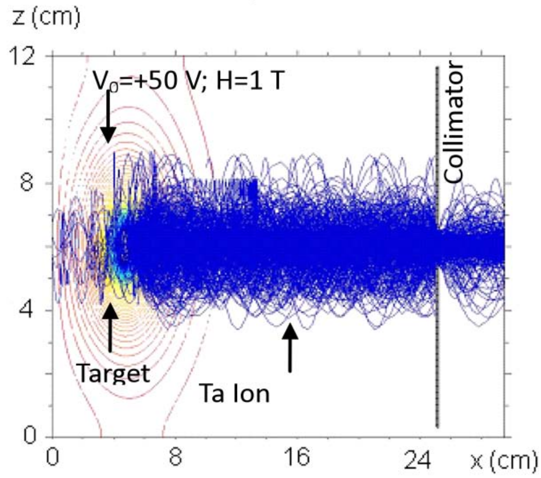


Figure 4: Ta ion focalization due to 50 KV acceleration voltage and 1T magnetic field application.

The ion focalization increases the dose of the implanted surfaces, while the ion post-acceleration induces different ion ranges in the substrates and consequently it diffuses the ion energy deposition in large surface layers.

Implanted ion beams on silicon substrates, extracted from a Ge laser-generated plasma, have been accelerated by 50 kV post acceleration in presence of a 0.1 T magnetic focalization, then they have been analyzed off-line by means of 2 MeV Rutherford backscattering spectrometry (RBS). This analysis has permitted to calculate the implanted ion dose and the ion depth profile

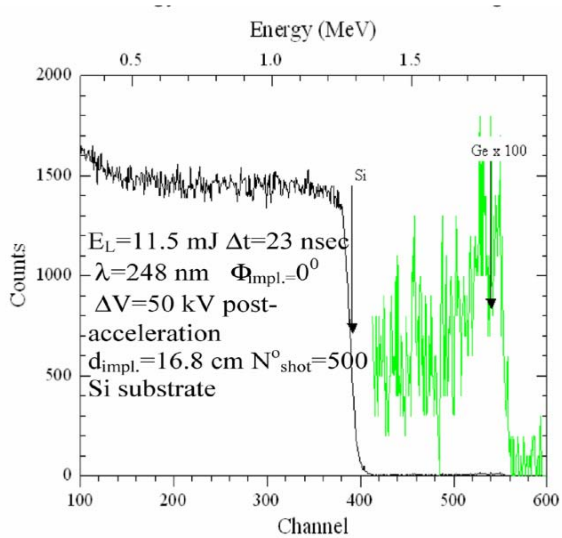


Figure 5: RBS spectrum of Ge ion implantation on Si-substrate.

in the substrate. Obtained results are in good agreement with the ion energy distributions measured through IEA.

Fig. 5 shows a RBS spectrum of Ge ion implantation on Si-substrate (a). The implantation, obtained at 800 mJ laser pulse energy, is direct along the normal to the target surface direction, i.e. along the maximum value of the electric field acceleration. The Ge depth profile indicates that the ion range reaches about 300 nm, corresponding to Ge ions energies of about 450 keV, in agreement with an ion acceleration of $Ge^{9+}$ due to 50 kV acceleration voltages [9].

## DISCUSSION AND CONCLUSION

The results shown in this paper confirm that the laser-generated plasmas accelerate ions along the normal to the target surface. The accelerated ions are not mono-energetic but multi-energetic, and they have high charge state and quite high current density.

At lower laser intensities the laser repetition rate can reach more than 30 Hz and a near cw ion beam current can be extracted. In this case a post-acceleration system may be used in order to increase the beam intensity and directivity.

Experiments performed at INFN-LNS of Catania permitted to deposit, or to implant high ion doses on different substrates. The use of electrical and magnetic field located near the target surface may be used in order to have a better control of the ion dose implanted in the substrate at lower laser intensities. Moreover, their use can be employed to select the ion species or to implant only the energetic ions without interaction of electrons, neutrals, clusters and contaminants with the substrate surface.

The multi-energetic ion implantation is a process very useful for the surface property modifications. Hardness, wear, mechanical and chemical resistance, chemical reactivity, electrical conductivity, semiconductor's parameters and wetting represent some properties which can be modified through the use of multi-energetic ion implantation obtained with laser-generated ions.

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