PROTONS PRODUCTION BY THIN FILMS LASER ABLATION

F. Caridi[1,4], L. Torrisi[2,3], L. Giuffrida[2,3], M. Cutroneo[2,4]

[1]Facoltà di Scienze MM. FF. NN.-Univ. di Messina, Ctr. Papardo 31, 98166 S. Agata, Messina, Italy
[2]Dip.to di Fisica, Univ. di Messina, Ctr. Papardo 31, 98166 S. Agata, Messina, Italy
[3]INFN-LNS of Catania, V. S. Sofia 64, 95125 Catania, Italy
[4]INFN-Sez. CT, Gr. Coll. Messina, Ctr. Papardo 31, 98166 S. Agata, Messina, Italy

Abstract

Proton beams production by ns low intensity pulsed Nd:Yag laser ablation of thin solid hydrogenated targets is investigated. The ion emission is analyzed with the time-of-flight (TOF) technique using ion collectors in backward and forward detection directions. The IC spectra deconvolution through Boltzmann-Coulomb-shifted function permits to evaluate the plasma temperature, density, proton energy and relative yield, ion energy and charge state distributions.
Special targets, based on polymers coupled to metals or to nanostructures, can be used to obtain a high protons acceleration up to a kinetic energy of about 200 eV.

INTRODUCTION

The ion acceleration from thin targets irradiated by low energy pulsed lasers is a research field several investigated in the last years. However the proton acceleration has been less considered in this regime due to the difficulty to detect the low energetic protons, to measure the proton energy distribution and to analyze the low proton amount involved in the plasma acceleration process.
Generally proton energies remain below 100 eV at laser intensities of the order of 10^{10} W/cm^2 or less. However, the use of a post-ion acceleration process may permit to increase the ion energy proportionally to the applied acceleration voltage and to the ion charge state [1]. Moreover, the use of suitable magnetic and electric fields permits to focus the ion beam and to increase its emittance [2]. The kinetic proton energy can also be increased by choosing opportunely the laser irradiated target, for example by using hydrogenated and metal doped polymers, as recently reported in literature [3].
The ion and proton detection based on time-of-flight (TOF) technique remains a simple but very efficient method to investigate about the ion stream emission of the fast non-equilibrium plasma produced by a laser shot, as will be demonstrated in this article.

MATERIALS AND METHODS

A *Q*-switched Nd:Yag pulsed laser operating at 532 nm second harmonic wavelength, with 3 ns pulse duration and 150 mJ pulse energy, in single laser shot, is employed for this experiment.
The laser beam is focused, through a 50 cm focal lens placed in air, on the surface of a thin (1-150 μm thickness) target placed inside a vacuum chamber at 10^{-6} mbar. The laser light passes through a thin glass window and hits the target, on which it produces a 1 mm^2 spot size, with an incidence angle of 45°.
The employed targets are hydrogenated materials, in order to produce high proton emission. In particular, they are: thin mylar films, from 2 μm up to 100 μm thickness, covered or uncovered by thin metallic films, 50 nm-100 nm in thickness, of aluminium and gold, and thin UHMWPE films doped with Fe_2O_3 nano-particles and CNT (Carbon NanoTubes) at a concentration ranging from 0.05% to 10% in weight.
The mylar transmission coefficient at 532 nm wavelength is high, of the order of 87% for 100 micron mylar thickness and its refraction index is also high, of about 1.65 in the visible region [4].
The target is placed on a holder, externally mobile vertically and angularly, in order to change the target position and the incidence angle. A scheme of the experimental setup is reported in Fig. 1.

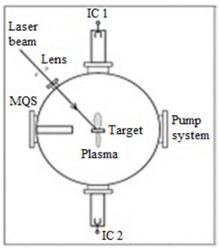

Fig. 1: A scheme of the experimental setup.

Two ion collectors (IC) are placed along the normal to the

target surface. They are used to detect ions emitted from the laser-generated plasma in backward direction, i.e. towards the laser (IC1) and in forward direction, i.e. the direction of incidence laser (IC2), both along the normal to the thin target surface, by using the time-of-flight (TOF) technique [5]. To this aim a fast storage oscilloscope, 1 GHz with 50 Ω input resistance is employed.

The spectra shapes depend on the detection angle (in forward or in backward direction) and on the number of laser shots given, in the same place, before the thin target drilling.

The Coulomb-Boltzmann-Shifted (CBS) function was employed to deconvolve the experimental ion spectra in the different ion specie and charge state contributions [6]. The experimental IC spectra follow the CBS time relationship:

$$F(t) = A \cdot \left(\frac{m}{2\pi kT}\right)^{3/2} \cdot \left(\frac{L^4}{t^5}\right) \cdot \exp\left[-\left(\frac{m}{2kT}\right)\left(\frac{L}{t} - \sqrt{\frac{\gamma kT}{m}} - \sqrt{\frac{2zeV_0}{m}}\right)^2\right]$$

where m is the ion mass, kT the equivalent plasma temperature, L the target-IC detector distance, γ the adiabatic coefficient, ze the ion charge and Vo the equivalent acceleration voltage developed in the non-equilibrium plasma.

RESULTS

Fig. 2 shows four typical IC1-TOF spectra obtained irradiating, from the metal side, the 500 Å Au thin film covering 3.5 μm mylar film (a) and the 0.1 μm Al covering 3.5 μm mylar film (b), and, from the polymer side, the 100 μm mylar covered with 500 Å Au film (c) and the 3.5 μm mylar covered by 0.1 μm Al (d), and detecting the ion emission in backward direction at 51 cm distance from the target surface and at the first laser shot.

The first two spectra (a, b) show the metallic ions (Au and Al, respectively) coming from the irradiated surface and the fast protons and carbon ions coming from the backside mylar, which is also involved in the plasma formation.

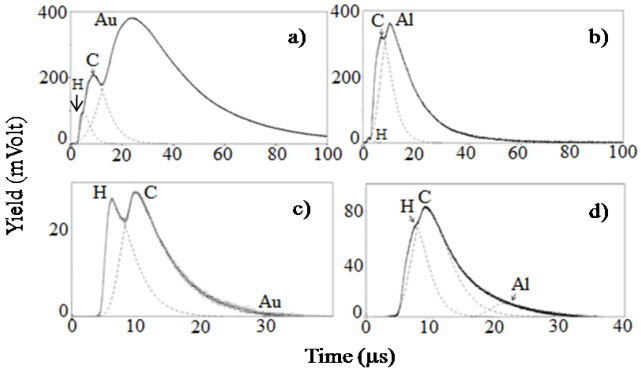

Fig. 2: Four typical IC1-TOF spectra obtained irradiating, from the metal side, the 500 Å Au thin film covering 3.5 μm mylar film (a), the 0.1 μm Al covering 3.5 μm mylar film (b), and, from the polymer side, the 100 μm mylar covered with 500 Å Au film (c) and 3.5 μm mylar covered by 0.1 μm Al (d), and detecting the ion emission in backward direction.

The other two spectra (c, d) show C and H as the main ion emission from the irradiated surface. The metallic ions are nearly absent in such last spectra because they are reached by a laser shot transmitted by the mylar absorber, i.e. by a low laser intensity inducing a lower plasma temperature. Thus the metallic ion emission, if present, will be represented by a low energetic component interfering with the spectrum tail of the TOF carbon peak and its contribution is of difficult evaluation, especially if thick mylar films are employed. The spectra of Fig. 2 show the Boltzmann deconvolution curves (dot lines) due to the different ion specie contributions.

Fig. 3 shows four typical IC2-TOF spectra obtained by irradiating, from the polymer side, the 2 μm mylar film covered by 0.1 μm Al (a), the 3.5 μm mylar film covered by 0.1 μm Al (b), the 100 μm mylar film covered by 500 Å Au (c), and, by irradiating from the metal side, the 0.1 μm Al thin film covering 2 μm mylar film (d) and detecting, at the first laser shot, the ion emission in forward direction at 51 cm distance from the target surface.

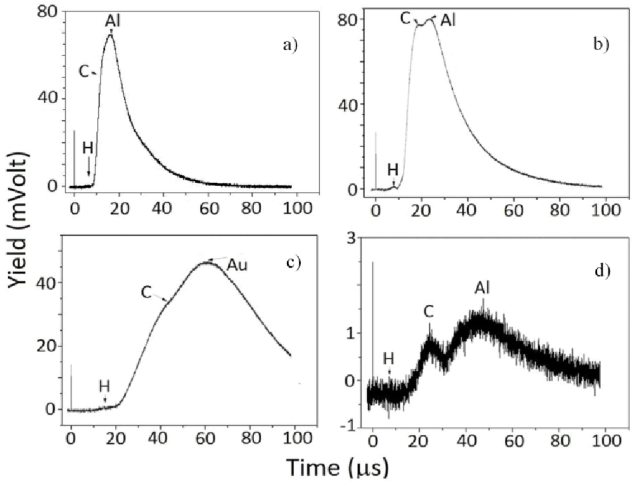

Fig. 3: Four typical IC2-TOF spectra obtained by irradiating from the polymer side the 2 μm mylar film covered by 0.1 μm Al (a), the 3.5 μm mylar film covered by 0.1 μm Al (b), the 100 μm mylar film covered by 500 Å Au (c), and by irradiating, from the metal side, the 0.1 μm Al thin film covering 2 μm mylar film (d) and detecting the ion emission in forward direction.

The first two spectra (a, b) show a carbon content (yield) increase and a little Al energy decrease with the mylar thickness. The third spectrum (c) shows the presence of the H, C and Au ions, demonstrating that, although the mylar film is 100 micron thick, a high ion emission yield is obtained in forward direction. This result is justifiable by the low absorption coefficient of the mylar film at the 532 nm laser wavelength, which permits to transmit a part of the laser pulse to the Au film, where it is absorbed generating a plasma.

This plasma, convolving Au, H and C ion emission, has a temperature lower than that one obtainable if the Au film had been placed on the target surface.

The fourth spectrum shows the forward emission of the Al

(0.1 μm)/mylar (2 μm) target (d). In this case the spectrum shows the peaks due to H, C and Al ions, with TOF times higher than the case of backward direction detection.
In this case, in fact, the most energetic ions are generated at the metal-polymer interface but they have to cross a gas phase and a very thin solid mylar film before reaching the IC2 detector.
Fig. 4 shows the obtained TOF results for the proton energies (a) and yields (b) as a function of the target configuration in backward (full squares) and forward (open dots) directions.

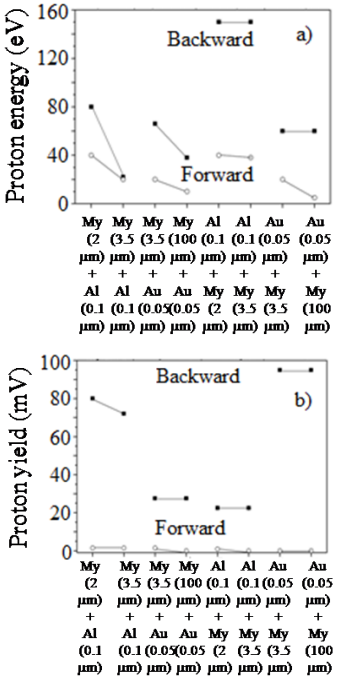

Fig.4: Proton energies (a) and yields (b) as a function of the target configuration and of the detection direction.

Protons are generated by the hydrogenated polymer and by the hydrogen gas absorbed in the metal film. In many cases protons have energy of the order of 60 eV, but using Al (0.1 μm)/Mylar coupling they can reach a kinetic energy of the order of 150 eV. Thus, as a first approximation, by assuming the plasma temperature to be about one third with respect to the proton energy along the target normal direction (for protons the energy is approximately equally distributed between thermal interactions, adiabatic expansion in vacuum and Coulomb interactions), the plasma temperature is generally of the order of 20 eV, in good agreement with previous measurements of temperature obtained in similar conditions [7], but in special cases, such as the above discussed, it can reach about 50 eV. It is possible to observe that by using a thin mylar covered by a thin metal film and by irradiating from the mylar face, the backward and forward proton energy decreases with the mylar thickness. These results can be explained on the base of the relatively low mylar laser light absorption.
The plasma is generated mainly at the metal surface, due to the high metal photon absorption; by increasing the mylar thickness the laser energy arriving to the metal surface decreases and the particles generated from the plasma, involving metal and polymer atomic species, are ejected with a lower kinetic energy.
This effect is confirmed also by the proton energy emission from the back target face, i.e. in forward direction, which has a comparable or lower value with respect to the backward direction, due to the proton energy loss in the very thin solid metallic phase (or high density vapour phase) of the target when ions move in the IC2 detector direction.
By irradiating the target from the thin metal face the proton energy in backward direction is independent on the mylar thickness placed below. Of course, the proton energy in forward direction decreases with the mylar thickness and it reaches a minimum value for the irradiation of the thick Au (500Å)/Mylar (100) μm target.
The proton yields in backward direction are always higher than the forward direction. Its value is of 95 mV in the case of Au (500Å)/Mylar (3.5 μm) and Au (500Å)/Mylar (100 μm), a result due to the high hydrogen quantity absorbed in the Au thin film. The proton yield in forward direction is always negligible. Fig. 5 shows two IC experimental spectra detected at a laser pulse energy of 150 mJ and in backward configuration for UHMWPE+Fe_2O_3 (a) and UHMWPE+CNT (b) thin films, at 0.05% doping concentration. The IC distance from the target surface is 113 cm.

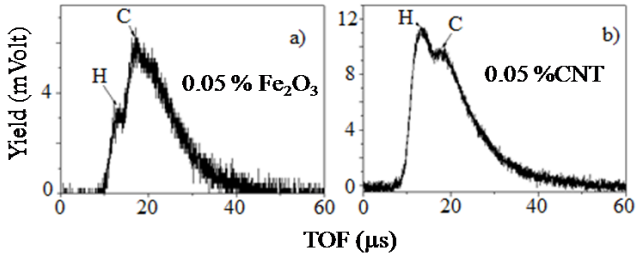

Fig. 5: Two IC experimental spectra detected at a laser pulse energy of 150 mJ and in backward configuration for UHMWPE+Fe_2O_3 (a) and UHMWPE+CNT (b) thin films, at 0.05% doping concentration.

Fig. 6a reports the proton peak energy as a function of the doping concentration, for the backward detection configuration. The relative peak yield between protons and carbon ions, Y_H/Y_C, is reported in Fig. 6b as a function of the doping concentration, for the backward configuration. It de-

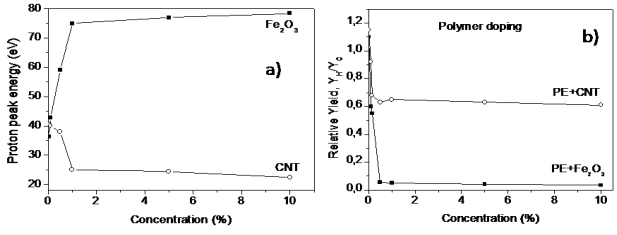

Fig. 6: The proton peak energy as a function of the doping concentration, for the backward detection configuration (a) and the relative peak yield between protons and carbon ions, Y_H/Y_C, as a function of the doping concentration (b).

creases for both targets composition.
Fig. 7 shows two IC experimental spectra detected at a laser pulse energy of 150 mJ and in forward configuration for UHMWPE+Fe_2O_3 (a) and UHMWPE+CNT (b) thin films, at 0.05% doping concentration. The IC distance from the target surface is 42.5 cm.

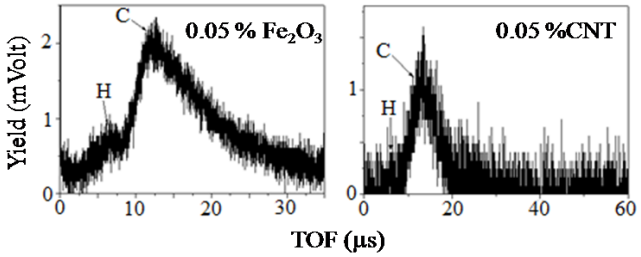

Fig. 7: Two IC experimental spectra detected at a laser pulse energy of 150 mJ and in forward configuration for UHMWPE+Fe_2O_3 (a) and UHMWPE+CNT (b) thin films, at 0.05% doping concentration.

Fig. 8a reports the proton peak energy as a function of the doping concentration, for the forward detection configuration and for the experimental spectrum immediately prior to the drilling of the sample. It decreases for both targets composition.
The relative peak yield between protons and carbon ions, Y_H/Y_C, is reported in Fig. 8b as a function of the doping concentration, for the forward configuration.

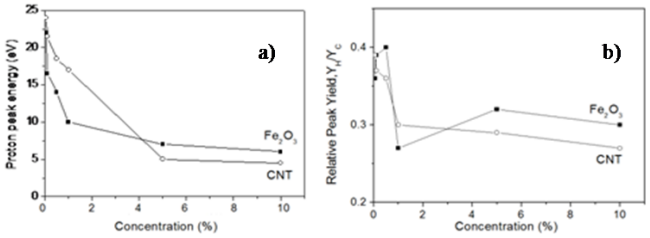

Fig. 8: The proton peak energy as a function of the doping concentration, for the forward detection configuration (a) and the relative peak yield between protons and carbon ions, Y_H/Y_C, as a function of the doping concentration (b).

DISCUSSION AND CONCLUSIONS

The production of hot plasmas, with duration comparable with the laser pulse (3 ns) is possible by using *ns* laser pulse intensities of the order of 10^{10} W/cm^2, in agreement with literature [8, 9]. The ion emission can be investigated "on line" by using IC in TOF configuration to evaluate the ion emission contribution in backward and forward direction in terms of emitted species and yield. The proton kinetic energy and yield depend on the target composition and on laser shot parameters used in the experiment. The high proton current detected gives the possibility to post-accelerate protons up to energies of the order of 100 keV, by using 100 kV acceleration voltage. This is a possible experiment to generate proton beams useful for different nuclear applications, such as for nuclear fusion. Results reported in this article represent a further contribution in the production and acceleration of protons from plasmas produced at laser intensity of the order of 10^{10} W/cm^2.

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