Proton emission from laser-generated plasmas at different intensities

Lorenzo Torrisi, Mariapompea Cutroneo, Salvadore Cavallaro, Lorenzo Giuffrida, Daniele Margarone

Abstract. Proton acceleration from laser-generated plasma is carried out at intensities ranging between 10^{10} and 10^{19} W/cm^2, by using *ns*, *ps* and *fs* laser systems. The high energy density transferred from the pulsed laser beam into the solid target generates ionized species released in vacuum from the solid surface. Fast electrons followed by slower ions build up a double-layer and a consequent electric field, which is responsible for the ion acceleration mainly along the target-normal. Polymeric targets containing nanostructures (or metallic species) with high laser absorbing capacity, and metallic hydrates (or H-enriched metals), permit to increase the plasma temperature and density, thus to improve the proton beam energy and current. Thick targets and low laser intensities, operating in repetitive pulse, allows to generate high currents of low energy protons. On the other hand, through the use of thin targets and high laser intensities enabled the generation of high proton energies, above 1 MeV.

Key words: laser-generated plasma • hydrogenated targets • proton acceleration

L. Torrisi✉
Laboratori Nazionali del Sud,
Istituto Nazionale di Fisica Nucleare (INFN),
(National Institute for Nuclear Physics),
62 S. Sofia Str., 95123 Catania, Italy
and Dipartimento di Fisica, Università di Messina,
Ctr. da Papardo-Sperone 31, 98166 Messina, Italy,
Tel.: +39 095 542 260, Fax: +39 090 395 004,
E-mail: Torrisi@lns.infn.it

M. Cutroneo
Dipartimento di Fisica, Università di Messina,
Ctr. da Papardo-Sperone 31, 98166 Messina, Italy

S. Cavallaro
Dipartimento di Fisica, Università di Catania,
46 S. Sofia Str., 95124 Catania, Italy
and Laboratori Nazionali del Sud,
Istituto Nazionale di Fisica Nucleare (INFN),
(National Institute for Nuclear Physics),
62 S. Sofia Str., 95123 Catania, Italy

L. Giuffrida
Laboratori Nazionali del Sud,
Istituto Nazionale di Fisica Nucleare (INFN),
(National Institute for Nuclear Physics),
62 S. Sofia Str., 95123 Catania, Italy

D. Margarone
Institute of Physics, Academy of Sciences of the Czech Republic v.v.i.,
2 Na Slovance Str., 18221 Prague, Czech Republic

Received: 26 September 2011
Accepted: 15 November 2011

Introduction

We are aware of the interest for the proton production, from laser-generated plasma. As a consequence of this focusing, the increase of investigations in the last years for many advantageous aspects that this complex phenomenon may promote the present and forthcoming applications. Energetic protons are useful for: medicine, nuclear physics, energy production, astrophysics, radiobiology, chemistry and engineering. In addition, the use of protons from laser-generated plasma permits to obtain ion beams with different energetic ranges, from about 100 eV to about 50 MeV at laser intensities from 10^{10} up to roughly 10^{20} W/cm^2, respectively [4, 5].

As has been already made clear, the protons beams so obtained are not monochromatic and are involved in beams containing other ion species such as carbon or metal atoms, depending on the nature of the laser irradiated target. However, special filters such as a Wien filter or electron and/or magnetic deflections, permit to separate protons from other species. The possibility to obtain Boltzmann distributions may be not disadvantageous because many times it is desirable to implant ions at different depth in a given substrate.

For these reasons, the research to better investigate the target nature, geometry and special composition and the laser irradiation conditions, especially for the intensity and wavelength, which remain important factors to be improved. Target and laser irradiation conditions, in fact, permit to enhance the proton yield and energy, to find special conditions of irradiations to improve

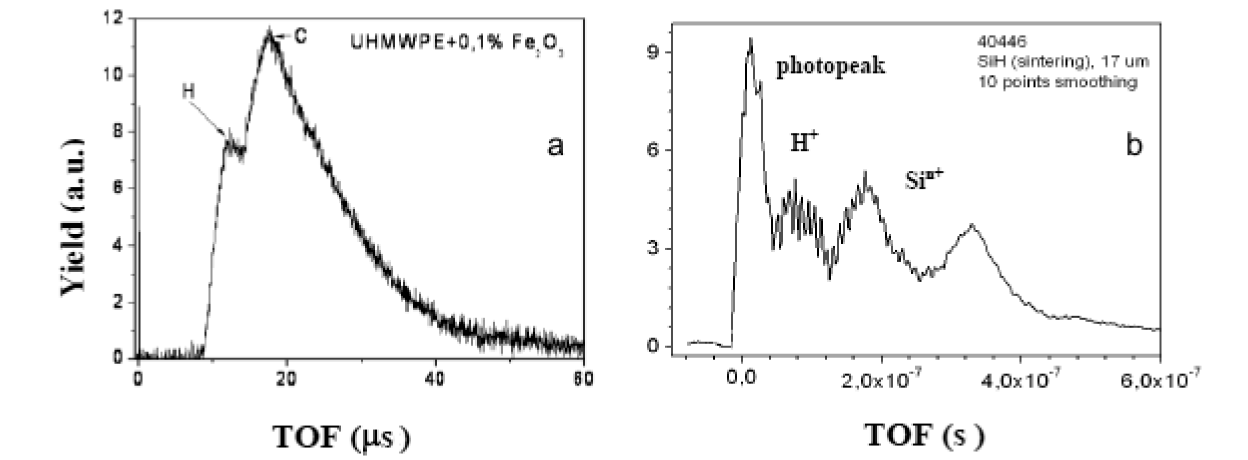

Fig. 1. IC spectrum relative to the low intensity irradiation of polyethylene enriched with 1% of Fe_2O_3 nanostructures (a) and spectrum relative to the irradiation of a thin film of Si:H irradiated at high intensity (b).

effects of self-focusing or of resonant absorption and nonlinear phenomena that may produce very amazing effects on the proton laser-driven acceleration [2].

Experimental set-up

The main measurements of proton generation are achieved with two laser systems: the Nd:Yag laser of 800 mJ of Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare (INFN-LNS, Catania, Italy), working in fundamental (1064 nm) wavelength, 9 ns pulse duration, in single mode or in repetition rate up to 30 Hz, and the Asterix iodine laser of the Prague Asterix Laser System (PALS, Prague, the Czech Republic) working at 1315 nm wavelength, 600 J maximum energy, 300 ps pulse duration, operating in single mode.

The first laser operates at intensities of the order of 10^{10} W/cm^2 while the second may reach about 10^{16} W/cm^2. The proton generation and evaluation in terms of proton energy distribution and yield was followed by different "on line" techniques. Many of them concern the time-of-flight (TOF) technique performed by using an ion collector (IC), a SiC detector or a windowless-electron-multiplier (WEM) associated with an electrostatic ion energy analyzer (IEA). We deal with the first measurements (TOF) via detectors placed at known distances from the irradiated targets and fast oscilloscopes were availed to record the start signal due to the laser shot and the stop signal due to the arrive of the ions. Useful measurements were devoted also by using a Thomson parabola spectrometer (TPS). This spectrometer is equipped with two input pin-holes of 1 and 0.1 mm in diameter, a magnetic deflection of about 0.1 T and a deflection voltage of the order of 3 kV, and a multi channel plate (MCP) to detect the parabola curves on a plane orthogonal to the incident ions. Details on the IC, IEA, SiC and TPS are given in the literature [1, 3, 6].

The treated targets were hydrogenated targets based on polymers such as polyethylene, polymethylmetacrylate and mylar, hydrated metals such as TiH_2, and semiconductors such as amorphous Si:H growth in CH_4 environment. Targets were employed as bulk and as thin films, in order to produce protons in backward and in forward direction, respectively. Specific targets contained nanostructures, with dimensions comparable with the laser light wavelength, such as carbon nanotubes and Fe_2O_3 at different concentrations, have been irradiated. These targets permitted to enhance the effects of laser resonant absorption in thin and thick targets with consequent increment of the proton energy and yield.

Results

Two typical IC spectra are reported in Fig. 1 for TOF ion detection acquired at low (Fig. 1a) and at high (Fig. 1b) laser pulse intensity.

The first one is relative to the laser irradiation of polyethylene enriched by 0.1% of nanostructures of Fe_2O_3, irradiated at a 30° incidence angle at 300 mJ, at a wavelength of 1064 nm, at a 0.4 mm spot diameter, with the IC placed along the normal to the target surface (in backward direction). The target-IC distance is 1.2 m, thus the proton peak corresponds to a kinetic energy of 52 eV. The relative H/C atomic ratio that in the normal polyethylene is represented by a value of about 0.1, in this case assumes the higher value of about 0.67. The second spectrum (b) reports an IC spectrum acquired by irradiating at 0° incidence angle a thin (17 μm) amorphous Si:H target irradiated at 490 J, at a wavelength of 1315 nm, at a 70 μ spot diameter, with the IC placed in forward direction along the normal to the target surface. The proton energy in this case corresponds to 3.2 MeV. This value is very high with respect to the 0.5 MeV obtained in the same experimental conditions by irradiating thick targets and detecting protons in backward direction.

A typical SiC spectrum, determined via ion detection from laser-generated plasma at high laser intensity, is reported in Fig. 2a. It indicates that the SiC detector is very fast, permitting a signal rise of about 100 V in time of the order of 20 ns, as indicated by the H^+ peak. This spectrum is relative to 25 μm polyethylene thickness irradiated at 0° incidence angle with 500 J laser pulse, with 30° backward direction detection at a TOF distance of 1 m. The protons peak at 65 ns corresponds to a kinetic energy of 1.2 MeV. The spectrum shows also

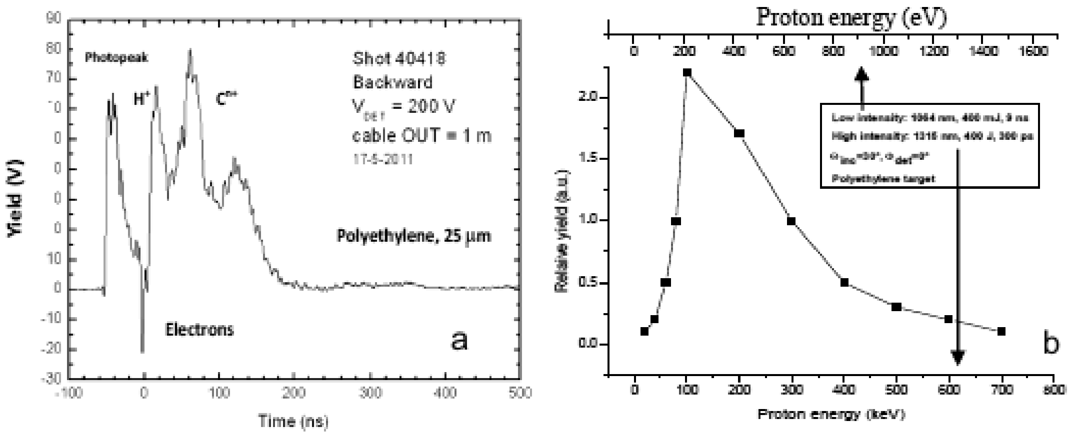

Fig. 2. Typical SiC spectrum relative to the thin polyethylene irradiation at high laser intensity (a) and typical IEA proton energy distribution obtained by irradiating polyethylene at low laser intensity (upper scale) and high laser intensity (bottom scale) (b).

the negative peak at 40 ns due to electrons detection at energy of about 18 keV.

The IEA spectrometer enables to measure the proton energy distribution by varying the potential voltage of the deflector plates. Two examples of proton energy distributions obtained at low and high intensity are reported in Fig. 2b. The upper proton energy scale is obtained at about 10^{10} W/cm^2 at which they are emitted with an average kinetic energy of about 150 eV and with a Boltzmann distribution having a tail up to values higher than 1 keV. In the second case the proton energy distribution is obtained at about 10^{15} W/cm^2 at which, from a polyethylene target, they are emitted with an average kinetic energy of about 150 keV and with a Boltzmann distribution having a tail up to values higher than 700 keV. Thus, five orders of increment in the laser pulse intensity increase the proton peak distribution by about three orders of magnitude in kinetic energy.

At last, proton energy was also monitored by a Thomson parabola spectrometer fixed in the forward direction along the normal to the target surface. TPS was availed for thin films irradiated by high laser intensities. Two typical examples, referred to the irradiation of 2.5 μm Au target, are reported in Fig. 3. The first spectrum is provided impinging at 530 J with a focal position placed at 100 μ in front of the target surface, while the second one is obtained at the same energy but with the focal position placed on the target surface. Results shows that in the first case protons show a Boltzmann distribution with a maximum kinetic energy of about 3 MeV, while in the second case the energy distribution is strongly limited from about 1 MeV up to about 2 MeV, strengthening that the target composition and geometry and the laser irradiation conditions may be responsible for the obtainment of a near monochromatic proton beam.

Discussion and conclusions

The proton beam production can be achieved by repetitive laser pulses occurring at low intensity and at high intensity regimes. In the first case the protons are characterized by means of energies of the order of 100 eV and are generated in the backward direction, while in the second case, by using micrometric thin targets proton beams of energy higher than 1 MeV, may be obtained in the forward direction. In both cases generally protons have Boltzmann energy distributions with long tails at higher energies. Of course, the proton beams ejected from the plasma are accomplished by other ion species coming from the target compositions. Often protons are mixed with carbon or metallic ions and to be used they must be separated electrostatically and/or magnetically by the other ion species.

The ion acceleration from laser-generating plasma is strongly dependent on the laser parameters (inten-

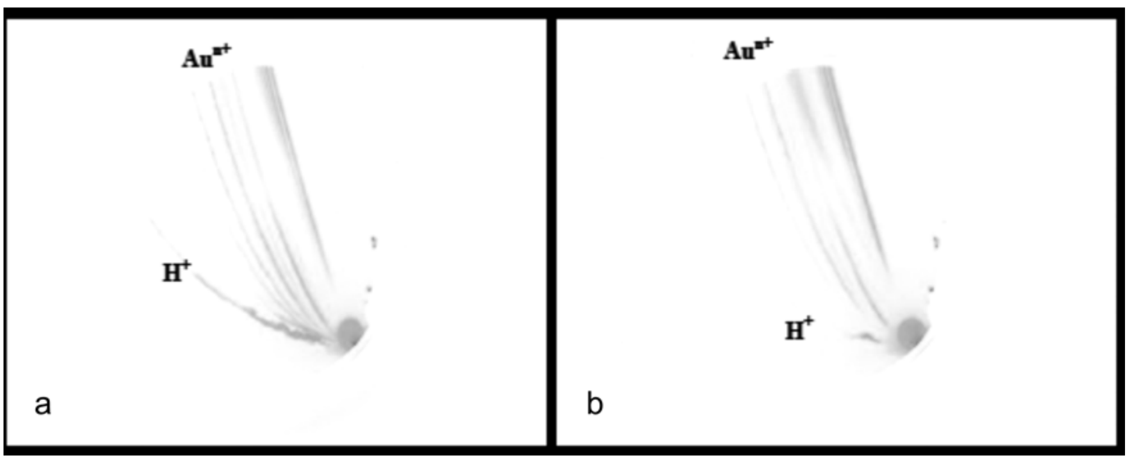

Fig. 3. TPS spectra obtained by irradiating 2.5 μm Au film with 100 μm focal position (a) and with 0 μm focal position (b).

sity, wavelength, pulse duration, focal position, focal dimension,…), target composition (metals, polymers, ceramics, electron density, doping concentration, nanostructures,…) and target geometry (film thickness, surface curvature, multilayer disposition, thin films in cavities,…). Particularly interesting appears the case of target composition inducing resonant absorption that can produce hotter plasmas with high ion yield and ion acceleration. This high absorption can be obtained using special nanostructures such as the Fe_2O_3 embedded in polyethylene or with SiH surface layers, as described in this article. The resonant effect can be due to the agglomerations of the nanostructures having dimensions comparable with the laser wavelength, or due to the electronic plasma density resonant with the laser frequency. In both cases an increment of the proton yield and energy can be obtained, as described in the results reported in Figs. 1 and 2 of this article.

At high intensities also the self-focusing effects can be employed, in order to generate hotter plasma with higher ion yields, kinetic energies and charge states. Focusing the laser in front of metallic flat targets, at about a 100 μm distance, it is possible to generate a pre-plasma with a refraction index gradient capable of inducing a further laser focalization up to dimensions of the order of the laser wavelength, increasing the pulse intensity and generating higher ion energies in the forward direction, as in the case reported in the TPS spectrum of Fig. 3a for the detection of the ions emitted from a thin gold film.

Generally, increasing the film thickness the forward proton energy decreases, due to the ions stopping power in the residual dense solid/vapor matter along the detector direction. On decreasing the film thickness, the proton energy increases but their yield decreases. Thus it is possible to find a compromise in the target thickness in order to have high proton energy and high yield, sometimes this choice permits also to obtain a more restricted energy range of the protons such as in the case reported in the TPS spectrum of Fig. 3b. Actually, the research is going in the direction to use *fs* TW laser, in repetitive mode, in order to obtain proton beams in the forward direction from thin films with kinetic energy above 60 MeV.

Acknowledgment. The reported studies were supported by Laserlab Europe and LIANA INFN Project.

References

1. Harres K, Schollmeier M, Brambrink E *et al.* (2008) Development and calibration of a Thomson parabola with microchannel plate for the detection of laser-accelerated MeV ions. Rev Sci Instrum 79:093306(1–9)
2. Laska L, Jungwirth K, Krása J *et al*. (2006) Self-focusing in processes of laser generation of highly-charged and high-energy heavy ions. Laser Part Beams 24:175–179
3. Margarone D, Krása J, Giuffrida L *et al*. (2011) Full characterization of laser-accelerated ion beams using Faraday cup, silicon carbide, and single-crystal diamond detectors. J Appl Phys 109:103302(1–8)
4. Torrisi L, Caridi F, Giuffrida L (2010) Comparison of Pd plasmas produced at 532 nm and 1064 nm by a Nd:YAG laser ablation. Nucl Instrum Methods Phys Res B 268:2285–2291
5. Torrisi L, Minniti T, Giuffrida L (2010) Data elaboration of proton beams produced by high-energy laser-generated plasmas. Radiat Eff Defects Solids: Inc Plasma Sci Technol 165:721–729
6. Woryna E, Parys P, Wolowski J, Mroz W (1996) Corpuscular diagnostics and processing methods applied in investigations of laser-produced plasma as a source of highly ionized ions. Laser Part Beams 14:293–321