Proton and ion detection from laser-generated plasma at intensities of 10^{10} W/cm^2

F. Caridi[1], L. Torrisi[2,3], N. Gambino[2], L. Giuffrida[2,3] and S. Gammino[2]

[1]*Facoltà di Scienze MM. FF. NN., Università di Messina, Ctr. Papardo 31, Messina, Italy*

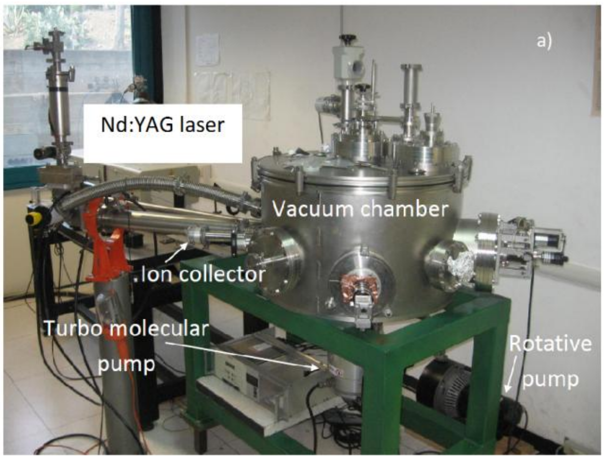
[2]*INFN-LNS di Catania, Via S. Sofia 62, 95123 Catania*

[3]*Dipartimento di Fisica, Università di Messina, Ctr. Papardo 31, 98166 S. Agata, Messina*

Abstract - A Nd:YAG laser with 9 ns pulse duration and 800 mJ energy is employed to irradiate in vacuum different targets. Ion collectors configured in time-of-flight (TOF) technique are employed in order to detect the ion emission from laser-generated plasma along the direction normal to the target surface. TOF spectra can be transformed in ion velocity and energy distributions. Ion spectra can be deconvolved in the contributions of different ion species and charge states. The deconvolution process is possible thank to a special ion energy analyzer (IEA) which permits to measure the ion charge states and ion energies. The TOF de-convolution is performed by the using the "Coulomb-Boltzmann shifted" ion energy distribution, which gives information about the equivalent plasma temperature and acceleration voltage.

Introduction - The ion acceleration from targets irradiated by low energy pulsed lasers is a research field several investigated in the last years. Nanosecond lasers produce pulsed laser ablation (PLA) by means of high pulse intensity that generates hot plasma at the target surface; the plasma plume expands in vacuum at supersonic velocity along the normal to the target surface and it accelerates ions. At high laser intensity, the fast evaporative process interacts with the same laser pulse and, due to the inverse Bremsstrahlung effect, generates high charge-states, high fractional ionisation and plasma super-heating effects [1]. The pulsed laser ablation (PLA) of targets was employed in the last years for several purposes: generation of non-equilibrium plasma with peculiar properties (high ion density, high charge state, high plasma temperature,…); generation of high ion energy and high directional emission; deposition of thin films assisted by ion implantation; laser ion source (LIS) and ion injection in high energy accelerators [2]; etc.. A special interest is devoted to proton acceleration from laser-generated plasma for application of proton beams in different fields: chemistry, nuclear physics, bio-medicine, ion source, etc.

Materials and methods - A *Q*-switched Nd:Yag pulsed laser operating at 1064 nm fundamental wavelength, with 9 ns pulse duration and 1 to 900 mJ pulse energy, in single laser shot mode, is employed for this experiment. The laser beam is focused, through a 50 cm focal lens placed in air, on the surface of a thick (1-2 mm) target, with a 0.5 mm^2 spot size, placed inside a vacuum chamber at 10^{-6} mbar. The employed targets are hydrogenated materials, in order to produce high proton emission. The target is mounted on a holder (externally vertically and angularly mobile) at an incident angle of 30°. A photo and a scheme of the experimental setup are reported in Fig. 1a and Fig. 1b, respectively.



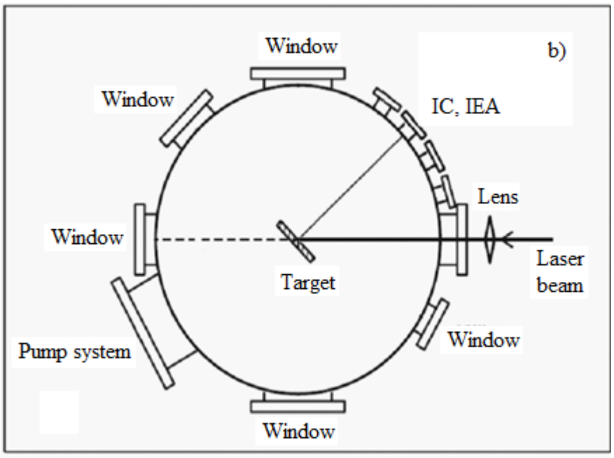


Fig. 1: A photo (a) and a scheme (b) of the experimental setup.

An ion collector (IC), placed horizontally along the normal to the target surface at 60 cm distance from the target surface, is used in time-of-flight (TOF) approach [3]. An electrostatic ion energy analyzer (IEA), placed at 160 cm from the target, permits to measure the energy-to-charge ratio through the ion deflection and to know the number of charge states of the plasma ions [4]. The experimental IC spectra, recorded with a fast storage oscilloscope and represented in terms of ion time distributions, follow the CBS relationship [5]:

$$F(t) = A \cdot \left(\frac{m}{2\pi kT}\right)^{3/2} \cdot \left(\frac{L^4}{t^5}\right) \cdot \exp\left[-\left(\frac{m}{2kT}\right)\left(\frac{L}{t} - \sqrt{\frac{\gamma kT}{m}} - \sqrt{\frac{2zeV_0}{m}}\right)^2\right] \qquad (1)$$

where m is the ion mass, kT the equivalent temperature (in eV), 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 - IEA spectra permitted to measure the number of charge states in the experimental used conditions of laser-target interaction. As an example, Fig. 2 (a) shows an IEA spectrum reporting the seven charge states measured in the Ti target. In this case also a peak due to the presence of absorbed hydrogen is detected. The measured charge states for the elements analyzed in the other laser irradiated targets were 4, 5, 10 for C, Al and Au, respectively.

Taking into account the maximum number of charge states measured through IEA, it was possible to evince the possible deconvolution of the integral spectrum of the detected ions.

As an example, Fig. 2 (b) shows the CBS ion deconvolution spectrum for the integral ion signal (dots) of Ti covered by 50 μm CH_2 thin film.

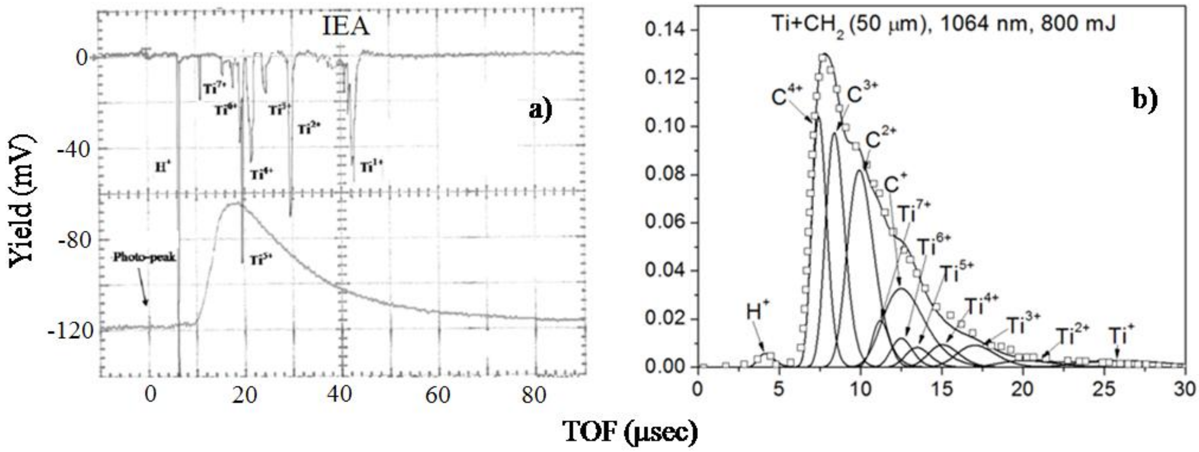


Fig. 2: Typical IEA spectrum relative to the seven charge states measured in the Ti target (a) and the CBS ion deconvolution spectrum for the integral ion signal (dots) of Ti covered by 50 μm CH_2 (b).

The mathematical process was developed by applying the CBS function with the ion equivalent temperature, kT, and acceleration voltage, V_0, as input parameters. A summary of the obtained results is reported in Tab. I (a, b).

(a)

Target	CH_2					$Au+CH_2$ (50 μm)														
Ions	H^+	C^+	C^{2+}	C^{3+}	C^{4+}	H^+	C^+	C^{2+}	C^{3+}	C^{4+}	Au^+	Au^{2+}	Au^{3+}	Au^{4+}	Au^{5+}	Au^{6+}	Au^{7+}	Au^{8+}	Au^{9+}	Au^{10+}
Energy (eV)	90	90	157	224	291	195	195	335	475	615	195	335	475	615	755	895	1035	1175	1315	1455
KT (eV)	7					27														
V_0 (V)	67					140														

(b)

Target	$Al+CH_2$ (50 μm)										$Ti+CH_2$ (50 μm)											
Ions	H^+	C^+	C^{2+}	C^{3+}	C^{4+}	Al^+	Al^{2+}	Al^{3+}	Al^{4+}	Al^{5+}	H^+	C^+	C^{2+}	C^{3+}	C^{4+}	Ti^+	Ti^{2+}	Ti^{3+}	Ti^{4+}	Ti^{5+}	Ti^{6+}	Ti^{7+}
Energy (eV)	165	285	405	525	645	285	405	525	645	765	155	155	265	375	485	155	265	375	485	595	705	815
KT (eV)	21										19											
V_0 (V)	120										110											

Tab. I: Summary of obtained results on the ion detection

Moreover, the plot of Fig. 3 compares the proton kinetic energy, the equivalent ion temperature and the equivalent acceleration voltage, as a function of the electrical conductivity of the metallic substrate target, for the ablation of CH_2, Ti, Al and Au targets.

These three parameters increase with the electrical conductivity, i.e. with the density of free electron states in the target. Increasing the free electron density the laser absorption coefficient increases and the plasma becomes hotter. Thus, in order to obtain higher proton energy, it is better to use an Au target, with the higher free electron density and electrical conductivity, covered by a thin polyethylene film.

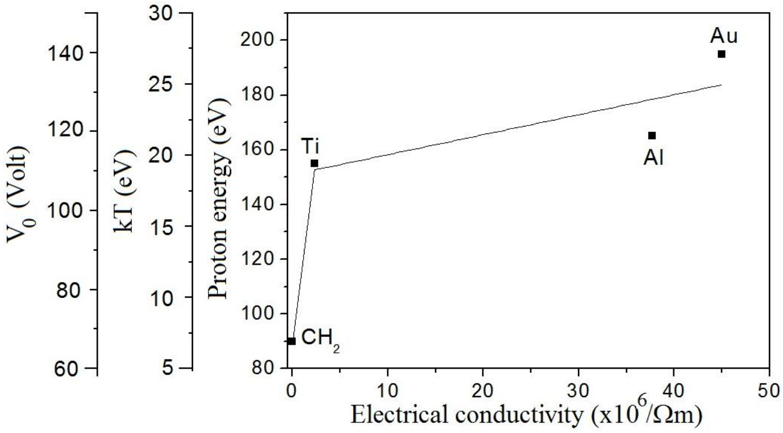


Fig. 3: The proton kinetic energy, the equivalent ion temperature and the equivalent acceleration voltage as a function of the electrical conductivity of the metallic substrate target.

Discussion and Conclusions - The ns laser pulse intensities of the order of 10^{10} W/cm^2 are sufficient to produce hot plasmas, with duration comparable with the laser pulse (9 ns) and temperature ranging between about 7 and 27 eV. The ion emission can be investigated on line by using IC and IEA detectors in TOF configuration and by applying the CBS distribution function. In particular the proton emission can be implemented by using hydrogenated thick target that can be prepared through thin polymeric films covering the metallic surface or by using thick polymers. The proton kinetic energy and yield are a function of the target composition and of the laser shot parameters used in this experiment. The maximum equivalent plasma temperature is reached by using a thin polyethylene film covering the high electrical conductive gold substrate. The maximum proton energy is of the order of 200 eV and the maximum proton emission is obtained by using a bulk hydrogenated target. Measurements are in progress in order to increase the proton energy and yield.

References

[1] D. Giulietti and L.A. Gizzi; *Rivista Nuovo Cimento* 21 (10), 1-93, (1998).

[2] S. Gammino, L. Torrisi, G. Ciavola,et al.; *J. Appl. Phys.* 96(5), 2961, (2004).

[3] E. Woryna, P. Parys, J. Wolowski, W. Mroz (1996). *Laser Part. Beams* 14, 293

[4] L. Torrisi, F. Caridi, D. Margarone, L. Giuffrida (2008). *Plasma Physics Reports*, Vol. 34, No. 7, 547

[5] F. Caridi, L. Torrisi, L. Giuffrida; *Nucl. Instr. and Meth. B* 268, 499 (2010).