PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *February 2, 2017*
REVISED: *March 16, 2017*
ACCEPTED: *March 24, 2017*
PUBLISHED: *April 10, 2017*

THE 3RD ELIMED WORKSHOP MEDICAL AND MULTIDISCIPLINARY APPLICATIONS
OF LASER-DRIVEN ION BEAMS AT ELI-BEAMLINES
7–9 SEPTEMBER 2016,
LABORATORI NAZIONALI DEL SUD, CATANIA, ITALY

2017 JINST 12 C04011

# Experimental investigation of ion production and acceleration mechanism in laser-produced plasma at moderate intensity for nuclear studies @ ELI-NP

**C. Altana,**[a,b,1] **S. Tudisco,**[a] **G. Lanzalone,**[a,c] **D. Mascali,**[a] **A. Muoio,**[a,d] **F. Brandi,**[e,f] **G. Cristoforetti,**[e] **P. Ferrara,**[e] **L. Fulgentini,**[e] **P. Koester,**[e] **L. Labate,**[e] **D. Palla**[e,g,h] **and L. Gizzi**[e,g]

[a] *INFN-LNS, Laboratori Nazionali del Sud, Via Santa Sofia 62, 95123 — Catania, Italy*
[b] *Dip. di Fisica e Astronomia — Università di Catania, Via Santa Sofia 64, 95123 — Catania, Italy*
[c] *Università degli Studi di Enna "Kore", Via delle Olimpiadi, 94100 — Enna, Italy*
[d] *Università di Messina, Viale F.S. D'Alcontres 31, 98166 — Messina, Italy*
[e] *CNR-INO — Intense Laser Irradiation Laboratory, Via G. Moruzzi 1, 56124 — Pisa, Italy*
[f] *Istituto Italiano di Tecnologia, Via Morego 30, 16163 — Genova, Italy*
[g] *INFN — Sezione di Pisa, Largo B. Pontecorvo 3, 56127 — Pisa, Italy*
[h] *Dipartimento di Fisica, Università di Pisa, Largo B. Pontecorvo 3, 56127 — Pisa, Italy*

*E-mail:* altana@lns.infn.it

ABSTRACT: High-power lasers allow to produce plasmas extremely appealing for the nuclear physics studies. An intense scientific program is under preparation for the experiments that will be conducted at the Extreme Light Infrastructure for Nuclear Physics (ELI-NP) in Magurele, Romania. Among the several planned activities, we aim to study low-energy fusion reactions and nuclear structure in a plasma environment. In this work, we discuss the results of some preliminary tests related to the experimental set-up, which is in phase of preparation, for the conduction of this scientific program at ELI-NP. Tests have been performed at ILIL laboratory in Pisa, where a Terawatt laser is installed. The goal of this experimental campaign was a systematic experimental investigation of ion production and acceleration mechanism that occur in laser-produced plasma at moderate intensity, I=$10^{18}$–$10^{22}$ W/cm$^2$. We particularly focus the attention to identify the role of the target composition: surface contaminants versus volume contribution.

KEYWORDS: Ion identification systems; Plasma diagnostics - charged-particle spectroscopy; Spectrometers

---

[1] Corresponding author.

doi:10.1088/1748-0221/12/04/C04011

## Contents

## 1 Introduction

High-power lasers have proven being capable to produce high-energy $\gamma$, charge particles and neutrons, and to induce all kinds of nuclear reactions. For the first time, at ELI-NP, it will enter into new domains of power and intensities: 10 PW and >$10^{23}$ W/cm$^2$. The future availability of such intense beams at high repetition rates will give the unique opportunity to investigate nuclear reactions and fundamental interactions under the extreme plasma conditions [1] where it is expected that the physical properties of nuclear matter (structure, lifetimes, reaction mechanisms, etc.) could be drastically changed inside the plasma [2]. On the other hand, these studies represent one of the largest, most difficult and challenging research areas today; the implications could cover others fields, from quantum physics to cosmology, astrophysics, etc.

We have proposed the construction of a general-purpose experimental apparatus in order to investigate these research topics: by using colliding plasma plumes [3], it will be possible to study the electron-screening effects [4] at low-energy fusion reactions, in a wide variety of cases and configurations, and the structure of the weakly bound nuclear states (see for instance the papers of Hoyle [5], Afimov [6], etc.).

The apparatus can be schematized in three main sections [2]: the interaction zone, the charged particles detection-wall and the neutrons detection-wall. In the interaction zone, two plasmas are produced and collide with each other. The basic interaction principle is the following: a first high-power laser pulse impinges on a primary solid thin target producing, through the TNSA (Target Normal Sheath Acceleration) acceleration scheme, a plasma. This plasma collides with a secondary plasma, produced through the interaction of another laser pulse on a supersonic gas jet (made for example by $^4$He, H, D$_2$, $^3$He etc.). By using this configuration, we intend to minimize the “plasma-plasma friction”, i.e. the energy dissipation of the collision between fast-flowing and gas-jet plasmas. Moreover this configuration allows to work in a more “classical” nuclear physics experimental scheme (i.e. projectiles on a fixed target).

Moreover, in order to reconstruct the reaction kinematic, the construction of two highly-segmented detection systems for neutrons and charged particles is required.

2017 JINST 12 C04011

The charged particles detection-wall will be realised by Silicon Carbide (SiC) detectors [7]. SiC have been proven recently to have excellent properties: high energy and time resolution, resistance to radiation damage, insensible to visible light, etc. Such detectors are able to work in a time of flight (ToF) configuration or in single particle detection mode.

For these studies, the "ideal" neutron detection module should have high efficiency, good gammas versus neutrons discrimination, excellent timing for the energy reconstruction in time of flight of neutrons. In addition, it should be able to work in hard environmental conditions, i.e. in the laser-matter interaction area. All these aspects may be met by configuration based on new PPO-Plastic scintillator [8] coupled with a Silicon Photomultiplier [9] and a totally digital read-out system.

## 2 The target normal sheath acceleration

Thanks to the unique opportunities provided by ELI-NP (high repetition rate and Petawatt laser beams), by operating at around $10^{18}$ W/cm$^2$ (typically TNSA regime) with large focal spot, it will be possible to ensure the production of a very large flux of ions and plasma with optimized energy distributions for our nuclear purpose. Such conditions ensure the possibility to study, in a plasma environment, the nuclear reactions at very low cross-section.

TNSA was intensively studied in the last years; experiments [10] and models [11] show that this acceleration scheme works very well for the surface protons acceleration. Protons and ions flows are expected expanding along a cone, whose axis is normal to the target surface [12]. The observed energy distributions present an exponential shape [13] with a high-energy cut-off, linearly depending on the laser intensity [10] and scaling with the atomic number.

A simple description of the TNSA mechanism is the following: laser driven electrons penetrate the foil, escape at the rear side of the target inducing a strong longitudinal electric field (~TV/m), which ionizes atoms in the surface layer and accelerates them in the target normal direction. Typically, this field accelerates simultaneously several ion species, but suffers of two drawbacks. The first is related to the fact that only a thin layer of ions on the back surface of the foil is accelerated. This is called "surface acceleration" and it is less efficient with respect to the "volumetric acceleration", which is originated by the bulk material. The second drawback arises from acceleration of contaminants layers (hydrocarbon, water, etc.) present on both sides of the target foils. The protons of contaminant layer are accelerated at first, due to their lower charge-to-mass ratio, thus shielding the region behind the front and inhibiting the acceleration of heavier ions.

Several experiments have demonstrated that, even though the thickness of the contaminant is only few nanometers, this is sufficient to damp the acceleration of heavier ions [14, 15]. Other experiments, in which hydrogen-rich contaminant layers were removed from the target, either by thermal heating [16, 17] by an argon-ion sputter gun [18, 19] or using a secondary laser to ablate the surface [20, 21], have showed more efficient acceleration of the bulk target material.

Target cleaning is technologically challenging, therefore the aim of this work is to understand if heavier ions can be efficiently accelerated in the TNSA regime when contaminants are present.

A systematic experimental investigation to identify the role of surface contaminants and volume contribution was carried out by using a Thomson parabola Spectrometer (TPS) with adequate charged species discrimination capability in order to detect the energy spectra of individual ion species.

2017 JINST 12 C04011

## 3 Experimental apparatus

The preliminary tests for studies of nuclear reactions at ELI-NP [22] have been performed at the Intense Laser Irradiation Laboratory (ILIL) in Pisa. A Ti:Sapphire laser system, which delivers 40 fs - 800 nm pulses with energy on target up to 450 mJ, was employed. The ILIL laser pulse exhibits an ASE (Amplified Spontaneous Emission) contrast greater than $10^{10}$ and a ps contrast of $10^5$ at 1ps before the peak pulse. The beam is focused on the target at an angle of incidence of 15°using an off-axis parabolic mirror; the corresponding maximum intensity at the target position was up to $2 \times 10^{19}$ W/cm$^2$. Furthermore the target was mounted on a three-axis translation stage system and centered respect a 640 mm diameter interaction chamber.

Deuterated plastic ($CD_2$) 10 μm thick foil was used as a target. The choice of this material is based on two points. Since the target is composed of deuteron and carbon atoms, protons are certainly originated from surface impurities. Moreover, after protons, deuterons are the ions with smallest atomic mass, thus they are more easily detectable than heavier ions.

To investigate ions acceleration [23] in laser-matter interaction, at TNSA regime, a Thomson Parabola Spectrometer was employed. It was placed normally to the target rear side, housed in a separate vacuum chamber, operating at a pressure of $10^{-6}$ Torr, and differentially pumped with respect to the main target chamber. Details about TPS are given elsewhere [24]. The ions position is detected using an imaging system consisting of a micro-channel plate coupled to a phosphor screen, 75 mm in diameter (MCP-PH), and an EMCCD camera.

## 4 Results and discussion

Deuterated plastic targets were irradiated by changing the focal conditions in order to investigate the behaviour of the accelerated ions.

Typical energy spectra for the all detected species (protons, deuterons and carbons of different charge states) are shown in figure 1. As expected from TNSA mechanism, broad Maxwellian-like shapes are produced (i.e. a linear drop is observed in the semilog-scale). Since during the measurements we focused our attention on highest energies values, the electric and magnetic fields have been chosen in such a way to have a broad high-energy region. For this reason, due to the MCP dimension, protons and deuterons at lower energies were cut in the spectra.

Our goal was to investigate the behaviour of superficial protons acceleration versus deuterons bulk emission. Therefore, the cut-off energies of the two ion species were obtained from energy spectra in different laser focus conditions. The results are plotted in figure 2.

Protons and deuterons cut-off energies exhibit an opposite trend: where protons exhibit a maximum, corresponding to the best focus, deuterons show a minimum. Therefore, the contribution of surface seems to prevail in the optimal z-focus, while in off-focus positions the two contributions (surface and bulk target) tend to equalize [25]. Focus conditions were monitored by means of a pin-diode, plotted in same graph of figure 2, and giving information about X-rays flux.

Protons and deuterons spectra were also integrated in order to obtain information about the total yield, in arbitrary units, as reported in table I. The mean values were estimated among different focus condition, because we did not observe significant changes within the error by changing the focusing conditions.

2017 JINST 12 C04011

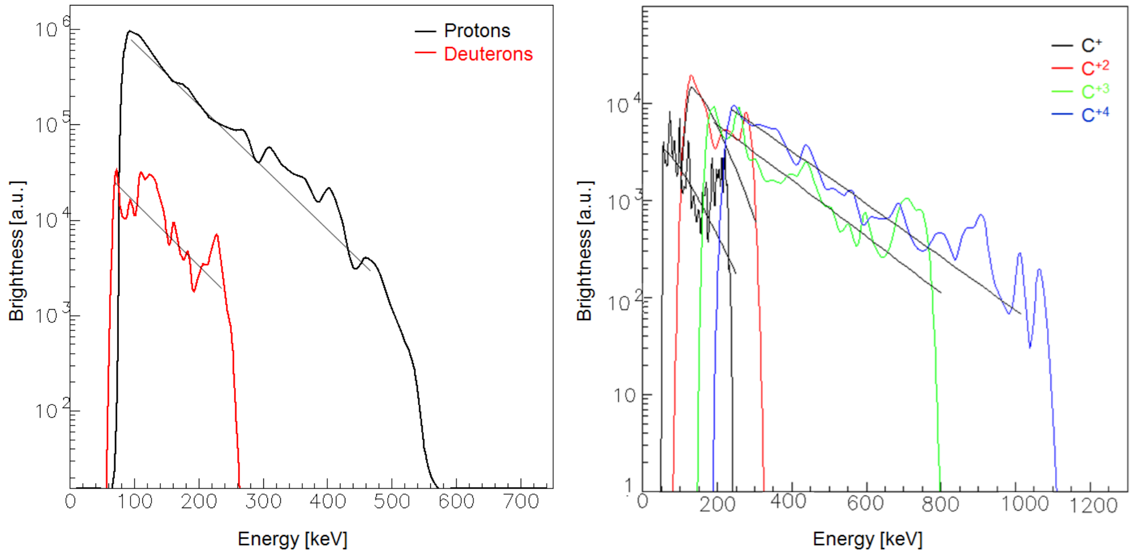

**Figure 1**. Left — Comparison between protons and deuterons spectra. Right — Comparison among ($C^+$,$C^{+2}$,$C^{+3}$ and $C^{+4}$) spectra showing the Coulomb shift. Maxwellian fits are also plotted.

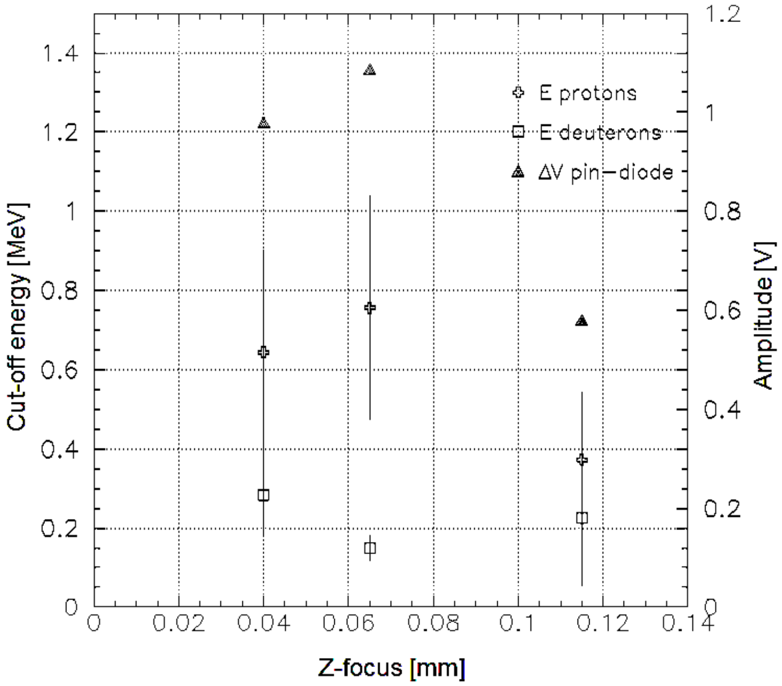

**Figure 2**. Trend of the maximum energy values at the cut_off versus z-focus, for a $CD_2$ target.

**Table 1**. Mean protons and deuterons yield.

| | |
|---|---|
| Protons yield (a.u.) | $1.26 \times 10^7 \pm 5.78 \times 10^6$ |
| Deuterons yield (a.u.) | $1.61 \times 10^5 \pm 7.67 \times 10^4$ |

We can conclude that at 0°, where TP has been placed, the surface contribution (in terms of number of protons) is dominant compared to deuterons bulk emission. The total yields, both for protons and deuterons, have not dependence from focus laser condition.

Concerning the carbons energy spectra, as can be noticed, each spectrum shows a different energy threshold, which is shifted at higher energies relying to the different charge state; while the total yield seams behaving vary similarly to that of deuterons.

## 5 Conclusions

Experimental investigations on ions production and acceleration mechanism in laser-produced plasma at moderate intensity were performed with a TPS as preliminary test of the configuration that is under preparation for the nuclear physics activity at ELI-NP.

In order to identify the role of the surface versus bulk contribution a $CD_2$ target was irradiated. Data show that ion acceleration originates from a complex scenario set by the laser-target interaction conditions. It is possible to argue that protons, coming from the surface contaminant layer, feel earlier the accelerating electric field due to their lower charge-to-mass ratio, and consequently shield the deuterons. Therefore, protons are accelerated at higher velocities, while the deuterons are accelerated from the remaining shielded electric field at relatively lower velocities.

More complex to explain it is the energy cut-off dependence on focus condition. The two species could be emitted with different angular distributions. Since the TPS is placed at 0°respect the target emission, it is possible that deuterons are accelerated at larger angles. Therefore, when the beam is defocused, a larger target surface is hit, consistent with the higher deuterons cut-off energies.

Interesting results coming also from the carbons data, where an energy shift (several thresholds) has been observed as a function the different charge states.

## References

[1] D. Mascali et al., *Calculation of fusion rates at extremely low energies in laser plasmas*, *Proc. IAU* **274** (2010) 44.

[2] F. Negoita et al., *Laser driven nuclear physics at ELI-NP*, *Rom. Rep. Phys.* **68** (2016) S37.

[3] D. Mascali et al., *Colliding laser-produced plasmas: a new tool for nuclear astrophysics studies*, *Radiat. Effects Defects Solids* **165** (2010) 730.

[4] S. Cherubini et al., *Cross-section of* $^8Li(\alpha,n)^{11}B$*: inhomogeneous big bang nucleosynthesis*, *Eur. Phys. J.* **A 20** (2004) 355.

[5] F. Hoyle, *On nuclear reactions occuring in very hot stars. I. The synthesis of elements from carbon to nickel*, *Astrophys. J. Suppl.* **1** (1954) 121.

[6] V. Efimov, *Few-body physics: giant trimers true to scale*, *Nature Phys.* **5** (2009) 533.

[7] A. Muoio et al., *Silicon carbide detectors study for NUMEN project*, *EPJ Web Conf.* **117** (2016) 10006.

[8] N. Zaitseva et al., *Plastic scintillators with efficient neutron/gamma pulse shape discrimination*, *Nucl. Instrum. Meth.* **A 668** (2012) 88.

2017 JINST 12 C04011

[9] E. Sciacca et al., *Arrays of Geiger mode avalanche photodiodes*, *IEEE Photon. Technol. Lett.* **18** (2006) 1633.

[10] A. Macchi et al., *Ion acceleration by superintense laser-plasma interaction*, *Rev. Mod. Phys.* **85** (2013) 751.

[11] M. Passoni and M. Lontano, *Theory of light-ion acceleration driven by a strong charge separation*, *Phys. Rev. Lett.* **101** (2008) 115001.

[12] M. Borghesi et al., *Multi-MeV proton source investigations in ultraintense laser-foil interactions*, *Phys. Rev. Lett.* **92** (2004) 055003.

[13] T. Dzelzainis et al., *The TARANIS laser: a multi-Terawatt system for laser-plasma investigations*, *Laser Particle Beams* **28** (2010) 451.

[14] M. Zepf et al., *Proton acceleration from high-intensity laser interactions with thin foil targets*, *Phys. Rev. Lett.* **90** (2003) 064801.

[15] P. McKenna et al., *Effect of target heating on ion-induced reactions in high-intensity laser-plasma interactions*, *Appl. Phys. Lett.* **83** (2003) 2763.

[16] P. McKenna et al., *Characterization of proton and heavier ion acceleration in ultrahigh-intensity laser interactions with heated target foils*, *Phys. Rev.* **E 70** (2004) 036405.

[17] B.M. Hegelich et al., *Laser acceleration of quasi-monoenergetic MeV ion beams*, *Nature* **439** (2006) 441.

[18] M. Allen et al., *Direct experimental evidence of back-surface ion acceleration from laser-irradiated gold foils*, *Phys. Rev. Lett.* **93** (2004) 265004.

[19] D.T. Ofermann et al., *Observations of proton beam enhancement due to erbium hydride on gold foil targets*, *Phys. Plasmas* **16** (2009) 093113.

[20] J.C. Fernandez et al., *Laser-ablation treatment of short-pulse laser targets: toward an experimental program on energetic-ion interactions with dense plasmas*, *Laser Part. Beams* **23** (2005) 267.

[21] S.M. Pfotenhauer et al., *Spectral shaping of laser generated proton beams*, *New J. Phys.* **10** (2008) 033034.

[22] G. Lanzalone et al., *Study of nuclear reactions in laser plasmas at future ELI-NP facility*, *EPJ Web Conf.* **117** (2016) 05008.

[23] C. Altana et al., *Investigation of ion acceleration mechanism through laser-matter interaction in femtosecond domain*, *Nucl. Instrum. Meth.* **A 829** (2016) 159.

[24] F. Schillaci et al., *Calibration and energy resolution study of a high dispersive power Thomson Parabola Spectrometer with monochromatic proton beams*, 2014 *JINST* **9** T10003.

[25] S. Tudisco et al., *Investigation on target normal sheath acceleration through measurements of ions energy distribution*, *Rev. Sci. Instrum.* **87** (2016) 02A909.

2017 JINST 12 C04011