TOWARDS COMPACT LASER-DRIVEN ACCELERATORS: EXPLORING THE POTENTIAL OF ADVANCED DOUBLE- LAYER TARGETS

A. MAFFINI
Politecnico di Milano Milano, Italy
Email: alessandro.maffini@polimi.it

F. MIRANI
Politecnico di Milano Milano, Italy

A. FORMENTI
Politecnico di Milano Milano, Italy

D. VAVASSORI
Politecnico di Milano Milano, Italy

D. DELLASEGA
Politecnico di Milano Milano, Italy

V. RUSSO
Politecnico di Milano Milano, Italy

M. ZAVELANI-ROSSI
Politecnico di Milano Milano, Italy

M. PASSONI
Politecnico di Milano Milano, Italy

Abstract

The interest towards compact, cost-effective and versatile accelerators is increasing for many applications of great societal relevance, ranging from nuclear medicine to agriculture, pollution control and cultural heritage analysis and conservation. In this context superintense laser-driven ion acceleration represents a promising alternative to conventional accelerators, addressing some of their limitations.

The great potential of laser-driven ion acceleration has stimulated different research approaches aimed at the enhancement of the acceleration performances, especially in terms of energy and number of accelerated ions. A widely investigated strategy relies on the continuous progress in laser technology, which can ensure an improvement of the relevant laser parameters (pulse energy, intensity, repetiton rate) and hence of the overall acceleration performance. This approach is of primary importance for the advancement of fundamental research and the study of novel laser-plasma interaction regimes; however, since it ultimately relies on the availability of a limited number of top-class, state-of-the-art laser facilities, it cannot find a widespread diffusion in developing countires and will hardly lead to a practical compact and cost-effective alternative to conventional accelerators in the near future. A complementary approach focuses on the optimization of the laser-target coupling, since a more efficient laser absorption results in an enhancement of ion current and energy with reduced requirement on the laser side.

Among the advanced target concepts that have been explored, one appealing option is given by double-layer targets, where a very low-density layer, which acts as the enhanced absorbers, is attached to a micrometric solid foil. In the paper contribution we present some of the most recent results in the field of laser-driven ion acceleration with advanced double-layer targets, with a specific focus on non-destructive material characterization technique.

1. INTRODUCTION

Compact, flexible and versatile ion and neutron are key for many applications scientific and technological applications of great societal relevance. Laser-plasma based ion acceleration are attracting growing interest as a promising solution to circumvent some limitations of conventional accelerators, such as non-tunable energy, high costs, non-portable size, radioprotection issues. Laser- driven ion acceleration scheme is typically based on the interaction of an ultra-intense ultra-short laser pulse (I > 10^{18} W cm^{-2}) with a target, which rapidly ionizes turning into a plasma. The coupling of the laser with the plasma induces a strong charge separation and, consequently, intense longitudinal electric fields which are responsible for the ion acceleration process [1]. The resulting ion beam can give rise to secondary neutron sources by exploiting a suitable converter material, in the so-called *pitcher-catcher* scheme.

Among the various laser-based ion acceleration mechanisms that have been proposed in the last two decades, the target normal sheath acceleration (TNSA) is one of the most reliable, robust, and understood schemes. In TNSA, laser pulses are focused on micrometric solid target and their energy is partially absorbed by the electrons of the target. Electrons are heated up to relativistic energies and expand towards the back side, generating a very intense longitudinal sheath electric field (few MV μm−1). This field is responsible for the acceleration of the light ions (mostly protons) located on the rear surface of the target. The result is the emission of bunches of light ions (10^{8} up to 10^{12} protons per shot) with a broad energy spectrum (e.g. exponential distribution with an effective temperature in the order of few MeV) and a well-defined cut-off energy, ranging from few MeV up to several tens of MeV.

Thanks to these features, laser-driven ion sources are already of potential practical interest for some applications in the field of Ion Beam Analysis techniques, such as Particle Induced X-ray Emission (PIXE). Nevertheless, in order to make laser-driven acceleration attractive for most challenging applications (e.g., those requiring fast neutron generation), an enhancement in acceleration performance in terms of energy and current of accelerated ions is required.

A widely investigated approach relies on the continuous progress in laser technology along two main directions: multi-petawatt laser systems, characterized high pulse energy (tens to hundreds of J) and low repetition rate (from few shots per minute down to few shots per day) and table-top lasers, with peak powers of tens to hundreds of terawatts (energy from tens of mJ up to few J) and a high repetition rate (from Hz up to kHz regime). A complementary strategy aims at the enhancement of energy and number of accelerated ions by focusing on the on the control and optimization of the laser- target coupling by acting on the target properties [2].

2. DOUBLE-LAYER TARGETS

In this framework, many approaches have been proposed to design, fabricate and test advanced target solutions optimized for specific laser-matter interaction regimes. One of the most interesting possibilities comes from the fact that laser-plasma coupling is governed by the value of the plasma electron density n_e compared with the critical value n_c (i.e., the theoretical density for which the plasma frequency matches the laser optical frequency):

$$n_c = m_e\omega^2/4\pi e^2 \qquad \text{(Equation 1)}$$

Where e is the fundamental charge, m_e the electron rest mass and ω is the laser frequency (in Gauss units). If the laser-generated plasma is overdense (n_e>n_c), it will reflect most of the laser pulse energy, if it is underdense (n_e>n_c) laser will propagate through and the process of electron heating will be inefficient. It has been shown (both theoretically [3] and experimentally [4]) that the laser-plasma coupling is maximum in the near-critical regime ($n_e \sim n_c$), thus allowing for an efficient electron heating that, in turn, results in an enhanced acceleration process.

Exploiting the near-critical interaction regime in TNSA is surely appealing, however it poses a significant challenge from the point of view of material science and technology. Indeed, one can rework Equation 1 to show the typical values of near critical densities as a function of the laser wavelength: the density of nuclei in a fully ionized critical plasma is n_c/Z, and the nuclear mass can be approximated as A × m_p (being Z the atomic number, A the atomic mass and m_p the proton mass), and hence the mass density of a near-critical material can be expressed in terms of the laser wavelength λ:

$$\rho_c = n_c\frac{A}{Z}m_p = \pi m_p\frac{A}{Z}\frac{1}{R_c}\frac{1}{\lambda^2} \approx \frac{A}{Z}\frac{1.865}{(\lambda[\mu\mathrm{m}])^2}\ \ \mathbf{mg/cm^3} \qquad \text{(Equation 2)}$$

Where the last equality is obtained by substituting the numerical values of the classical electron radius R_c and the proton mass m_p. Since the typical wavelength of high intensity laser systems is around 0.8–1 μm and the *A/Z* ratio is around 2 for most elements, the near-critical requirement corresponds to a mass density of few mg cm^{-3} a few times the density of air is standard conditions.

Given that the TNSA process requires a solid target with a flat back surface, very few options are available. One of the most studied involves the design of Double Layer Targets (DLTs) made of a thin solid foil (e.g., a metallic substrate) coated by a near-critical layer. In order to match the critical density value, the near-critical layer should be a very porous material, such as a *nanofoam*. We have extensively studied the production of near-critical layers by means of the Pulsed Laser Deposition (PLD) technique, demonstrating how cluster-assembled carbon nanofoams deposited by PLD represent an ideal material to be used as a near critical layer in DLT configurations [5, 6]. A sketch of a DLT based on PLD carbon nanofoam is shown in Fig. 1.

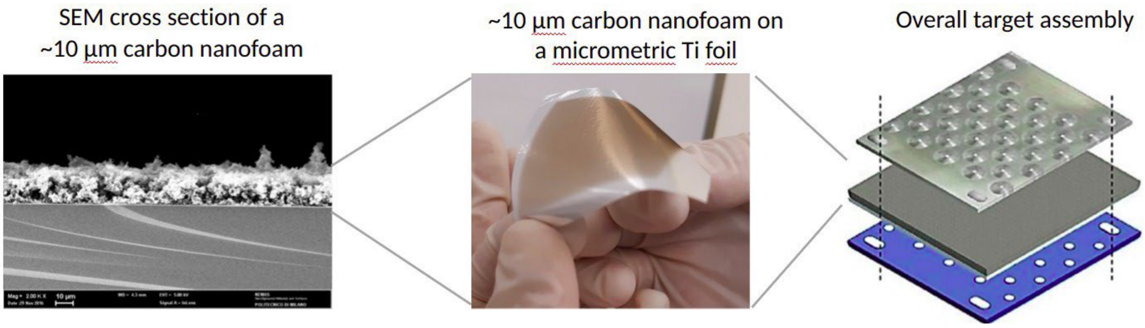

Figure 1: Double-Layer Target based on pulsed laser deposited nanofoam. Left: a Scanning Electron Micrograph of ~10 micron thick near-critical carbon nanofoam. Middle: a photograph of a ~10-micron-thick carbon nanofoam deposited on a micrometric titanium foil. Right: a drawing of the final target assembly (laser propagates downward)

3. CASE STUDY: LASER-DRIVEN MATERIAL CHARACTERIZATION

Among the various techniques belonging to the family of Ion Beam Analysis (IBA), PIXE is particularly suitable to be performed with present-day laser-driven ion sources, given its moderate requirements in terms of ion energies (few MeV/u). Moreover, differently from other IBA techniques, PIXE does not strictly requires a monochromatic source of ions. On the contrary, it can be demostrated that is possible to retrieve the depth profile of elemental concentration using a well- characterized broad-spectrum ion source (the so-called differential PIXE scheme).

We demonstrated the potentials of laser-driven PIXE in an experimental campaign carried out at the Centro de Láseres Pulsados in Salamanca (Spain) using the 200 TW laser VEGA-II [7]. A multi-layered sample made of 2.2 μm thick of chromium deposited onto a millimetric copper substrate has been used as reference sample. In laser-driven acceleration a mixed radiation field (mostly electrons and ions) is present, a feature that is not shared with conventional accelerators. While this could be in principle detrimental for the purpose of IBA, we show that this inherent feature does not represent a limitation. The experiment reported in [7] has been carried out in two different setups, shown in Fig. 2. In the first configuration (Fig.2, left side panels) the irradiation is done with both laser-accelerated electrons and protons. Since the electron contribution to the x-ray generation is dominant, this configuation is dubbed "EDXS" setup, in analogy with the standard Energy Dispersive X-rays Spectroscopy that exploits conventionally accelerated electrons. The proper PIXE setup, in which electrons are removed with a high-field (~0.26 T) magnet placed between the target and the sample. Characterstic x-rays were detected with a charge-coupled device (CCD) that works in single- photon counting mode.

The yield of x-ray generation with electron irradiation is very high, thus allowing for the detection even of trace elements. As shown in Fig. 2 left, bottom peaks of copper and chromium are clearly discernible, thus demonstrating a succesful instance of laser driven EDXS elemental analysis. On the other hand, material analysis in which electron irradiation is present has additional difficulties with respect to pure IBA. In fact, the long electrons range (several mm in solids with MeV energies), the unpredictability of trajectories and the generation of secondaries (δ-rays) capable of inducing ionization are major drawbacks if one is looking for a quantitative analysis about sample composition. To overcome the aforementioned limitations, we resorted the PIXE setup. The x-rays signal (Fig.2 bottom, left) has been exploited for a quantitative stratigraphic analysis using the procedure described in [8]. Assuming a pure Cr film and Cu substrate, i.e., neglecting the presence of oxygen contamination, we estimate a layer thickness of 1.90 ± 0.39 µm, while including the 7% oxygen contamination of the Cr film we estimate a 2.01 ± 0.39 µm film thickness, a value remarkably close to the actual value of 2.2 µm.

In conclusion we note that, since the number of accelerated protons in this configuration is about 109 to 1010 particles per shot, the resulting current is approximately 1 to 10 nA assuming a 10 Hz repetion rate. These values are compatible with the currents in conventional PIXE analysis for cultural heritage studies.

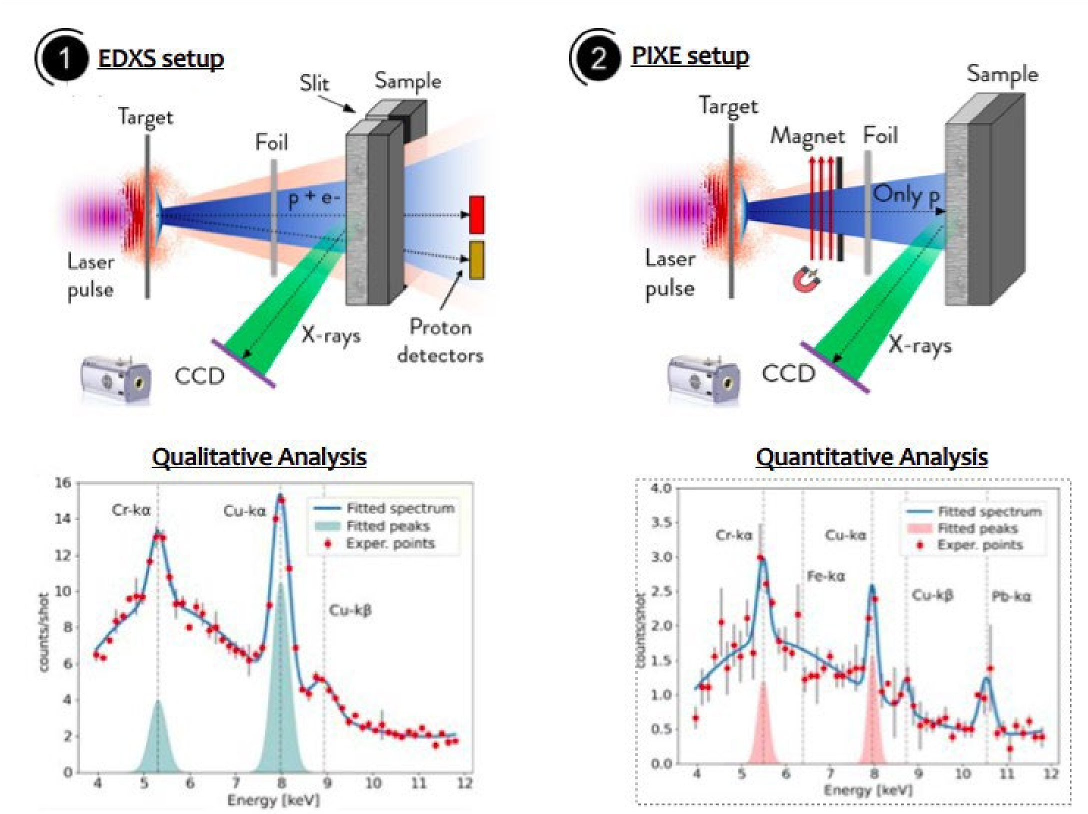

Figure 2: Left, top: EDXS setup, irradiation with both electrons and protons; left, bottom: corresponding characteristic x-ray signal. Right, top: PIXE setup, irradiation with only protons; right, bottom: corresponding x-ray signal, which allows a quantitative characterization of the elemental distribution

ACKNOWLEDGEMENTS

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ENSURE grant agreement No 647554). This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 – EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

REFERENCES

[1] MACCHI A., BORGHESI M, PASSONI, M., Ion acceleration by superintense laser-plasma interaction. Rev. Mod. Phys. 85, 751–793 (2013).

[2] PASSONI M., ET AL., Advanced laser-driven ion sources and their applications in materials and nuclear science. Plasma Phys. Control. Fusion. 62, 14022 (2019).

[3] PAZZAGLIA A., FEDELI L., FROMENTI A., MAFFINI A., PASSONI M., A theoretical model of laser-driven ion acceleration from near-critical double-layer targets. Commun. Phys. 3, 133 (2020)

[4] PRENCIPE I., ET AL., Efficient laser-driven proton and Bremsstrahlung generation from cluster-assembled foam targets, New Journal of Physics, 23 093015 (2021)

[5] MAFFINI A., PAZZAGLIA A., DELLASEGA D., RUSSO V., PASSONI M., Growth dynamics of pulsed laser deposited nanofoams, Physical Review Materials 3, 083404 (2019)

[6] MAFFINI A., ORECCHIA D., PAZZAGLIA A., ZAVELANI-ROSSI M., PASSONI M., Pulsed laser deposition of carbon nanofoam, Applied Surface Science 599, 153859 (2022)

[7] MIRANI F., ET AL., Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source, Science Advances 2021; 7 : eabc8660

[8] PASSONI M., FEDELI L., MIRANI F., Superintense Laser-driven ion beam analysis, Scientific Reports 9.1 (2019): 9202