Position paper
Micro- and nano-structured materials for experiments with high-power lasers

High-power lasers are used worldwide for a very wide range of applications. To cite a few of them, nanosecond terawatt-scale peak power laser facilities are employed for research on clean energy production in the context of Inertial Confinement Fusion (ICF), while picosecond and femtosecond petawatt-scale peak power lasers are used for the acceleration of charged particle (electrons and protons/ions) and the generation of bright XUV, X-ray and gamma-ray sources. In the majority of these experiments, the choice of the target material and its structure is crucial to achieve the desired interaction regime or enhance the source performance.

Micro-structured materials, often referred to as porous materials or foams, find many applications in the context of ICF. Their internal structure, characterized by randomly assembled membranes, filaments, or clusters separated by empty spaces, can offer a significant advantage in improving the implosion performances of a fusion target by smoothing laser irradiation inhomogeneities [1]. Low density foams can be used to study plasmas with very long density gradients as the ones expected in the corona of fusion targets [2]. In addition, they can also be used to study the equation of state of plasmas relevant to ICF [3] and for efficient conversion of the laser energy into plasma X-rays [4]. They are used as components in targets for laboratory astrophysics experiments [5]. Recent manufacturing techniques, such as two-photon polymerization, are enabling access to a new class of micro-structured materials [6,7] whose internal structure can be tailored for each experiment.

Particle acceleration at high energies by the use of ultrashort lasers requires controlled plasma parameters. In this context, micro- and nano-structures can enhance the efficiency of laser-target interaction. Ad hoc micro-structured materials are used to generate a uniform large-scale plasma of near-critical density and use it for direct laser acceleration (DLA) of electrons. This approach enabled a breakthrough in the conversion efficiency of laser energy into relativistic high-current electron beams [8], MeV bremsstrahlung and neutrons [9], and bright betatron emission [10]. A layer of nano-scale structures such as nanoparticles [11], nanowires [12] or nano-spheres [13], allowed to obtain particles accelerated at higher energy, compared to the irradiation of the sole substrate, and an ion beam of a higher quality for the desired applications. Such controlled ion beams have potentially many applications, such as hadron therapy for example, allowing for future table-top accelerators in place of the traditional cyclotrons or linear accelerators.

Recent studies on particular microfabrication, as "free-standing membranes target" based on silicon materials, together with the highly enriched doped targets by hydrogen and boron, attracted attention from the scientific community, also in the framework of the laser-driven particle acceleration and nuclear fusion reaction respectively [14–18].

The aims of the Expert Group are:

- To foster the scientific collaboration among its members for organizing experiments at the various laser facilities active in Europe;
- To support the efforts in applying to funding calls from the European Union and from national governments;
- To promote the cross-fertilization among the different expertise of the Group members, for generating new concepts for innovative techniques and applications: to this end a database of the member's expertise is available in the cloud space dedicated to the Group activities; each member can refer the database to find research groups suitable to start a collaboration about new ideas requiring interdisciplinary skills;
- To support the dissemination of scientific results with the organization of on-line seminars and in-person workshops.

The research on this topic requires:

- Theoretical studies to model and predict the behavior of each material under laser irradiation;
- Experimental test to assess an aspect of the interaction predicted by the theory or to investigate new features of the interaction;
- New production techniques for the fine control of the internal morphologies of the material and the efficient production of the samples.

Due to the broadness of the interests and the expertise, the Group is organized in three work packages, each taking care of a particular research aspect.

Work Package 1: Modeling and simulations of laser interaction with micro- and nano-structured materials

- Promote the development of modeling the interaction of high-power lasers with structured materials to understand the role of the different physical processes;
- Indicate the potential new applications of the materials based on the theoretical understanding of the interaction process.

Work Package 2: Experimental characterization of laser interaction with micro- and nano-structured materials and applications

- Investigate the interaction of high-power laser beams in the nanosecond or picosecond/femtosecond regimes with structured materials through collaborative experiments;
- Promote collaboration among the members to perform collaborative experimental campaigns;
- Encourage the preparation of joint proposals for experiments for facilities with competitive access;
- Foster communication among the members for developing new applications and experimental schemes.

Work Package 3: Micro- and nano-structured targets for high-power laser experiments

- Promote the exchange of information among the members to identify the most suitable target manufacturer for each experiment;
- Link the Group to the manufacturer networks already established to simplify the preparation of each experiment.

Laserlab-Europe AISBL is an international not-for-profit association, bringing together 47 leading laser research infrastructures in 22 European countries. Jointly, they are committed to coordinate operation and R&D efforts in order to facilitate the development of advanced lasers and laser-based technologies, and to promote the efficient utilisation of advanced laser facilities by users from academia and industry. The majority of the members provide open access to their facilities to scientists from all over the world to perform experiments in a large variety of inter-disciplinary research, covering advanced laser science and applications in most domains of research and technology.

References

[1] S. Depierreux, C. Labaune, D. T. Michel, C. Stenz, P. Nicolaï, M. Grech, G. Riazuelo, S. Weber, C. Riconda, V. T. Tikhonchuk, P. Loiseau, N. G. Borisenko, W. Nazarov, S. Hüller, D. Pesme, M. Casanova, J. Limpouch, C. Meyer, P. Di-Nicola, R. Wrobel, E. Alozy, P. Romary, G. Thiell, G. Soullié, C. Reverdin, and B. Villette, Laser Smoothing and Imprint Reduction with a Foam Layer in the Multikilojoule Regime, Phys. Rev. Lett. 102, 195005 (2009).

[2] V. Tikhonchuk, Y. J. Gu, O. Klimo, J. Limpouch, and S. Weber, Studies of Laser-Plasma Interaction Physics with Low-Density Targets for Direct-Drive Inertial Confinement Schemes, Matter and Radiation at Extremes 4, 045402 (2019).

[3] D. Batani, A. Balducci, W. Nazarov, T. Löwer, T. Hall, M. Koening, B. Faral, A. Benuzzi, and M. Temporal, Use of Low-Density Foams as Pressure Amplifiers in Equation-of-State Experiments with Laser-Driven Shock Waves, Phys. Rev. E 63, 046410 (2001).

[4] K. B. Fournier, M. J. May, J. D. Colvin, J. O. Kane, M. Schneider, E. Dewald, C. A. Thomas, S. Compton, R. E. Marrs, J. Moody, E. Bond, P. Michel, J. H. Fisher, C. D. Newlander, and J. F. Davis, Multi-KeV x-Ray Source Development Experiments on the National Ignition Facility, Physics of Plasmas 17, 082701 (2010).

[5] Loupias, B., Gregory, C.D., Falize, E. et al. Experimental results to study astrophysical plasma jets using Intense Lasers. Astrophys Space Sci 322, 25–29 (2009).

[6] O. S. Jones et al., Experimental and Calculational Investigation of Laser-Heated Additive Manufactured Foams, Physics of Plasmas 28, 022709 (2021).

[7] T. Wiste, O. Maliuk, V. Tikhonchuk, T. Lastovicka, J. Homola, K. Chadt, and S. Weber, Additive Manufactured Foam Targets for Experiments on High-Power Laser–Matter Interaction, Journal of Applied Physics 133, 043101 (2023).

[8] O. N. Rosmej et al., High-Current Laser-Driven Beams of Relativistic Electrons for High Energy Density Research, Plasma Phys. Control. Fusion 62, 115024 (2020).

[9] M. M. Günther, O. N. Rosmej, P. Tavana, M. Gyrdymov, A. Skobliakov, A. Kantsyrev, S. Zähter, N. G. Borisenko, A. Pukhov, and N. E. Andreev, Forward-Looking Insights in Laser-Generated Ultra-Intense γ-Ray and Neutron Sources for Nuclear Application and Science, Nat Commun 13, 170 (2022).

[10] O. N. Rosmej, X. F. Shen, A. Pukhov, L. Antonelli, F. Barbato, M. Gyrdymov, M. M. Günther, S. Zähter,V. S. Popov, N. G. Borisenko, and N. E. Andreev, Bright betatron radiation from directlaser-accelerated electrons at moderate relativistic laser intensity, Matter Radiat. Extremes 6, 048401 (2021).

[11] M. Passoni, F. M. Arioli, L. Cialfi, D. Dellasega, L. Fedeli, A. Formenti, A. C. Giovannelli, A. Maffini, F. Mirani, A. Pazzaglia, A. Tentori, D. Vavassori, M. Zavelani-Rossi, and V. Russo, Advanced Laser-Driven Ion Sources and Their Applications in Materials and Nuclear Science, Plasma Phys. Control. Fusion 62, 014022 (2019).

[12] S. Vallières, M. Salvadori, A. Permogorov, G. Cantono, K. Svendsen, Z. Chen, S. Sun, F. Consoli, E. d'Humières, C.-G. Wahlström, and P. Antici, Enhanced Laser-Driven Proton Acceleration Using Nanowire Targets, Sci Rep 11, 2226 (2021).

[13] D. Margarone et al., Laser-Driven High-Energy Proton Beam with Homogeneous Spatial Profile from a Nanosphere Target, Phys. Rev. ST Accel. Beams 18, 071304 (2015).

[14] A. Picciotto, D. Margarone, A. Velyhan, P. Bellutti, J. Krasa, A. Szydlowsky, G. Bertuccio, Y. Shi, A. Mangione, J. Prokupek, A. Malinowska, E. Krousky, J. Ullschmied, L. Laska, M. Kucharik, and G. Korn, Boron- Proton Nuclear-Fusion Enhancement Induced in Boron-Doped Silicon Targets by Low-Contrast Pulsed Laser, Phys. Rev. X 4, 031030 (2014).

[15] L. Giuffrida, K. Svensson, J. Psikal, D. Margarone, P. Lutoslawski, V. Scuderi, G. Milluzzo, J. Kaufman, T. Wiste, M. Dalui, H. Ekerfelt, I. G. Gonzalez, O. Lundh, A. Persson, A. Picciotto, M. Crivellari, A. Bagolini, P. Bellutti, J. Magnusson, A. Gonoskov, L. Klimsa, J. Kopecek, T. Lastovicka, G. A. P. Cirrone, C.-G. Wahlström, and G. Korn, Nano and Micro Structured Targets to Modulate the Spatial Profile of Laser Driven Proton Beams, J. Inst. 12, C03040 (2017).

[16] L. Giuffrida, K. Svensson, J. Psikal, M. Dalui, H. Ekerfelt, I. Gallardo Gonzalez, O. Lundh, A. Persson, P. Lutoslawski, V. Scuderi, J. Kaufman, T. Wiste, T. Lastovicka, A. Picciotto, A. Bagolini, M. Crivellari, P. Bellutti, G. Milluzzo, G. A. P. Cirrone, J. Magnusson, A. Gonoskov, G. Korn, C.-G. Wahlström, and D. Margarone, Manipulation of Laser-Accelerated Proton Beam Profiles by Nanostructured and Microstructured Targets, Phys. Rev. Accel. Beams 20, 081301 (2017).

[17] A. Picciotto, M. Crivellari, P. Bellutti, M. Barozzi, M. Kucharik, J. Krasa, A. Swidlosky, A. Malinowska, A. Velyhan, J. Ullschmied, and D. Margarone, Fabrication of Advanced Targets for Laser Driven Nuclear Fusion Reactions through Standard Microelectronics Technology Approaches, J. Inst. 12, P10001 (2017).

[18] D. Margarone, O. Klimo, I. J. Kim, J. Prokůpek, J. Limpouch, T. M. Jeong, T. Mocek, J. Pšikal, H. T. Kim, J. Proška, K. H. Nam, L. Štolcová, I. W. Choi, S. K. Lee, J. H. Sung, T. J. Yu, and G. Korn, Laser-Driven Proton Acceleration Enhancement by Nanostructured Foils, Phys. Rev. Lett. 109, 234801 (2012).

Status: September 2023

For further information on the Expert Group 'Micro- and nano-structured materials for experiments with high-power lasers' please contact Mattia Cipriani (ENEA): mattia.cipriani@enea.it

Laserlab-Europe AISBL
Rue du Trône 98
1050 Brussels
Belgium

www.laserlab-europe.eu