Proposed laser-targets design for space radiation simulation at ELI-NP

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Abstract. The space radiation environment consists of radiation fields of protons, electrons, and ions with broadband-energy spectra \cite{1}, a feature hard to mimic with classical accelerators. In this purpose, the unique parameters foreseen at the upcoming ELI-NP facility, will allow us to generate a complex, tunable, multien energetic, multicomponent, space-like radiation by means of high power lasers, in order to perform radiobiological and materials studies in a ground-based laboratory, which will improve the understanding of radiation exposure risks, and of the required radioprotection for deep space missions with human crew, and for the establishment of permanent habitats on Mars. ELI-NP’s Targets Laboratory \cite{2} has dedicated equipment for coating, (micro)assembly and characterization of, mainly, solid targets. We fabricate targets optimized for the production of cosmic-like radiation when high-power laser pulses are focused on them. Two proposed strategies for in-house target manufacturing for the above-mentioned application at ELI-NP are described: multilayer multicomponent foil and monolayer multicomponent nanostructured foil.

1. Introduction

Health effects of space radiation on astronauts is one of the major limiting factors for long-duration space missions \cite{1, 3}. For the evaluation of radiation exposure risks, conventional accelerators (linacs and cyclotrons) are currently used to reproduce the mission-specific space radiation environment, but they are limited to the production of mono-energetic beams, while the space radiation is broadband; on the other hand, producing broadband energy radiation is the inherent regime of the laser-plasma accelerators (LPAs). Since the space radiation features are hard to mimic with classical accelerators, LPAs can be an alternative, due to their ability to produce particle beams with the energy distribution depending on tunable laser-target parameters, and therefore they may become a viable tool for space radiation testing \cite{4}.

First reported studies on electron and proton fluxes production with energies in the range of 1-10 MeV for electrons and of 1-20 MeV for protons, similar to those from Earth's radiation belts, using laser-driven particle acceleration via Target Normal Sheath Acceleration (TNSA) mechanism \cite{4}, are promising. As for the simulation of the radiation beyond the low earth orbit (LEO), higher energies are needed to be obtained \cite{5, 6}, the solar flares providing accelerated protons, helium, and heavy ions with broad energy spectra around 100 MeV/nucleon and beyond \cite{1}.
High-Z, highly charged (Fe$^{+24}$, Fe$^{+25}$, and Fe$^{+26}$) ion beams ($\geq 10^6$ Fe ions per shot) with energies in the range of 0.56 - 0.89 GeV (10 - 16 MeV/n) have been successfully obtained from the interaction of a 200 TW laser with a 0.8 $\mu$m thick Al foil, covered with ~5 nm Fe impurity layer and 10 nm H$_2$O contaminant layer [7]. The p-polarized laser pulses had an energy of 8 J, wavelength of 0.8 $\mu$m, duration of 35 fs, a contrast of $10^{10}$ and a peak intensity of $10^{21}$ W/cm$^2$. PIC simulation also showed a resulting multicomponent H$^+$, O$^{8+}$, Al$^{13+}$, Fe$^{+18-26}$ ion beam [7].

A multicomponent H$^+$ and C$^{6+}$ ion beam with energies of 12 - 93 MeV for protons, and of 36 - 174 MeV (3 - 14.5 MeV/n) for C$^{6+}$ ions has been obtained using a PW laser system delivering circularly polarized (CP) laser pulses. An ultrathin, freestanding, 15 nm polymer (F8BT - polyfluorene derivative) target was used for the experiment, with a laser energy of 8.5 J, a duration of 30 fs, a wavelength of 800 nm, a high temporal contrast of $3 \times 10^{11}$, and a maximum intensity of $7 \times 10^{20}$ W/cm$^2$ [8], [9].

In view of the above, our main goal is to investigate the efficiency of novel nanostructured targets [10] with optimum properties, suitable for space-related applications. Tunable key-parameters (structure, composition, thickness, lateral dimensions, nano-pattern features, spacing, periodicity, etc.) will allow us to identify the most effective target design for which the proton and ion outputs are most appropriate, particularly for in-vitro irradiation experiments of cell monolayers [11]. In this paper we present two proposed configurations for the fabrication of targets that can be used for material testing and radiobiological studies in space-like conditions.

2. ELI-NP E5 experimental area

ELI-NP, as one of the upcoming most advanced research facilities in the world, outlined by a very high intensity laser of two 10 PW arms able to reach intensities of $\sim 10^{22}$-10$^{23}$ W/cm$^2$, two 1 PW, and two 0.1 PW arms, is focused on the study of photonuclear physics and its applications. The High Power Laser System (HPLS) is based on Ti:sapphire technology, and delivers ultra-short pulses (25 fs), with a pulse repetition rate of 1/60 (10 PW), 1 (1 PW), and 10 Hz (0.1 PW), respectively [12].

The main focus of the laser driven Nuclear Physics mission of ELI-NP is the study of new nuclear phenomena induced by high power laser interaction with matter, and the development of the related applications. ELI-NP will also develop research in the field of materials behavior in extreme environments and radiobiology, with applications in shielding solutions for equipment and human crew in long term space missions [13]. This research will take place in the E5 experimental area, hosting the two 1 PW arms of the HPLS. A design of E5 experimental area is shown in figure 1.

![Figure 1. Design of ELI-NP E5 experimental area.](image-url)
In this experimental area, some of the foreseen studies will be relevant for understanding the interaction of biological systems with tunable multicomponent radiation with broad energy spectrum.

The space radiation will be simulated by complex radiation fields generated from the interaction of the PW laser with solid targets. Particles like those from space can be obtained by tuning the laser-target interaction process, which is highly dependent of the target parameters and design. In the C1 experimental chamber (figure 1) the laser will be focused on target by means of a F/3.5 focal length off-axis parabolic mirror, employing the Target Normal Sheath Acceleration (TNSA) process.

A Circular Polarization system in the C2 chamber will make possible studies of novel acceleration mechanisms in solid targets such as Radiation Pressure Acceleration (RPA). At the same time, electron acceleration in gaseous targets will be available by focusing the 1 PW laser beam by means of a F/25 focal length off-axis parabolic mirror.

In the C1 experimental chamber, a F/3.5 parabolic mirror together with the F/25 long focusing mirror will allow the simultaneous or independent generation of ion and electron beams for material irradiation studies.

3. Proposed target strategies
In order to experimentally simulate the space radiation, consisting of protons, He and high Z and high energy (HZE) ions (C, O, Si, Fe, among others) with broad energy spectra around 100 MeV/nucleon and beyond, special targets are required. High energy protons of 93 MeV [8] have been obtained using LPAs. Aiming at the simultaneous production of HZE complex ion beam at the ELI-NP E5 experimental area, some tailored types of targets will be developed and fabricated in the ELI-NP Targets Laboratory, which is equipped with a broad range of state-of-the-art equipment for material deposition (of thick/(ultra)thin films, multi-layers, nanoparticles), processing (structuring, surface modification, patterning), surface conditioning (plasma, ion-beam, high temperature thermal treatments), micro-machining (micro-assembly, mechanical processing, cold rolling), and characterization (chemical composition, morphology/topography, structure/texture/phase). A more detailed description of the ELI-NP’s Targets Laboratory is given in reference [2].

Although mono- and multi-layer, mono- and multi-component targets like 0.1 μm CH deposited layer on a 1.0 μm Au foil rear surface [14] have been reported so far in the laser-driven ion acceleration studies, they are not appropriate for this specific application, due to the unsuitable composition and energy of the accelerated ions: the ion beam contains only one or two components of interest and/or the energies of the accelerated ions are too small. For instance, C+ ions with energies around 1 GeV (83 MeV/n) have been obtained from 200 nm-thick diamond-like carbon target [15], Fe+ ions with energies around 16 MeV/n from 0.8 μm thick Al foil with ~5 nm Fe impurity layer and 10 nm H2O contaminant layer [7], Si+ ions with energies of 0.8 MeV/n from 50 nm-thick Si3N4 target and O+ ions were accelerated from contaminants located on the target surface [16].

In order to overcome these issues, two novel target designs are proposed, along with a complementary study of their efficiency which will allow the identification of the most effective configuration. Accordingly, the key-parameters of the targets will be tuned (substrate material, target thickness, its lateral dimensions, nano-pattern dimensions, spacing, periodicity), with the selection of the optimum properties, for which the ion outputs will be most suitable for space applications. Preliminary fabrication and testing of simpler targets, such as a pure carbon target, an iron foil target and two components iron carbide target will also be considered for comparison purpose.

3.1. Multilayer multicomponent target
The first design considers a multilayered target consisting of one semi-conductive layer of silicon dioxide (SiO2) followed by a layer of iron carbide (Fe:C) on a silicon (Si) substrate with the thickness of about 350 μm. In the final step, the substrate can be completely removed, resulting in a freestanding configuration. The fabrication process is briefly presented in figure 2.
For the proposed multilayered target design, two sputtering targets (silicon dioxide, and iron carbide) will be used for the deposition of the consecutive layers. The percentage of the components will be controlled by the thicknesses of the two individual layers.

To obtain the free-standing configuration, the substrate will be removed using photolithography process (by means of mask aligner, spin coater and hot plates), and plasma etching process by means of Reactive Ion Etching (RIE) system. RIE system includes a mass spectrometer to identify the ending of the etching process, and has the capability of using both Bosch and cryogenic processes, although for this particular stage only Bosch process will be used. For the photolithography process, the wafer will be spin coated with a positive photoresist film with the thickness of approximate 8 μm.

![Multilayer target fabrication process design.](image)

The deposition of the different layers will be performed in the Ultra-High Vacuum (UHV) Sputter Deposition cluster system (figure 3) existent within the ELI-NP Targets Laboratory. The system consists of three interconnected vacuum chambers: one vacuum chamber as a loadlock used also for the in-situ cleaning by argon ion milling of the substrate surface before the deposition, allowing a contaminant-free interface; a second vacuum chamber dedicated for the deposition of metallic and/or nitride films, and a third vacuum chamber for deposition of oxide films. The system allows for in-situ transfer of the sample between chambers, without braking the vacuum, a critical aspect for obtaining sharp interfaces between different materials of a multilayered or hybrid (e.g., metal/oxide) structure.

The lateral sizes of the free-standing film will be about 200 μm x 200 μm and the total thickness will range from 200 nm down to few tens of nanometers. Also, the order and the thickness of the individual layers can be varied in the total thickness range, to identify the optimal configuration of the target.

The main advantages of the proposed targets, with a multilayer configuration, is that it allows us to obtain a specific multicomponent structure in a relatively simple fabrication process, and to cover a broader range of thicknesses. The group of D. C. Carroll reported that for carbon ions acceleration, the energy was decreased by using a multicomponent target (CH), in comparison with the pure carbon target, for a given target thickness [14], which can be a disadvantage that needs to be eliminated.

### 3.2. Monolayer multicomponent nanostructured target

The second proposed design is a monolayer, multicomponent foil. The main feature of this strategy is the target fabrication which uses one multicomponent sputtering target, giving the possibility of obtaining a homogeneous multi-species single layer target type. In this approach, the target thickness can be significantly reduced to few nanometers (ultra-thin films), which is more difficult to obtain in the multilayered target case.
Moreover, in order to enhance the laser energy absorption, iron nanoparticles deposition can be performed in an additional step. The multicomponent nanostructured target fabrication process is presented in figure 4.

For the fabrication of the second design, a multicomponent, homogeneous sputtering target will be manufactured, consisting of a mixture of different elements (Si, Fe, C, O) in the desired stoichiometry, prepared as a pellet that will be used as sputtering target for the UHV system. The lateral size and the thickness range will be similar to those for the multilayer targets. The freestanding target structure will be obtained similarly with the previous case, by back-side plasma etching of the substrate (Si wafers), while the metallic nanoparticles deposition will be performed using NANOGEN tool from the UHV sputtering system.

The presence of the nanoparticles on the target front-side is expected to enhance the absorption of the laser beam, and consequently, to increase the maximum ion beam energy and to improve the energy conversion efficiency from laser to the ion beam.

The production of the homogeneous multicomponent monolayer target, comparing to that of the multilayer target, is a more complex process, as it requires additional manufacturing steps, such as fabrication of the pellet used as sputtering target.
Figure 4. Monolayer multicomponent nanostructured target fabrication process design.

The water layer usually present on the target surface will be removed by UV heating of the target, or by other appropriate method, and this is expected to result in an increase in the energy of the heavier ions [18].

4. Conclusions
Two proposed multicomponent target designs were presented, a multilayered structure and an ultrathin single-layered target. These targets will be used for the simultaneous production of a multicomponent beam with composition similar to that of space radiation, therefore recreating some of the conditions from space in a ground-based laboratory, by laser-driven mixed ion species acceleration. The novelty in concept of the two proposed target configurations consists in four high-Z specific elements (C, Fe, O, Si) in the target composition.

Furthermore, PIC simulations of the experiment with the proposed targets are currently underway, taking into consideration different target thicknesses (from a few nm to about 1 μm), in order to identify and fabricate the most suitable targets for laser-driven accelerated ion beams with space-like radiation features: complex radiation with broad energy spectra around 100 MeV/nucleon. For both proposed designs the final range of target thicknesses will be chosen with respect to the laser parameters, in order to maximize the energy of the accelerated ions.

The nanostructured targets with iron nanoparticles deposited on the laser side of the target is expected to increase the laser energy absorption, the laser energy coupling to the plasma, and consequently, the ion acceleration process. Moreover, the targets will be tested at ELI-NP PW laser facility for efficiency studies and performance analysis.

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References
[1] Norbury J W et al. 2016 Galactic cosmic ray simulation at the NASA Space Radiation Laboratory Life Sci. Space Res. 8 38-51
[2] Gheorghiu C C, Leca V, Popa D, Cernaianu M O and Stutman D 2016 J. Instrum. 11 C10011
[3] Hidding B, Karger O, Königstein T, Pretzler G and Rosenzweig J B 2013 Study of Space Radiation Effects with Laser-Plasma-Accelerators ESA NPI Activity Final Report 4000102854
[4] Hidding B et al. 2017 Laser-plasma-based Space Radiation Reproduction in the Laboratory Scientific Reports 7 42354
[5] Mewaldt R A, Davisa A J, Binnsb W R, De Nolfoc G A, Georged J S, Israelb M H, Leskea R A, Stonea E C, Wiedenbecke M E and Von Rosenvingec T T 2005 29th Int. Cosmic Ray Conf. (Pune) 00 pp 101-104
[6] Schimmerling W 2016 Life Sciences in Space Research 9 2-11
[7] Nishiuchi M et al. 2015 Physics of Plasmas 22 033107
[8] Kim I J et al. 2016 Physics of Plasma 23 070701
[9] Choi I W et al. 2011 Applied Physics Letters 99 181501
[10] Margarone D et al. 2013 Proc. of SPIE 8780 878023
[11] Bobeica M, Aogaki S, Asavei T, Cernaianu M O, Ghenuche P, Negoita F and Stutman D 2016 Radiobiology Experiment Design and Modeling for Space Applications at ELI-NP Proc. Int. Conf. of Aerospace Sciences “AEROSPATIAL 2016” (Bucharest) (Bucharest: Incas) p 1
[12] Negoita F et al. 2016 Romanian Reports in Physics 68, Supplement, S37–S144
[13] Asavei T et al. 2016 Romanian Reports in Physics 68, Supplement, S275–S347
[14] Carroll D C et al. 2010 New Journal of Physics 12 045020
[15] Jung D et al. 2013 Physics of Plasmas 20 083103
[16] McGuffey C et al. 2016 New Journal of Physics 18 113032
[17] Design and drawing by Mantis Depositions Ltd, UK; http://www.mantisdeposition.com
[18] McKenna P et al. 2004 Physical Review E 70 036405