Nanostructured targets irradiation by ns-laser for nuclear astrophysics applications: first results

A. Muoio,[a,c,1] **C. Altana,**[a,d] **M. Frassetto,**[b,e] **G. Lanzalone,**[a,f] **L. Malferrari,**[b] **D. Mascali,**[a] **F. Odorici**[b] **and S. Tudisco**[a]

[a]*INFN — LNS,*
  Via S. Sofia 62, 95123 Catania, Italy

[b]*INFN — Sezione di Bologna,*
  Viale B. Pichat, 6/2, 40127 Bologna, Italy

[c]*Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Messina,*
  Viale F.S. D'Alcontres 31, 98166 Messina, Italy

[d]*Dipartimento di Fisica e Astronomia, Università di Catania,*
  Via S. Sofia 64, 95123 Catania, Italy

[e]*Dipartimento di Fisica e Astronomia, Università degli Studi di Bologna,*
  Viale Berti Pichat 6/2, 40127 Bologna, Italy

[f]*Università degli Studi di Enna "Kore",*
  Via delle Olimpiadi, 94100 Enna, Italy

  E-mail: muoio@lns.infn.it

Abstract: The studies discussed in this work are related to a scientific program that aims to reproduce astrophysical-plasmas in laboratory in order to better understand the nuclear processes involved in the stellar burning. An experimental campaign aiming to investigate the effects of innovative nanostructured targets based on Ni, Fe and Co nanowires on laser energy absorption in the ns time domain has been carried out at the LENS (Laser Energy for Nuclear Science) laboratory of INFN-LNS, Catania. Nanowires structures are tuned to increase the light absorption in the visible and infrared range due possibly to plasmonic excitation driven by the incoming photons. Different diagnostics techniques permit to monitor the plasma and to determine its reproducibility. Targets were then irradiated by Nd:YAG 2J, 6 ns infrared laser ($\lambda = 1064$ nm) at different pumping energies. Some preliminary results will be illustrated.

Keywords: Lasers; Nuclear instruments and methods for hot plasma diagnostics; Targets (spallation source targets, radioisotope production, neutrino and muon sources); X-ray detectors

---

[1]Corresponding author.

Contents

1 Introduction

The measurements of the relevant astrophysical reactions have been studied over the years by using conventionally accelerated ion beams impinging on solid targets [1]. On the other hand, inside the plasma the physical properties of nuclear reactions could be drastically changed. Therefore, the study of nuclear reaction rates in plasma is one of the most important issues of modern science [2], with interdisciplinary implications in astrophysics, cosmology, etc [3]. One of the main issues is whether or not electron screening plays a role in stellar nucleosynthesis, and if the current theories about the screening correctly describe the processes in the stars interiors. The investigation of this physics in laboratory plasmas requires sufficiently high densities in the electron clouds, and ion temperatures lying in the ranges of stellar ones. Thermalization of the whole plasma is another crucial aspect. These requirements induced to argue that ns-laser generated plasmas are suitable environments for nuclear astrophysics studies, as already mentioned in [4, 5].

The aim of this experiment is to study the behaviour of targets based on metallic nanowires (NWs), under ns-laser irradiation. This idea is motivated by the unique capability of the NWs to absorb light at very high efficiency. Therefore the use of such NWs could allow obtaining plasma conditions different from those achievable from ordinary bulk targets, and investigate nuclear reactions and fundamental interactions under those conditions [5]. These expectations are confirmed from recent experiments, for laser pulses in the fs to ns time scale and at various intensities [6–9]. With this goal, new nanostructured targets based on Co, Ni and Fe NWs have been developed and irradiated with a 2J, 6 ns infrared laser. Some characteristics of the obtained plasmas were compared.

2 Experimental setup

Laser irradiation tests were carried out at the LENS laboratory (Laser Energy for Nuclear Sciences) at INFN-LNS laboratory in Catania, using a Q-switched Nd:YAG laser with 2 J max energy, 1064 nm fundamental wavelength, 6 ns pulse duration, operated in single shot mode. The laser pulse was focused on the target with a spot of about $100 \, \mu$m, at an angle of 30° with respect to the normal, at an intensity of about $4 \cdot 10^{12}$ W/cm^2, inside an interaction chamber operated at 10^{-5} Torr. The target

position and the beam focusing were adjusted with an X-Y-Z translation stage with 1 μm resolution. The chamber was equipped with several devices, able to characterize the plasma expansion and ions dynamics. In the present preliminary work, only data collected with an X-ray sensitive CCD camera (X-CCD) [10] have been used, while the complete data set will be analyzed in future. The X-CCD was used to measure the X-ray intensity emitted from the plasma, at about 60° from the normal axis. A pin-hole array was placed in front of the X-CCD, equipped with aluminum absorbers of different thickness (5, 6, 8, 12 and 17 μm), in order to suppress low energy photons and to estimate the energy of the X-rays. Nanostructured targets are fabricated starting from aluminum sheets, which are electrochemically anodized into porous alumina, through a consolidated technique [11]. Targets used in the present work all have 10 μm alumina thickness, 15 nm pores diameter and 100 nm interpore distance (pitch). Co, Ni and Fe NWs were electrochemically deposited in the alumina pores [12], to fill about 2/3 of the channel length.

3 Results and discussion

Targets with Co, Ni and Fe NWs have been irradiated along with a bulk aluminum target to be used as reference. The only difference among nanostructured targets was the metal inside the alumina pores. In figure 1, average X-ray intensities as a function of Al-absorber thickness are shown for each target: a larger X-ray intensity was found for NWs samples compared to bulk-Al, with about a ten-fold increase for Co and around a five-fold increase for Ni and Fe. The X-ray intensity normalized to bulk-Al is reported in table 1 for the 6 μm thick absorber. Such a large difference among Co and Ni or Fe cannot be explained in terms of different atomic numbers, since the expected difference would be much smaller [13].
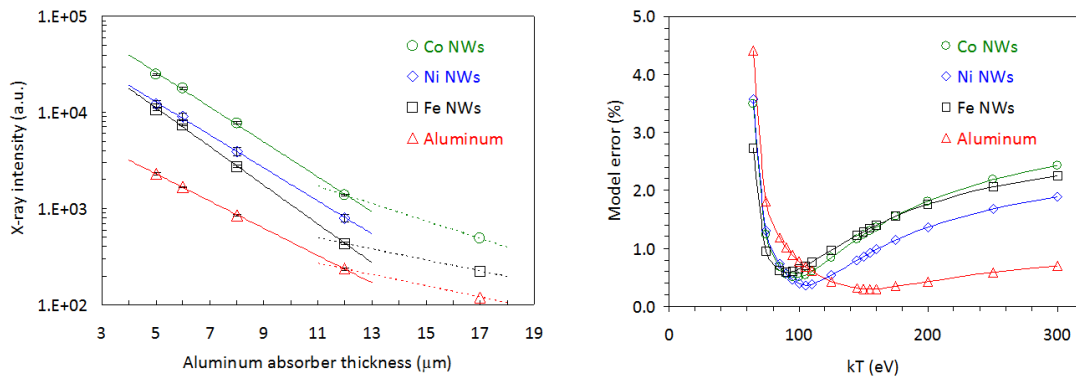

Figure 1. Left-side: X-ray intensity after Al absorbers of different thickness, for various target types, as measured on a CCD. Indicated errors are statistical only. For each target a linear fit is shown for absorber in the range 5÷12 μm (continuous line) and in the range 12÷17 mm (dashed line). Right-side: fit of the X-ray intensity data with a theoretical model for bremsstrahlung and recombination [14], in order to estimate the plasma temperature as the one that minimizes the relative errors w.r.t. the data.

As shown in figure 1 left-side, considering only the 4 absorbers in the range 5÷12 μm, the X-ray intensity as a function of absorber thickness, can be well represented by an exponential fit, for all samples. In fact, at the present laser intensity, the relatively soft X-ray spectrum is "selected"

around the absorption k-edge of the aluminum, at 1.56 keV. Thus, assuming a *quasi* mono-energetic flux, attenuation lengths have been calculated from the fits and the corresponding X-ray energies have been extracted from literature data [14],[1] and reported in table 1. The energy associated to such a *quasi* monochromatic flux is characteristic of the plasma emission and can be defined as the "transmitted energy", E_{Tx}, through an Al thickness in the $5 \div 12 \, \mu m$ range. As shown in figure 1 left-side, at higher absorber thickness ($12 \div 17 \, \mu m$), fits have a lower slope, corresponding to higher attenuation lengths. This implies that a small component of the flux has energies higher (about 30%) than E_{Tx}, as expected. From table 1, it can be observed that among NWs the transmitted energy is quite similar, while the bulk-Al gives about a 10% higher value. This also means that the plasma temperature for bulk-Al is higher than for NWs plasmas. In fact, different plasma temperatures for the various targets have been estimated, as shown in table 1. Assuming X-ray spectrum to follow Planck's law, taking into account the CCD quantum efficiency [10] and the photon transmission probability through the absorbers [14],[1] the experimental X-ray intensities are fitted with the theoretical model to extract the black body temperature, T_{BB}, which minimizes the relative differences. Different plasma temperatures have been extracted by fitting the data with a model that assumes bremsstrahlung and recombination contributions, according to the following expressions for the spectral intensities [15]:

$$I_R(h\upsilon) \propto \sum_n 1/n^3 \exp\left[\left(Z^2 E_H/n^2 kT\right) - h\upsilon/kT\right] \quad \text{and} \quad I_B(h\upsilon) \propto \exp[-h\upsilon/kT],$$

with a relative ratio $I_R/I_B \approx 2.4 \cdot Z^2 E_H/kT$, where Z is the average ion charge and E_H the hydrogen ionisation energy. The relative differences between the model and data, as a function of the plasma temperatures, are shown in figure 1 right-side. As reported in table 1, the extracted bremsstrahlung-recombination temperatures, T_{B+R}, are larger than the black body temperatures, for all samples.

Table 1. For each target, the table contains: the X-ray intensity normalised to bulk-Al for the $6 \, \mu m$ thick absorber; the attenuation length λ, obtained by fitting the distributions of figure 1 for thin absorbers (5, 6, 8 and $12 \, \mu m$); the corresponding transmitted photon energy E_{Tx}; plasma temperatures, T_{BB} and T_{B+R}, which are estimated respectively with a black body emission model and with a recombination plus bremsstrahlung emission model. For all data, the first error is statistical and the second is systematic.

Target	Normalised X-ray intensity	λ [μ m]	E_{Tx} [eV]	T_{BB} [eV]	T_{B+R} [eV]
bulk-Al	1	3.05±0.04±0.52	992±8±90	$110 \pm 5^{+30}_{-25}$	$155 \pm 10^{+75}_{-40}$
Co NWs	10.6±0.3	2.39±0.03±0.42	913±15±60	75±5±15	$100 \pm 5^{+20}_{-15}$
Ni NWs	5.4±0.5	2.53±0.11±0.44	930±4±60	$80 \pm 5^{+20}_{-15}$	$105 \pm 10^{+30}_{-20}$
Fe NWs	4.4±0.1	2.15±0.02±0.70	885±8±100	70±5±15	$90 \pm 2^{+20}_{-15}$

---

[1]For updated values, see http://henke.lbl.gov/optical_constants/.

4 Conclusions

Special targets, based on Co, Ni and Fe NWs, with high absorbance in the VIS and NIR range, have been irradiated with a 6 ns laser pulse and 1064 nm wavelength, at an intensity of about $4 \cdot 10^{12}$ W/cm^2. From preliminary results, a higher X-ray intensity was observed for all samples compared to bulk-Al, with about a ten-fold increase for Co NWs and around a five-fold increase for Ni and Fe NWs. Further tests are needed to explain such a difference among metals, which cannot be accounted in terms of different atomic numbers. Moreover, there are strong indications that plasma conditions for NWs targets are quite different from those obtained for bulk targets. In fact, since the estimated plasma temperatures are quite similar for NWs and the bulk-Al targets, while X-ray intensities are much increased for NWs target, this indicates an increasing in terms of plasma density and/or in terms of plasma stagnation [4] for NWs targets. This indication could be very promising, since it could open the possibility to study specific nuclear reactions in plasma, at high rates. Concerning the results on the plasma temperature analysis, NWs and the bulk-Al target seams have close temperatures. This scenario is consistent with the indication that plasma conditions for NWs targets are quite different from those obtained for bulk targets, at least in terms of plasma density and/or plasma stagnation [4]. If confirmed, these results could be very useful for nuclear physics studies, because can contribute to the increasing of the total reaction events.

References

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

[2] F. Negoita et al., *Laser driven nuclear physics at ELI-NP*, Rom. Rep. Phys. **68** (2016) S37;
G. Lanzalone et al., *Study of nuclear reactions in laser plasmas at future ELI-NP facility*, *EPJ Web Conf.* **117** (2017) 4.

[3] S.L. Ivanovski et al., *Plasma astrophysics and laser experiments: hydrodynamical simulation of colliding plasmas*, *Radiat. Eff. Defect. Solid.* **165** (2010) 457;
B. Wang, C.A. Bertulani and A.B. Balantekin, *Electron screening and its effects on Big-Bang nucleosynthesis*, *Phys. Rev.* **C 83** (2011) 018801 [`arXiv:1010.1565`];
L. Romagnani et al., *Observation of Collisionless Shocks in Laser-Plasma Experiments*, *Phys. Rev. Lett.* **101** (2008) 025004.

[4] D. Mascali et al., *Colliding laser-produced plasmas: a new tool for nuclear astrophysics studies*, *Rad. Eff. Defect. Solid.* **165** (2010) 730.

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

[6] G. Cristoforetti et al., *Investigation on laser-plasma coupling in intense, ultrashort irradiation of a nanostructured silicon target*, *Plasma Phys. Control.Fusion* **56** (2014) 095001.

[7] M.A. Purvis et al., *Relativistic plasma nanophotonics for ultrahigh energy density physics*, *Nat. Photonics* **7** (2013) 796.

[8] H. Habara et al., *Efficient energy absorption of intense ps-laser pulse into nanowire target*, *Phys. Plasmas* **23** (2016) 6.

[9] G. Lanzalone et al., *Effect of advanced nanowire-based targets in nanosecond laser-matter interaction*, *Rev. Sci. Instrum.* **87** (2016) 02B324.

[10] ANDOR datasheet for X-ray CCD, model Newton DO920P-BN (december 2010), www.andor.com.

[11] O. Jessensky, F. Muller and U. Gosele, *Self-organized formation of hexagonal pore arrays in anodic alumina*, *Appl. Phys. Lett.* **72** (1998) 1173.

[12] L. Malferrari et al., *Alumina Template-Dependant Growth of Cobalt Nanowire Arrays*, *J. Nanotechnol.* **2009** (2009) 149691.

[13] K.M. Glibert et al., *X-ray yields of plasmas heated by 8-nsec neodymium laser pulses*, *J. Appl. Phys.* **51** (1980) 1449;
M.J. Collins, *A Study of the XUV Flux Emission from Laser-Plasmas Using a Multilayer Monochromator*, MSc Thesis, Physical Sciences, Dublin City University (1994).

[14] B.L. Henke et al., *X-Ray Interactions: Photoabsorption, Scattering, Transmission, and Reflection at E = 50–30,000 eV, Z = 1–92*, *Atom. Data Nucl. Data Tables* **54** (1993) 181.

[15] H.R. Griem, *Radiation processes in plasmas*, in *Handbook of Plasma Physics*, volume 1, A.A. Galeev and R.N. Sudan eds., North Holland, Amsterdam (1985).