“Noizy” low-density targets that worked as bright emitters under laser illumination

N.G. Borisenko, A.A. Akunets, L.A. Borisenko, A.I. Gromov, A.S. Orekhov, A.V. Pastukhov, V.G. Pimenov¹, S.M. Tolokonnikov, G.V. Sklizkov

P.N. Lebedev Physical Institute of RAS, RF;
¹N.D. Zelinsky Institute of Organic Chemistry RAS
E-mail: ngbor@sci.lebedev.ru

Abstract. Low-density structured targets are widely used to study some isolated problems of ICF. Here we compare selected laser experiments with our targets, mostly non-thermonuclear, non-standard, individually designed for plasma features quantitative investigations. The mutual cross-check and verification is done in past few years, because “noizy” nature is more pronounced at less density. Our targets were applied on European drivers of LULI 2000, PALS, LIL, PHELIX, also on GEKKO-XII, in Russian-Indian laser-foam interaction series.

1. Introduction

The low-density aerogel targets have now been studied for years. The target parameters, experimentally achieved are of particular interest. Many foams and production methods are published [1, 2]. But a question what to do next remains. So apart from theoretical requests we fulfill our own fragmentary analysis of the experiments with our targets in order to decide on the prospects of future requirements or possibility to decline the presently developing methods. To work out the target fabrication and standard characterization procedures we analyze plasma partial transparency, non-linear behavior as well as plasma emittance and dynamics effects. Those may be attributed to the target structure influence. Consequently fabrication and characterization methods should be adequate and precise enough for under-dense solids here considered as “noisy” due to their inner structure.

2. Access to the joint experiments

The structures of low-density targets that we provided were of several types: aerogels \((SiO_2)\), organo-aerogels \((CHO, polysterene\ PS)\), foams (agar, \(PS\)), nano-snow \((Au, (CD_2)_n)\), composites \((CHO+Cu)\).

Figure 1. Left to right: polymer (plastic) aerogel target; SEM image of polymer aerogel structure; metal nano-snow target; SEM image of \(Au\) nano-snow; multilayered aerogel target set with \(\rho\) steps.
By requirement they can intersect to form composites from polymers and copper powder \((CTA+Cu)\). Modern parameters of the targets are quite extreme from the point of view of the solid state physics, so the combinations of uniformity and density \(\rho\) can reach gaseous ones, \(\rho < 2\text{mg/cc}\) transparent samples. This enables profound studies of subcritical plasmas even with the basic laser wavelength including transient processes in subcritical plasmas.

For the laser experiments the thermonuclear target laboratory (TTL) of the P.N. Lebedev Physical institute was invited and collaborated with other groups as part of HiPER or bilateral projects. The research programs for the beam times appointed were led by principal investigators (PI) in charge of the submitted experiments: C. Labaune, S. Depierreux, J. Limpouch, Ph. Nicolai, M. Olazabal-Loume, V.T. Tikhonchuk, O.N. Rosmej, N.G. Borisenko, W. Nazarov (EU), as well as S. Fujioka (Japan), S. Chaurasia, L.J. Dhareswar (India). Russian institutions (partly cited below) laid basis for the start and for our current works.

Results that influenced our target activity are enumerated below.

Numerous series of experiments all dealt with plasma emittance and were devoted to:
- a) smoothing the target illumination by low-density layers (undercritical as well)
- b) SBS and SRS study, also in the scheme modelling the shock ignition (ps-laser with up to \(10^{16}\text{ W/cm}^2\))
- c) plasma transparency and emittance properties, their dynamics. [3-14].

Table 1. “Noisy” targets from TTL in some joint experiments

| Facility                          | \(\lambda\) [nm] | \(\tau, E\)          | Selected results                                      |
|----------------------------------|------------------|-----------------------|-------------------------------------------------------|
| MISHEN (TRINITI, Russia), many   | 1064             | 2.5 ns, 100J          | Hydro and thermal waves velocities, plasma jets       |
| Kanal-2 (LPI, Russia), many      | 1064             | 2.5 ns, 50 J          | Nonlinear scattering of broad-band laser light, energy|
| KEODYM (TsNIMash, Russia),       | 1064 805         | 10 ps, 15 J, 50 fs, 30mJ | Dependence of neutron yield on (CD\(_2\))\(_3\) density |
| BARC (India), PI S. Chaurasia,   | 1064             | 0.7 ns, 16 J          | X-ray and ion emission from nanosnow and aerogels,    |
| L.J. Dhareswar                   |                  |                       | energy balance, dynamics                              |
| PALS (Prague, Czech), PI J.      | 438              | 0.37 ns, 200 J        | Opacity and radiance of turbulent plasma, including   |
| Limpouch, O. Rosmej, Tikhonchuk  |                  |                       | indirect heating                                       |
| PHELIX (GSI, Germany), PI O.     | 532 1064         | 2 ns, 160 J, 0.75ps, 80-100J | Heavy ion stopping in plasma, x-ray heating of        |
| Rosmej                           |                  |                       | aerogel, e, n, \(\gamma\)-rays emittance, also at up to \(3\times10^{19}\text{ W/cm}^2\) |
| LULI-2000 (Ecole polytechnique,  | 532              | 1.5 ns, 500 J/1 ps, 70 J | SBS and SRS in plasma at laser intensities up to \(3\times10^{16}\text{ W/cm}^2\), shock ignition related topics |
| France), PI S. Depierreux, C.   |                  |                       |                                                         |
| Labaune                         |                  |                       |                                                         |
| LIL (Bordeaux, France)           | 355              | 2.7 ns, 10000 J       | Irradiation smoothing, supersonic waves, SBS, SRS,    |
|                                 |                  |                       | emittance                                              |
| GEKKKO-XII (Osaka University,    | 532              | 1.5 ns, 2000 J        | Shock waves, instability seeded and relaxed, plasma   |
| Japan), PI P. Nicolai, S.        |                  |                       | magnetization                                          |
| Fujioka                          |                  |                       |                                                         |

3. Direct scheme experiments with polymer aerogels

In all but two of the referred experiments (on PALS and on PHELIX two runs were indirect) the laser radiation was focused directly on the polymer aerogel targets [4,5]. Self-emission slit in the washer holder of the aerogel provided convenient use of x-ray streak-camera for emission temporal behaviour.
Figure 2. Polymer aerogels bright x-ray streak images Left: CTA 4.5 mg/cc 400 μm +Al foil 5 μm, frame 2 ns (PALS). Right: TMPTA 10 mg/cc 1000 μm +Cu foil 30 μm (LIL), x-ray streak [4,5]

Supersonic wave propagation in low-density polymer, light transmission through homogeneous and inhomogeneous undercritical plasma was studied on aerogels with various densities. CTA targets supplied from Moscow and TMPTA targets by Wigen Nazarov from Scotland demonstrated similar ionization wave velocity behaviour on different laser facilities (Figure 2). Equal inner structure of the targets, comparable densities and light fluxes demonstrate supersonic ionization wave existence for no less than 250 ps.

Figure 3. Comparison of the target luminosity experimental results obtained on PALS (left) and LIL (right) [6, 5] from the same targets

Red rectangular boxes on the Fig.3 show the evidence of the same target “noise” imprinted in plasma in the same manner for differing laser facility. The relaxation is within 0.5-0.8 ns on the left graph and between 0-1 ns on the right, where it coincides with SRS and SBS emittance time/

Aerogel smoothing in the far field was observed on LIL and correlated with calculations [6]. Stimulated Raman and Brillouin scattering were also studied on directly undercritical aerogel targets (Figure 3). Large amount (20%) of laser light reflected from plastic aerogel on PALS earlier, can now be attributed to SRS and SBS. Light transmission behavior indicates inhomogeneous (turbulent) plasma presence. Higher SBS intensity at target illumination by ps-laser in the scheme of shock ignition at laser intensity growth up to $10^{16}$ W/cm² was observed.

To produce 2 mg/cc targets the authors estimated preliminary the focusing conditions and resultant electrons’ heating by the experimental formula from publication [10]. The calculated charge brought away by the hot non-thermal electrons further scaled well with the data received in [12].
relativistic plasma of aerogels proved to have advantage compared to the heavy-Z solid metal as bright secondary sources of high-energy electron fluxes and e.m. radiation.

In PHELIX experiments the high-Z foil irradiated with high-contrast laser pulses produced electrons with effective temperature of 2 MeV, whereas the pre-ionized aerogel produced up to 13 MeV electrons and 1000-fold multiplication of γ-rays and hot electron yield (by 10-channel TLD), 2-ns pulse used for pre-ionization.

4. Indirect scheme and low-density aerogels
Irradiation of low-density aerogel targets with wide x-ray spectra provides milder conditions for solid to plasma transition.

Combined experiments with PHELIX laser together with UNILAC heavy ion beam in GSI (2011-2012) showed unpredicted results. On early times of aerogel irradiation with soft x-rays converted from 2nd harmonics of Nd-laser in Au hohlraum, a decrease of ion stopping power of the target in comparison with ion stopping in cold target was observed. Further increase of ion stopping power is predictable, as occurs due to ion scattering on plasma free electrons [7].

![Figure 4. Left to right: target construction (GSI); 2 mg/cc CTA target; target construction (PALS)](image)

Complementary studies on indirect irradiation of low-density CTA aerogel targets were performed on the PALS, Prague (in 2012). Ionization wave propagation velocities were recalculated later from the x-ray streak camera data.

The indirect scheme of multiple laser cones arriving at the entrance hole of hohlraum was studied on the Omega laser by means of the careful examining of collective stimulated Brillouin sidescattering - SBS. The laser field fluctuations prevailed enormously any target noise, but the possibility to stage the sensitive observations is precious [13].

5. Metal foams and high-Z doped polymer aerogels
In Bhabha Atomic Research Centre in Mumbai, India, the 700 ps Nd-laser (basic wavelength) was used to study plasma dynamics and x-ray self-emission. Metal nano-snow low density layers, high-Z doped CTA aerogels were used as the targets and demonstrated high x-ray yield and softening of plasma self-emission spectra. [8]

![Figure 5. Bi nano-snow target in the washer with self-emission slit (left); x-ray reemission in polymer aerogel CTA and several-fold higher yield from metal seeded polymer aerogel targets (centre, vertical scale logarithmic), more soft x-rays from nano-snow Bi than from polished target (right).](image)
The results of [11] obtained in the same research centre on the low-density metal foams though done in direct-drive illumination scheme have proved the slow ion emission of the snow-like layer and brighter x-ray yield, which have immediate application to the inside of the hohl-raum body.

Selections of non-linear effects from our home experiments are collected in [15].

6. Discussions

With some difference of heavier-Z, the well-prepared nano-snow layers and plastic or organo-aerogels have similar structures on the scale of 1 micron (Fig. 1).

On the nanoscale the organo-aerogel appears as 3D spatial structure formed by the solid elements around 37-nm diameter and submicron length as seen on Fig. 6. Stochastic to some extend it is uniform in every 1 micron and optically transparent while solid. It is a coherent structure for laser light until melt.

The calculation of reference [10] applied to this pattern provides the electron mean energies and electric charge loss by hot electrons in agreement with the measured ones from the ref. [12]. We are not contradicting to the simulation provided in the said work. Just it was our team guidance before the experiment [12] and we have already realised after ref. [11] that it works. Aerogels and nano-snow targets are bright sources of hot electrons, x-rays and gamma-rays not only due to low density, but also because of their stochastic nature – slight “noise” in their structure.

Small-scale “noise” in aerogel structure like shown here relaxes under laser irradiation in 1/4-1/2ns as from Fig.3, orders of magnitude longer than the rod’s burst into vacuum, as is frequently considered. In comparable time period the mechanism of stochastic electron heating can take place due to the random phase jumps in the laser-beam electro-magnetic field. Qualitatively estimated in the present paper, certain low-density target stochasticity - “noise” - is better than plain uniformity.

7. Conclusions

Various “noisy” targets were done and applied in laser experiments: oxide aerogel, organo-aerogel, (CD2)n for ps- and fs-lasers, Au (Bi, Sn et al) nano-snow targets, CHO+Cu composites for different drivers. They all are of nanoworld and are slightly “noisy” as the coherent laser light meats them. Light energy smoothing and particle and rays bright emittance in “noisy” targets have been demonstrated and validated. There are physical processes in plasma to be further studied, taken into account and included into the codes as feedback of our target performance, functionally connected with target intrinsic structure “noise”:

1. partial laser light transmission through plasma and transparent target in the beginning of the pulse
2. aerogel-and-foil preheating
3. pulsations and structure formations: the variable transmittance coefficient for laser light
4. essential role of non-linear effects from structure
5. transient processes, structure induced turbulence

Figure 6. SEM image of CHO-aerogel 3D-network. Ni-Mo deposited for sample charge escape. Quasi-regular open structure of 37-nm diameter rods and submicron pores. Optically transparent 1-mm thick sample.
6. efficient smoothing of laser speckles by thin polymer layers of very low density in the far field
7. indirect targets can be equipped by the layer of low-density metal, say Au, inside the converter for higher temperature of soft x-rays, higher conversion and smaller diameter
8. reaching orders of magnitude brighter x-ray, neutrons, γ- and ion-emittance

Even the restricted only 2 types of targets demonstrate an amazing diversity of the phenomena under laser illumination rich in physics and applications. The effects that noisy targets provide may be favourable or unwanted, but necessary to know for their right use. Here we wanted to stress and illustrate that aerogel and snow-like targets being “noisy” are extremely efficient and variable sources of x-rays and particles: nanoseconds through femtoseconds.

We continue to underride aerogel or nano-snow for every successful laser and foam-target interaction experiment.

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