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Metal nano-particles modernized layers and those with polymers for laser thermonuclear targets

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Abstract. The manufacturing and precision monitoring methods of the layers as promising direct and indirect targets for Inertial confinement fusion (ICF) are under study, as well as their application in the experiments. The metal-containing foams with a density that is several times or several orders of magnitude smaller than the full-density material of the same composition are of interest for higher laser light conversion into X-rays and for better energy delivery into the target in direct and indirect interaction schemes. Such targets are developed and provided. We report the interaction of Nd: glass laser with a low-density bismuth and gold targets. The plasma dynamics and X-ray emissions were observed using multiframe optical shadowgraphy and an X-ray streak camera. Enhanced X-ray intensities and festoon plasma flame are observed from the metal low-density layers.

1. Introduction

The analysis of laser radiation conversion has been presented in the publication by S. Yu. Gus’kov and Yu. A. Merkul’ev [1], where the authors considered the problems of conversion efficiency in a low-density polymer foam with an addition of nanoparticles of heavy elements, and the absorption that takes place in the external layer of the target. This layer plays the role of the laser radiation absorber and the converter of laser radiation into X-rays. The degree of conversion increases with the decrease of the laser wavelength, and for the intensity of $10^{14}$-$10^{15}$ W/cm², the degree of laser energy conversion is 60-80% [2].

In [3], the authors have theoretically predicted the increase of temperature in the converter due to the X-ray radiation when a foam with a low-density gold layer is introduced instead of solid gold. As shown in [4], the experimental verification of this important statement using a laser facility has confirmed the validity of this statement.

In addition, such layers may be helpful for the formation of spherical layers for the cryogenic targets and low-density media in the form of metal-polymer foams and ultra-dispersive powders (UDP) of metal, which are used both as free layers and as additives in the foam polymers.

The experimental studies at BARC, Mumbai, India, in collaboration with scientists from the Thermonuclear target laboratory, LPI, Moscow, at the Nd: Glass laser facility (wavelength, 1.062 µm; energy, 15 J; intensity, $\sim10^{14}$ W/cm²; duration, 0.5 ns) provided important results.
2. Experiment
In our previous experiment, using a low-density layer of ultra-dispersive (UDP) bismuth powder (0.1 g/cm$^3$), the conversion efficiency increased by 10% compared with the solid matter target in the soft X-ray region [5]. The physics of conversion of laser radiation into X-rays is discussed in our paper [6]. In addition, the abovementioned paper deals with a number of important technological aspects.

The Organic Chemistry Institute and LPI of the Russian Academy of Sciences has developed polymer aerogel layers with heavy metal nanoparticles. A multistep technological system of adding a metal cluster to the polymer is used [7]. Currently, similar studies are being continued and carried out based on the novel technological developments [8-9]. It is also noted that the parylene high-strength plastic (C$_8$H$_8$) is used, as a rule, in the form of a micrometer-thick protective coating of micro-circuit inner surfaces. The plastic may contain Br-parylene (C$_8$H$_7$Br) in a form that can be used for diagnostics in addition to the reaction of $^79$Br(n,2n)$^{78}$Br, which takes place in laser thermonuclear fusion targets with a reaction cross-section of 862 mbarn, $t_{1/2} = 6.5$ min, E $\gamma$-quanta 0.51 MeV. We have succeeded in obtaining a low-density porous material with densities of (1/3-1/12)$^9$ of solid C$_8$H$_7$Br. This is of interest for the diagnostics in thermonuclear experiments (Fig. 1a).

The development of coating deposition technology has allowed us to obtain more uniform and ultradispersive Bi and Au layers. The scanning electron microscope (SEM) image of UDP Bi with $\sim$40 nm particles is shown in Fig. 1b.

3. Results and discussion
The size of nanoparticles and density of layers depend on the pressure change of inert gas (Ar or He) that is used in the manufacturing installation. Based on our experience, in the case of He, we obtain a finer ultradispersive powder, smaller density of the layer, temperature rise regime, as well as a shorter time of the evaporation process. Besides, there is a dependence on the amount of evaporated matter and the type of evaporator, which is our exclusive development. Recently, we managed to deposit a uniform layer of Bi UDP (a 100-µm thickness and a density as low as 1/250$^9$ of full-density Bi) on a 0.5-µm thick cellulose nitrate film, which was placed on a holder with a 32-mm inner diameter opening, as shown in Fig 2a. The gold ultradispersive layer with a particle size of 30 nm is also obtained using an improved technique that is aimed at producing a finer powder, as shown in Fig. 2b.

Laser investigations were performed using the laser setup shown in Fig. 3.
Figure 2. (a) The 100-μm bilayer of UDP on a 0.5-μm cellulose nitrate foil, free and uniform over a 32-mm opening in the holder. The scale unit is 2 mm (between two ciphers). (b) SEM picture of a Au-modified UDP layer. The fine particle size is ~ 30 nm. Scale, 1 μm.

Figure 3. Schematic of the experimental setup for the foam target irradiation with high-power laser pulses.

Shadow photographs supplement the study into the stability of foam target and full-density target plasma (Fig. 4). The vertical strip is a shadow photo of the target profile under the action of laser radiation from the left. The shadow enlarges due to the formation of dense plasma and target-evaporated matter. The normal incidence laser beam initiates characteristic and repeatable, almost periodic, festoon picture and helps study radiation absorption and conversion together with hydrostability trends of low-density layers application in ICF. Green beam is used for the plasma shadowgraphy.

To interpret correctly the results from the ICF experiments, it is necessary to know exactly the constructional and physical parameters of the targets [10]. An important problem is a precision control of the metal ultradispersive layers, and among them, those in the combined layers of low-density metal polymers to be used in the ICF. The optical and X-ray methods of the layer characterization are used, including microradiography and X-ray tomography, scanning electron microscopy, and radiography. The monitoring methods are mutually complementary.

For comparison, a low-density CD₂ layer (300 μm thickness and the density of 1/3 of the solid polymer), which is mounted on the same holder as above and under the same irradiation conditions, was irradiated. The polymer targets show even and hydrodynamically tranquil flow (Fig. 5), and the festoon features are absent.
Figure 4. Plasma expansion from low-density Bi (thickness, 70 μm; density, 1/100 of solid Bi) on a 5-μm-thick Teflon substrate. (a): before the laser pulse; (b): 2 ns after the laser pulse start; (c): 8 ns after the laser pulse.

Figure 5. Plasma expansion from a low-density CD$_2$ target. (a) before the laser pulse; (b) 2 ns after the laser pulse is initiated; (c) 8 ns after the laser pulse.

This allows one to make quantitative comparison and calculate longitudinal and transverse motion of the waves and matter. Metal foams behave differently (Fig. 4), and it is typical that there are almost periodical perturbations of the opacity front along with the integrally united transverse and axial motion. The motion behavior does not strongly depend on the metal, but is notably dependent on the target matter structure: solid matter, massive or thin foil.

The X-ray emittance of Au foams was compared with that of bulk gold. In Fig. 6, color represents the intensity change in the signals from the foam with a 1/100$^{th}$ the density of bulk gold. The X-ray intensity curves are given above for each streak-image. The target matter has a noticeable spatial effect. At the maximum, the X-ray intensity is approximately 15% higher for the low-density metal layer than for the full-density one. Further data processing is required. This will also ensure the foam application for intensive particle generation [11] for the sake of science and ICF.

Currently, there is no obvious radiating capacity drop for the gold foam due to the presence of admixtures with a low atomic number. The possible explanation may be in the current fabrication technique, which ensures that the foam composition is close to that of the initial pure metal.
Figure 6. Signal from an X-ray streak camera for Au targets with a density of 200 mg/cc (a) and for Au targets with a density of 19.3 g/cc (b). Densitograms for both are placed above each signal.

4. Conclusions
The techniques aimed to obtain the low-density metal layers and metal-polymer foams for the purposes of ICF in a wide density range (5-500 mg/cm$^3$) have been developed. The discussed layers can be used to obtain a more effective conversion of laser radiation into X-rays, and the layers are stable enough for the transportation and mounting into the chamber at the laser facility with a subsequent vacuum pumping.

Materials that are better than the earlier UDP low-density layers of gold and bismuth on freestanding submicron foils have been developed, manufactured as plain targets, characterized and provided for laser exposure.

The experiments with metal targets, as compared with the low-density metals of the same composition, have confirmed the expected increase of X-ray radiation from the laser plasma of the initial foam target. The observed stable and repeatable hydrodynamic behavior demonstrated specific festoon features as compared with similar polymer layers. The abovementioned characteristics are promising for ongoing and future experiments.

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