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Aerogel foil plasma: Forward scattering, back scattering, and transmission of laser radiation

A.N. STARODUB, N.G. BORISENKO, A.A. FRONYA, YU.A. MERKULIEV, M.V. OSIPOV,
V.N. PUZYREV, A.T. SAHAKYAN, B.L. VASIN, AND O.F. YAKUSHEV
P.N. Lebedev Physical Institute of the RAS, Moscow, Russia

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Abstract

Experimental results obtained with “Kanal-2” facility under the study of powerful laser pulse interaction with the low density microstructure media are presented and discussed in this paper. Forward scattering, back scattering, and transmission of laser radiation by aerogel foil plasma have been investigated. The temporal, spectral, and energy characteristics of both the radiation scattering in the direction of heating radiation beam and the back scattering radiation were studied; the directional diagrams of forward and back scattering radiation were obtained for ω_0 and $2\omega_0$ frequencies. Analysis of intensity redistribution on the heating beam cross-section after passing through a polymer microstructure target was carried out.

Keywords: Aerogel foil; Foam target; Laser radiation absorption; Laser-plasma interaction; Nonlinear transparency; Smoothing; Transmission and scattering

INTRODUCTION

The penetration efficiency of laser energy to plasma is the important issue at the interaction of powerful laser radiation with matter (Foldes & Szatmari, 2008; Yu *et al.*, 2009*a*). Scattering processes occurring in plasma resulting in a loss of the heating energy radiation that affects the process of the laser radiation energy deposited on the target. For this reason, the important task is a comprehensive study of the scattering processes in laser plasma, in particular, the study of spectral, temporal, spatial, and energy characteristics of the scattered radiation.

Uniformity of energy distribution on the irradiated target surface, which affects the efficiency transmission of laser energy to plasma, is another important question to be solved (Ramis *et al.*, 2008). It is proposed to use the method of a dynamic plasma phase plate (Voronich *et al.*, 2001) for smoothing spatial intensity distribution of heating radiation on the target. The optical transparency of a plasma layer is an essential method of a dynamic plasma phase plate, which leads to the necessity of using the low density volume-structured media (Borisenko *et al.*, 1994, 2008; Khalenkov *et al.*, 2006; Moreau *et al.*, 2009; Yu *et al.*, 2009*b*)

Volume-structured materials are considered as different functional elements in the inertial confinement fusion (ICF) targets (Dunne *et al.*, 1995; Gus’kov & Rosanov, 1997; Bugrov *et al.*, 1997, 1999*a*, 1999*b*; Nazarov *et al.*, 1999; Cook *et al.*, 2008; Nobile *et al.*, 2006). First of all, smoothing of a heating inhomogeneity and production of a steady compression of the ICF targets prove to be possible applications of those materials. Therefore, investigation of the specific features of the laser radiation absorption and scattering by such media, as well as the energy transfer, plasma formation, and plasma dynamics are the topical problems.

This paper reports recent results obtained from studying the laser interaction with volume-structured media. The attention is focused on studying the back scattering, forward scattering, and the propagation of laser radiation through such media, including the spatial distribution of the transmitted radiation and its spectral and energy characteristics. The analysis of intensity redistribution on the beam cross-section after passing through a polymer microstructure target has also been performed.

EXPERIMENT

The experiments have been made with an Nd-glass laser facility “KANAL-2” with controllable coherence of radiation (Fedotov *et al.*, 2004). The laser radiation parameters were as follows:

Address correspondence and reprint requests to: Starodub Alexander, P.N. Lebedev Physical Institute of the RAS, 119991, Leninskiy prospect 53, Moscow, Russia. E-mail: starodub@sci.lebedev.ru

laser pulse duration, 2.5 ns; pulse energy, 10–100 J; degree of spatial coherence, ~0.05–0.015; degree of temporal coherence, $\sim 5 \times 10^{-4}$–5×10^{-3}; degree of radiation polarization, ~0.5; pulse radiation contrast $> 10^6$. As the targets, the triacetate cellulose aerogels (Khalenkov *et al.*, 2006) of the density changing within the range of 2–10 mg/cm^3 and the thickness of 100–500 μm have been used. In several experiments up to 10 weight percent of copper nanoparticles of the average diameter of 40 nm have been introduced into the polymer, but the electron concentration and average density did not change. The three-dimensional polymer nets do not change their structure under the change of density from 50 mg/cm^3 to 1 mg/cm^3. The distance between the filaments is 0.6 to 1.7 μm, and the filament diameter is 70 to 40 nm. The aerogel density fluctuations at volume averaging $0.3 \times 0.3 \times 0.3$ mm^3 do not exceed 0.5% at the aerogel average density higher than 4 mg/cm^3, and grow up to 3% for the aerogel density of 1 mg/cm^3.

The target is placed in to the interaction chamber with a complex of diagnostic devices, which allows registering the parameters of laser radiation and plasma with temporal, spectral, and spatial resolution. The complex consists of several channels: (1) a calorimetric system for measuring the plasma and laser energy characteristics; (2) a channel intended for investigation of plasma radiation spectral characteristics within the range 0.4–1.1 μm; (3) the temporal behavior of radiation registration system; (4) an optical system to obtain information on the direction of plasma expansion and laser radiation scattering in the given section with wide registration angle ($\Delta\alpha \sim 90^\circ$) and wide spectral range (0.4–1.1 μm); (5) X-ray diagnostic system for continuous X-ray radiation spectra measuring; (6) the system for registration of the distribution of radiation intensity in the near-field zone.

EXPERIMENTAL RESULTS AND DISCUSSION

Energy balance is an important aspect in the irradiation of foam targets; it may realize the problems of efficiency of conversion of the heating radiation into the X-ray and its transmission through such targets. In the experiments, the energy of the heating radiation, back scattering and (transited through the target) forward scattering radiation has been measured. The energy of the radiation scattered into the focusing aperture lens is less than 1% of the heating laser energy and, in particular, it is 0.2% for TAC target 9/400. That means that the nonlinear scattering processes

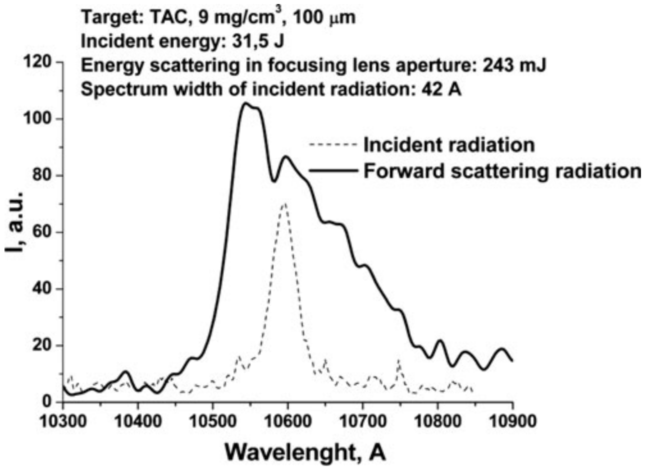


Fig. 1. Spectra of the heating laser radiation and the radiation transited through the aerogel target.

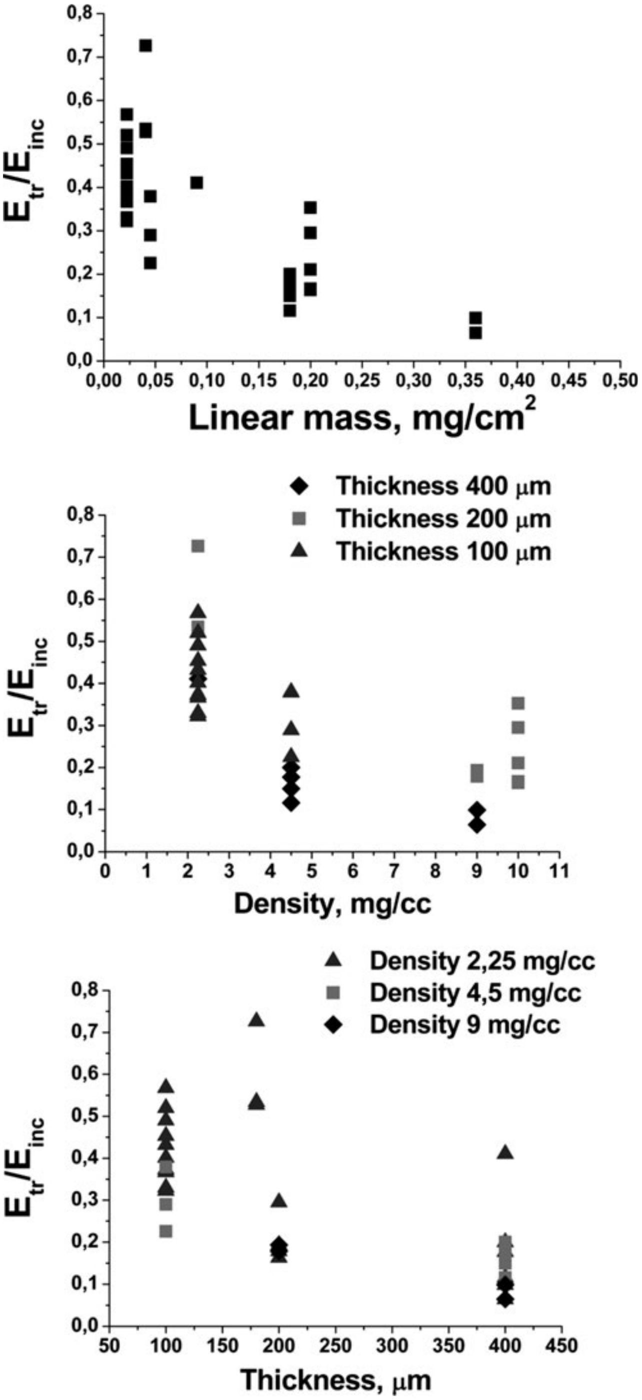


Fig. 2. Dependences of the energy transited through the target on the target linear mass, density, and target thickness.

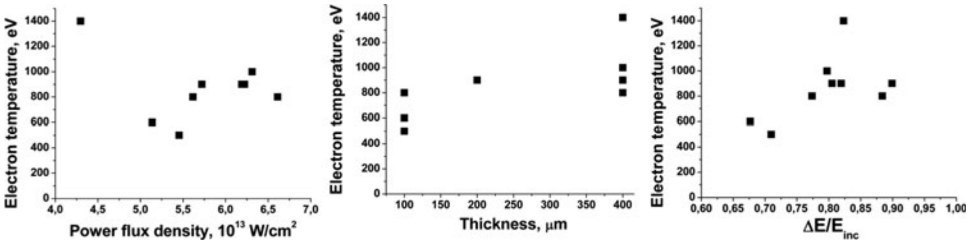


Fig. 3. Electron temperature dependences on power flux density, ΔE, target thickness.

such as back-SMBS and back-SRS are non-essential from the energy view point, and may affect the scattered radiation line width only. From that one may also conclude that the nonlinear processes of forward scattering due to SMBS and SRS are not energy essential. However, one can observe (see Fig. 1) a substantial (up to 200 Å) spectrum broadening of the transited radiation. The spectrum maximum of forward scattering radiation is shifted into the short-wave range relative to the laser wavelength. And that spectrum has asymmetrical broadening with a wing in a long-wave range at the heating radiation line width 42 Å and intensity $\sim 6 \times 10^{13}$ W/cm^2.

It was found, that the energy E_{tr} transiting through the target is compatible to the energy E_{inc} of the incident radiation, and the value of energy E_{tr} maximum amount 70% of the incident energy. In particular, it is 72.7% for the TAC target of density of 2.25 mg/cm^3 and thickness 180 μm at the power flux density 9×10^{13} W/cm^2.

The energy transited through the aerogel decreases with the increase in the aerogel thickness, increase in the target density, and the increase in the target linear mass (Fig. 2). The material mass interacted with laser radiation is growing with an increase of the thickness, density and, correspondingly, linear mass. Such increase of plasma layer size and dense plasma areas with the electron density nearly equal to the critical density $n \approx n_c$, where the reflection and absorption of major part of the heating radiation energy take place.

In the TAC target irradiation experiments, the plasma electron temperature value was 0.4–1.4 keV. The electron temperature dependences on the power flux density, target

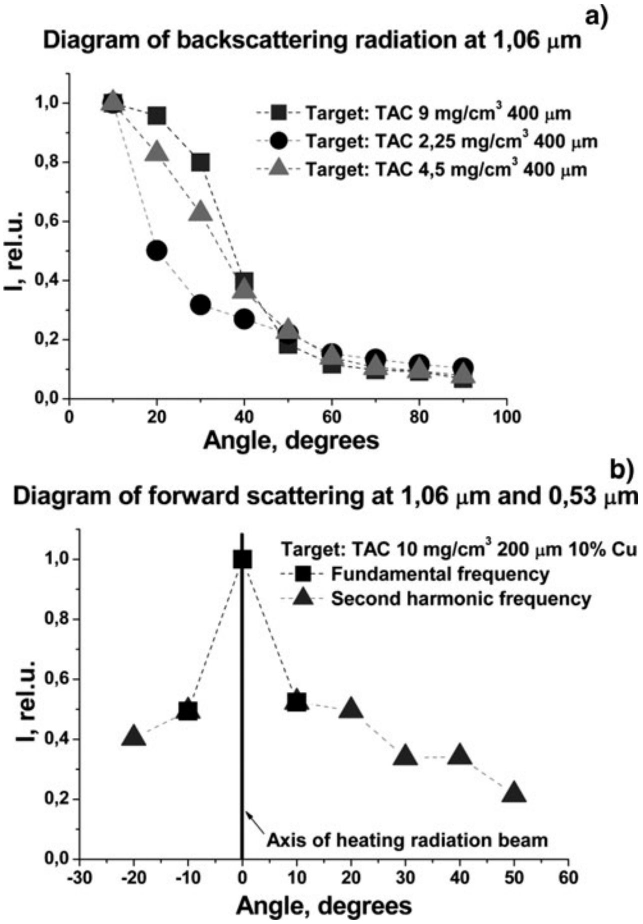
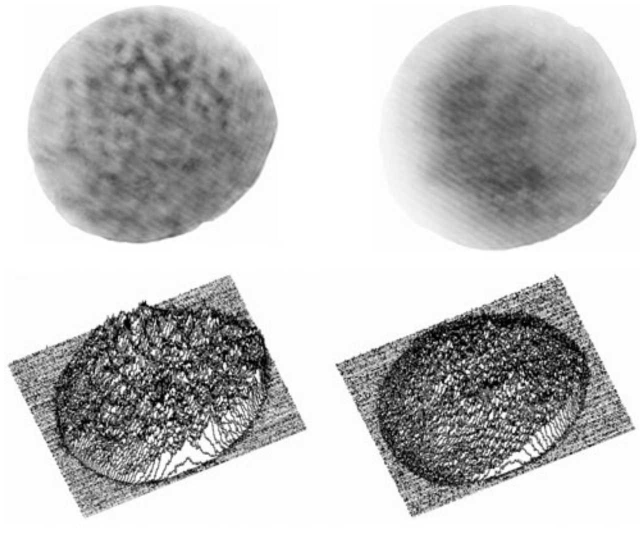


Fig. 4. (**a**) Directional diagram of backscattering radiation at the fundamental frequency. (**b**) Directional diagram of the radiation at the fundamental and second harmonic frequency transited through the aerogel target.



Without TAC target
Incident energy 75 J

With TAC target
Incident energy 75 J
Energy transited through the target 53 J

Fig. 5. Distribution of radiation intensity in the near-field zone.

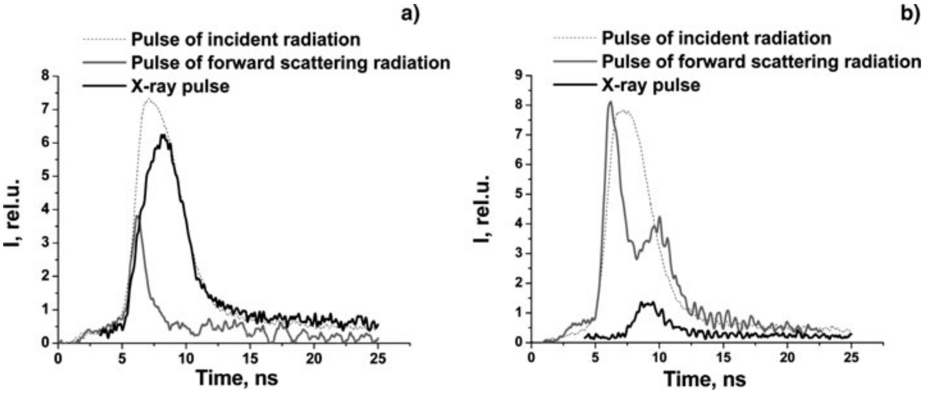


Fig. 6. Temporal behavior of the heating laser radiation pulse, the radiation pulse transited through the aerogel target, and the X-ray pulse for TAC target of the density 9 mg/cm^3, the thickness 500 μm (**a**), for the TAC target of the density 10 mg/cm^3, the thickness 200 μm, and 10% of copper nanoparticales (**b**).

thickness, and energy ΔE were revealed (Fig. 3). Here

$$\Delta E = E_l - E_{bs} - E_{fs+tr}$$

and E_l, the energy of incident laser radiation; E_{bs} is the back scattering radiation energy; E_{fs+tr} is the energy of the radiation transited through the target and forward scattering. It was found that plasma electron temperature is in direct proportion to ΔE. The observed electron temperature behavior may be due to the fact that with an increase of the power flux density of the heating radiation and the target thickness the foam plasma absorbs more energy.

The dependence of the radiation scattering angle on the target linear mass has been revealed for the polymer TAC targets at studying the back scattering at fundamental frequency. The diagrams of back scattering at the fundamental frequency for the TAC targets 4.5/400 (density/thickness) and 10/200 are similar. An increase of scattering angle, at which the scattering of the main part of energy (80–90%) occurs, has been observed for TAC target at changing of the linear mass from 0.09 to 0.36 mg/cm^2 (Fig. 4a). According to Figure 4b, the radiation transited through the aerogel target propagates practically along the axis of the heating laser radiation beam, and forward scattering on the second harmonic frequency occurs diffusely in space.

The distribution of radiation intensity in the near-field zone was obtained at the investigation of radiation transited through the target. As seen from Figure 5, the intensity redistribution on the beam cross-section can be achieved. Small-scale irregularities are presented in the laser beam, but after the laser-foam interaction these irregularities are smoothed. The intensity smoothing after passing through a polymer aerogel takes place at optimum correlation between the laser and target parameters. In our case, the TAC target had the density of 2.25 mg/cm^3 and the thickness 400 μm.

As one can see from Figure 6a, the energy comparable with the target incident energy transits through a target at the pulse beginning when the size of plasma is not large. As the plasma develops, the absorption grows, and the pulse passing ceases. As seen from X-ray measurements, the X-ray radiation intensity grows, and this corresponds to on going plasma heating. Pulse duration of a transited energy is comparable with the duration of the incident laser pulse.

The interpretation in frames of the target geometrical transparency (Gus'kov & Rosanov, 1997; Bugrov *et al.*, 1999*a*) is not capable to explain the observed duration of a transited energy pulse, and the value of that energy.

This seems to suppose that nonlinear transparency of plasma produced under aerogel irradiation may be responsible for the observed effect. Such a transparency arises due to the plasma density modulation in the laser field. As shown in the literature (Mironov, 1971; Vladimirsky *et al.*, 1977*a*, 1977*b*; Sauer & Gorbunov, 1977), due to such modulation, there may arise a full transparency of a plasma layer under certain relationship between the laser intensity, plasma layer size, and the radiation wavelength.

The second harmonic registration shows that such density modulation actually takes place. The registration of harmonics $(3/2)\omega_0$ and $(5/2)\omega_0$ indicates that such modulation is deep enough.

Another reason for nonlinear transparency of the aerogel target may be connected with anomalous burning (Koutsenko *et al.*, 1999).

It should be noted that the real picture of nonlinear transparency of the arising plasma (compare Figs. 6a and 6b) is more complicated, and is defined by the conditions of energy absorption and transfer, plasma formation and plasma dynamics. This means that the temporal behavior of the pulse transmitted through the aerogel target may change from shot to shot.

CONCLUSION

Anomalous laser energy penetration through aerogel in combination with no evident dynamic behavior is considered as nonlinear transparency of a plasma layer arising from the laser radiation interaction with low-density target. The intensity smoothing after passing through a polymer aerogel takes place. The spectrum of radiation transmitted through the aerogel plasma is considerably broadened up to 200 Å. It is suggested that the TAC target could be used for laser radiation conversion to optimize the light absorption and to obtain a broad line width of the incident radiation. As a result, the efficiency of energy yield from the active elements may be higher, and the laser efficiency may increase.

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