Energy transfer in low-density porous targets doped by heavy elements

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Abstract. A low-density plastic aerogel foams, including doped with copper clusters have been irradiated by the first (λ=1.315 µm) and third (λ= 0.438 µm) harmonics of the PALS iodine laser. Laser pulse duration was approximately 380 ps (FWHM), laser energy was up to 300 J, and laser intensity on the target was typically by an order of 10¹⁴–10¹⁵ W/cm². The targets were of a fine-grain structure with the pore size in the range of 1-2 µm. The energy transfer in plasma was measured by the X-ray and optical diagnostics. The observed phenomena are explained via mathematical modelling of the processes in plasma performed by fluid codes RAPID and LATRANT, developed at P.N. Lebedev Physical Institute and the Institute of Mathematical Modelling of RAS, Moscow. Our simulations take into account a microscopic structure of porous matter and energy transfer and loss by the X-ray emission. The plasma radiative characteristics were calculated by DESNA code. The analysis of the experimental and calculated data allows one to find the energy balance in the target and the plasma characteristics important for the dynamics of the processes.

1. Introduction

In the present paper the authors analyze the experiments on the irradiation of fine-structure cellulose triacetate (TAC) targets (C₁₂H₁₆O₈, the cell size 1-2 µm). The results for C₁₅H₂₀O₆ (TMPTA) targets are close to those for the TAC targets. The targets present a 400 µm thick foam disk (the experiments are made within the foam thickness range of 100-500 µm) about 2000 µm in diameter; from the backside of the laser a 5 µm thick Al foil is pasted. The density of the foam layers is as follows: 4.5 mg/cm³, 9.1 mg/cm³, and 9.1 mg/cm³ + Cu in the amount of 9.9% over the weight. Information on PALS laser presented in [3]. The discussed experimental results involve the temporal streak record of the target X-ray emission (perpendicular to the laser beam axis) as well as the optical streak record of Al foil emission within the optical range in the focusing spot projection onto the target (the Al surface temperature 1000 – 10 000 K). The energy of the registered X-ray quanta exceeds 1 keV. Note that the investigation of laser interaction with the targets made of structured low-density matter (foam) is a topical problem (see [1,2]). The problems of preparation of low-density targets and a detailed description of experimental results are given in [4].

2. Experimental results.
Typical results are shown in Fig. 1.

![Figure 1. Experimental results (details in the text).](image)

The upper picture presents the streak record of plasma X-ray radiation. The spatial scale (given by the foam thickness), and the streak record duration (~2 ns per picture) are known. The bottom picture illustrates the streak record of Al foil backside radiation within the optical range. The optical measurements are attached to the laser pulse maximum at 1ω frequency (0.34 ns after the start of the pulse): for 3ω experiments the time marker coincides with the laser pulse maximum, and for 1ω it defines a 3 ns delay of optical illumination; the streak record duration is 5.7 ns.

Figure 1a illustrates the pulse of the energy of $E_0=164$ J, the foam 4.5 mg/cm$^3$, Al foil thickness, 5 μm; 1b – $E_0=170.4$ J, 9.1 mg/cm$^3$, 5 μm; 1c – $E_0=166$ J, 9.1 mg/cm$^3$ + Cu, 5 μm (a,b,c – for 3ω); 1d – $E_0=174$ J, 4.5 mg/cm$^3$, 5 μm; 1e – $E_0=332$ J, 9.1 mg/cm$^3$, 2 μm (d and e – for 1ω).

Two types of optical emission are observed: a weak emission, which starts with the beginning of a laser pulse, and a stronger one, typical of a jump-like increase, which starts 1.5-7 ns after the laser pulse. The observation of a weak emission is indicative of the fact that the temperature at the back side of the Al foil reaches, at least, ~1000 K, and later, due to a certain process, the temperature reaches ~2000–10000 K. The brightness and size of X-ray streak records correlates with the time of the beginning of a brighter emission: the brighter is the X-ray picture the smaller is the time of the beginning of the second emission.

| $\rho_{\text{foam}}$ (mg/cm$^3$) | 4.5 | 9.1 | 9.1 + Cu | 4.5 | 9.1 | 9.1 + Cu |
|---|---|---|---|---|---|---|
| $t_{\text{opt}}$, ns | 4.0-4.2 | 5.0-5.2 | 7.0 | - | 2.0 | 4.0-4.5 |
| $\omega_{\text{LAS}}$ | $1\omega_0$ | $3\omega_0$ |

Table 1 lists the data on the time of the beginning of second optical emission for 1ω and 3ω experiments, for different foams 4.5 mg/cm$^3$, 9.1 mg/cm$^3$, and 9.1 mg/cm$^3$ + Cu (note that an addition of Cu does not practically change the density of the target matter), and different energies of the laser pulse. The focusing conditions in the experiments differed also. Their influence has not been discussed. Table 1 shows the time of the beginning of the optical emission $t_{\text{opt}}$, which combines the time the shock wave reaches the Al foil, and the time of shock wave passing through the Al foil. In all the experiments, listed in Table 1 the foam thickness is $\Delta=400$μm, the Al foil thickness, $\Delta=5$ μm.

### 3. Physical model and simulation.

Under described above experimental conditions one should conclude that, although the energy deposition into the focusing spot is defined by the laser pulse energy, the precise energy value is not known. So, it should be found from the optical measurements. The weak emission (emerges immediately) be associated with the heating of the Al foil the plasma eigen thermal nonequilibrium radiation. A more strong radiation (a jump-like delayed radiation) should be related to the shock wave, which emerges in plasma and comes through the Al foil. The shock wave parameters can be found...
from a well–known solution of the problem of a strong point explosion (L.Sedov & G. Taylor) and related to the energy generating shock wave. To take into account the time of the shock wave passing through Al foil one should make use of the Al real EOS [5]. Some of the data is given in Table 2 (see below), D is the shock wave velocity; U, the Al mass velocity behind the wave.

Taking into account all the above-mentioned remarks, the plasma energy may be estimated as shown in Table 3.

### Table 2.

| \( \rho / \rho_0 \) | \( p \) (Mbar) | \( T \), K | \( D \), km/s | \( U \), km/s |
|----------------|-------------|--------|-----------|-----------|
| 1.39           | 0.56        | 1300   | 8.6       | 2.4       |
| 1.55           | 0.99        | 3000   | 10.2      | 3.6       |
| 1.70           | 1.53        | 5600   | 11.8      | 4.8       |

### Table 3.

| \( \omega_{\text{las}} \) | \( \rho \), mg/cc | \( t \), ns | \( E \), J | \( U \), km/s |
|----------------|------------------|--------|--------|-----------|
| 1\( \omega_0 \)    | 9.1              | 4.2    | 5.7    | 30        |
| 1\( \omega_0 \) + Cu | 9.1              | 6.0    | 2.5    | 21        |
| 1\( \omega_0 \)    | 4.5              | -      | -      | -         |
| 3\( \omega_0 \)    | 9.1              | 1.5    | 40     | 78        |
| 3\( \omega_0 \) + Cu | 9.1              | 3.2    | 9      | 36        |

In Table 3 there are listed the values of energy \( E \) and the time of the shock wave (SW) arrival to the Al foil surface. The energy is calculated by the formula of strong point explosion \( E = 10 \rho U^2 / t^2 \) (the foam density \( \rho \) in mg/cm\(^3\), the time \( t \) in ns, the energy in J) that corresponds to the SW radius, \( \Delta = 400 \mu m \), and the foam mass velocity behind the wave is \( U = 0.8/(\gamma +1) \Delta t \). Optical measurements do not allow one to determine the plasma energy for the experiments with 3\( \omega_0 \) and \( \rho = 4.5 \) mg/cm\(^3\). The energy is probably close to the laser energy in the region of a focusing spot.

By using the data of Table 3 one may determine the processes, which are responsible for the plasma energy and energy balance. Such processes include absorption and reflection of the laser radiation, plasma ionization, and the respective energy expenses, and a transformation of the target material from a structured medium to a homogeneous matter. In the outer layer of matter those processes occur during the action of a laser pulse (~380 ps). The plasma radiation leading to substantial energy losses take a longer time of 0-4 ns.

Those processes were analyzed by means of numerical calculations using the 1D RAPID and 2D LATRANT programs [6,7]. In the 1D RAPID, a target was imitated by a set of thin layers in respect to the given average density. Laser radiation was described by the Maxwell equation. For the laser radiation transfer model the Maxwell equations are solved, the ray tracing model is not used.

In the calculations, one has determined a part of an absorbed energy \( \delta \) under different conditions. The results may be represented in the form of interpolation formula:

\[
\delta = 0.145 \left( \frac{\omega}{\omega_0} \right)^{1.25} \left( \frac{4.5}{\rho} \right)^{1.75} \left( 7.2 \cdot 10^{14} \right)^{0.8} \frac{t}{I}
\]

Value \( \delta \) was determined from a coincidence of the heat wave velocity front in the calculations and experiments by means of fitting of the electron heat conductivity. Reflection of the laser radiation from a target turns out to be essential especially for the radiation of 1\( \omega_0 \), when the density 4.5 mg/cm\(^3\) corresponds to 2.3 \( n_e \), and 9.1 mg/cm\(^3\) to 4.8 \( n_e \), where \( n_e \) is the critical density. From those data one could evaluate the range of energy values in plasma for different experimental conditions. The results see in Table 4, where \( E \) is in J.

All those peculiarities in the target behavior were studied in the 2D calculations by the LATRANT code, where the radiation transfer was taken into account in a multi-group approximation. The nonequilibrium radiative plasma characteristics obtained by the DESNA code [8] were used. Consideration of the radiation nonequilibrium behavior is important for the quantitative comparison of theoretical and experimental results. In view of the results of calculation, we have plotted the X-ray radiation streak records similar to those obtained experimentally.
Figure 2 illustrates the results of calculation at $1\omega$, $E=10$ J, and $\rho=4.5$mg/cm$^3$. Figure 2a shows X-ray plasma radiation streak records normal to the laser beam; Fig.2b depicts the 2D distribution of the electron temperature $T_e$ for $t=1.3$ ns; Fig.2c is the energy balance, where the energy is measured in J/$2\pi$, and Fig.2d is the pressure distribution at the laser beam axis.

The data of Figs. 2b-c shows that one can legitimately use the strong point explosion model. Within a wide range of conditions the ionization energy per particle keeps approximately constant.

In the discussed calculation, about 15% of absorbed energy is emitted; for the targets 9.1 mg/cm$^3$ +Cu the radiative losses constitute ~60%, and this explains the energy reduction in such targets as shown in Tables 3 and 4. The plasma emission is strong enough to heat the Al foil up to such a temperature which allows to observe the optical emission. The drop in the electron heat conductivity is quite significant at the stage of laser energy absorption (when the plasma is inhomogeneous within the cell size scale, and when the reflection of laser radiation is substantial). Later plasma behaves like a homogeneous medium, and the results weakly depend on the heat conductivity limit (within the range of 0.02-1). This confirms the physical validity of the earlier proposed EOS of the foam, which includes relaxation processes [2]. At small cell size the relaxation processes are finished in 0.1-0.3 ns.

### 4. Conclusions

The PALS laser experiments indicate the necessity of taking into account the balance of laser reflected energy and the plasma eigen nonequilibrium radiation. After the end of the laser pulse the plasma behaves like a homogeneous medium, and its further evolution corresponds to the strong point explosion model. In this case the shock wave corresponding to the model of a strong explosion fails to be formed and the aluminum illumination in the optical range is explained by heating of Al by the X-ray plasma radiation. The Al foil optical emission allows one to estimate the plasma energy, which turns to be essentially smaller than the laser pulse energy. For the experiments with TAC $\rho=4.5$ mg/cm$^3$ and $3\omega$ the strong point explosion model fails to take shape.

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