INVESTIGATION OF THE ENERGY CHARACTERISTICS OF A PLASMA CREATED IN AIR NEAR A TARGET BY CO_2 LASER RADIATION

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In spite of the large number of papers concerning different aspects of the interaction of powerful laser radiation with matter (see, for example, [1-7]), the processes of absorption and conversion of energy in a plasma flame have practically not been studied.

In this paper, we investigate a method for determining the energy absorbed by a laser plasma based on measuring the parameters of the shock wave (SW) arising in the cold gas surrounding the target. The energy characteristics of the plasma with cross section $S \simeq 90$ cm^2 are obtained near the threshold of its formation as a function of the target material and the intensity of the laser radiation.

It is shown experimentally that for a pulse duration $\tau \lesssim 10^{-6}$ sec and a characteristic flame size $h \leqslant 1$ cm, the motion of the SW at distances $z \geqslant 1$ cm is described by the theory of a point explosion. This permits determining the total energy of the gas in the shock wave Q_1 from measurements of a single parameter of the SW, for example, the Mach number M [8, 9]. The energy of the plasma layer near the target is estimated assuming that the formation of the SW and, therefore, the quantity Q_1 as well are due to the work performed by the plasma piston in the course of its adiabatic expansion.

The typical arrangement of the experiment is presented in Fig. 1. A powerful amplifying system based on CO_2–LUI-2 [10], from whose radiation flux a beam of radiation with square cross section $S = 90$ cm^2 was formed with the help of the diaphragm 1, was used as the energy source. The nonuniformity of the intensity distribution in the beam did not exceed 20%. A special chamber 2, consisting of polished Plexiglas in the form of a tube with cross section $S_1 = 10 \times 10$ cm and length 50 cm, was used to model the one-dimensional flow of gas at distances from the target $z \gtrsim 10$ cm. The target 3 was placed on one end of the chamber and laser radiation was introduced through the other. A NaCl wedge-shaped plate 4 served to remove part of the radiation, which was then attenuated by reflection from plates 5 and 6, made of KRS-5 and KRS-6, and was focused on the sensors 8 and 9 by a spherical metallic mirror 7. The energy and the form of the radiation pulse were recorded with a TPI-2-5 calorimeter 8 and germanium detector 9 [11]. The error in the measurement of the energy did not exceed 20%. The signal from the detector was fixed on a S8-12 oscillograph with time resolution ~7 nsec. A typical radiation pulse, presented in Fig. 2a, is characterized by an initial peak, in which 30% of the energy with power $I_r \geqslant 0.5\ I_{r\max}$ is liberated within $\Delta\tau \simeq$ 50 nsec and by a gentle drop with a duration of $\tau \simeq 0.8$ sec to a level of $0.1\ I_{r\max}$. The average power was found from the expression $I_r \sim Q_r/\tau$, where Q_r is the energy of the radiation pulse per unit area. To determine the law governing the motion and velocity of the shock-wave front, a double Töpler schlieren scheme was used [12, 13]. A LG-75 laser with $\lambda = 0.63$ μm (10 in Fig. 1), at whose output a diaphragm was placed to separate out a single transverse mode, was used as the source of radiation. The laser beam of the schlieren scheme at the inlet into the chamber was divided into two beams, separated by $\Delta z = 11.5 \pm 0.25$ mm, with the help of a plane-parallel plate 11. The change in the intensity of both beams was recorded by the single sensor 12 (FÉU-83) and, therefore, two pulses were observed on the oscillogram (Fig. 2b), with the delay between them at half-height equal to the time for the SW to traverse the distance Δz. The image of the region studied was focused on a "knife edge" 13 and projected onto the photocathode of the photomultiplier by the objective 14.

The main experiments were performed in air on targets with a small coefficient of reflection R for radiation $\lambda = 10.6$ μm, prepared from graphite ($R \approx 0.2$ [5]) and anodized aluminum ($R \approx 0.04$). The unfinished oxide layer, 10-20 μm thick, was obtained by an electrolytic method. We note that in order to achieve repeatibility of the interaction parameters, the graphite target was first

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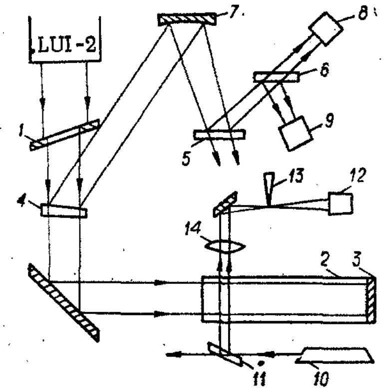

Fig. 1

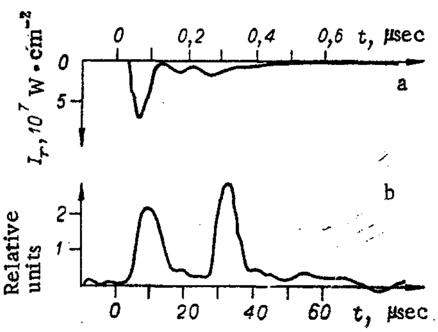

Fig. 2

aligned with a series of laser pulses. The anodized aluminum target was replaced by a new one after each pulse, since the action of the radiation led to partial destruction of the absorbing layer. In separate experiments, using a target without the oxide layer with a high coefficient of reflection, special measures were taken to suppress self-excitation of the amplifier.

Comparison of the laws of motion of the SW at the center of the chamber and in the region near the wall showed that at small distances $z \leqslant 4$ cm, the bending of the shock wave front constituted 1.2 cm and decreased with increasing z. Taking into account the fact that the magnitude of the bending was much smaller than the transverse size of the chamber, up to distances $z \simeq 50$ cm from the target, the flow can be analyzed by comparison with the theory of a planer explosion [8, 9].

Figure 3 presents the typical experimental values of the Mach number of the shock wave as a function of the distance up to the anodized aluminum target (points 1 and 3) and the graphite target (points 2 and 4) with a radiation energy flux of 10 J/cm^2 (points 1 and 2) and 4.5 J/cm^2 (points 3 and 4). The vertical lines, corresponding to the data 1-3, indicate the magnitude of the error in the measurements M and the lines corresponding to the data 4 show the experimental spread, which exceeded the error in determining M and was due to the instability of the conditions of formation of SW. The continuous line shows the results of calculations of the dependence $M = f(z)$ for shock-wave energy $Q_1 \simeq 2$ and 0.62 J/cm^2 (curves 5 and 6, respectively) [8]. The experiments on the graphite target showed that the regime of formation of the excitation in the gas changes when the energy flux Q_r increases above a threshold value $Q_{th} \simeq 4.5$ J/cm^2. For $Q_r < Q_{th}$, there is a considerable spread in the values of M. In the range of energy fluxes $Q_r \simeq 2.4$–4 J/cm^2, weak disturbances formed ($M \simeq 1.1$–1.2), whose velocity did not depend on Q_r and changed slowly with distance. For $Q_r > Q_{th}$, for the graphite target and in the entire range of radiation energy studied $Q_r \sim 2.4$-12 J/cm^2, the motion of the shock wave for the anodized aluminum target in the range of the measurement errors was described by the dependence $M = f(z)$, determined from the theory of a point explosion (TPE) with the selection of the corresponding SW energy Q_1.

Figure 4 shows the efficiency $\varkappa_1 = Q_1/Q_r$ of conversion of radiation energy incident on the target into the shock-wave energy Q_1 as a function of Q_r for the anodized aluminum (point 1) and graphite (point 2) target. The quantity Q_1 was found by comparing the experimental and computed (according to TPE) dependences $M = f(z)$. In this case, more accurate values of the energy parameter α were used. The quantity α was calculated from analytic equations presented in [9] for values of γ for air [15], which were determined according to the state of the gas behind the SW front and are determined by the value of M. We also took into account the fact that the point explosion occurred on the interface between the solid and the gas. For $Q_r < Q_{th}$, the maximum magnitude of Q_1 using TPE at large distances from the graphite target ($z \geqslant 10$–20 cm) was estimated.

Under the conditions of our experiment, i.e., for average energy fluxes $I_r \leqslant 10^7$ W/cm^2, the propagation of the plasma is apparently due to the formation of subsonic radiation wave (SRW) [2]. The shock wave is created as a result of cold gas displaced by the hot plasma [16] and, therefore, the energy of the SW is determined by the work performed by the plasma layer as it expands. The air behind the SW front is heated to comparatively low temperatures and is transparent to the incident radiation $\lambda = 10.6$ μm. Taking into account the finite

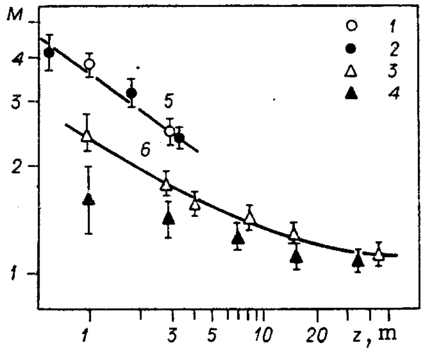

Fig. 3

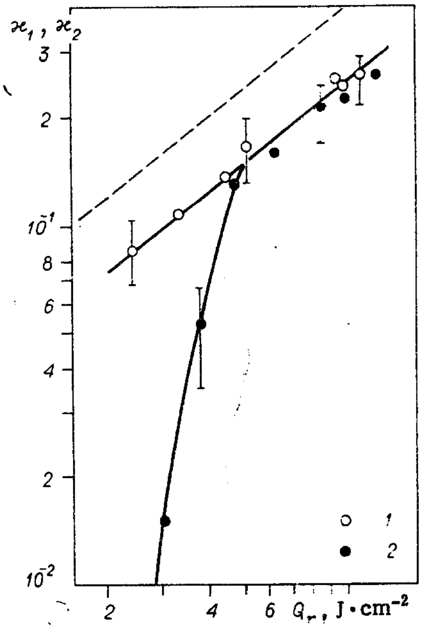

Fig. 4

dimensions of the plasma layer, we shall estimate the efficiency with which the absorbed radiation energy is transmitted by the shock wave, analogously to the calculations of the energy conversion by the expansion of detonation products in air with a definite initial volume [17, 18]. Assuming that the pressure in the flame is constant throughout the laser pulse [16], we find that the absorbed energy determines the increase of the enthalpy H of the plasma [1], i.e., $H = \varkappa_2 Q_r$, where $\varkappa_2$ is the total coefficient of absorption of radiation by the plasma layer. We note that the kinetic energy of directed motion of the plasma may be neglected, since for a gas temperature in the layer ~1.5 eV [2, 6], it does not exceed 10% of the total energy. The work performed by the plasma layer over a time τ constitutes

$$A_1 \approx H(\gamma - 1)/\gamma, \tag{1}$$

where γ is the effective adiabatic index of the hot gas.

After the laser radiation pulse terminates, during the course of the adiabatic expansion of the plasma, the shock wave transports an energy

$$A_2 \approx H[1 - (p_0/p)^{(\gamma-1)/\gamma}]/\gamma, \tag{2}$$

where p/p_0 is the ratio of the pressure in the plasma to the pressure of the undisturbed gas, $p_0 \simeq 10^5$ Pa.

From expressions (1) and (2), taking into account the fact that $Q_1 \simeq A_1 + A_2$, we can obtain a relation for estimating $\varkappa_2$:

$$\varkappa_2 \approx \varkappa_1\gamma/[\gamma - (p_0/p)^{(\gamma-1)/\gamma}]. \tag{3}$$

For a temperature of the laser plasma in air $\gtrsim$ 1 eV, the adiabatic index is close to 1 ($\gamma \simeq$ 1.2-1.3) and $\varkappa_2$, determined from (3), is nearly independent of the ratio p_0/p. This permits using the following relation for estimating $\varkappa_2$:

$$\varkappa_2 \approx k\varkappa_1, \tag{4}$$

where the coefficient $k \simeq 1.6$ may be assumed to be constant to within ~10% when p/p_0 varies in the range $p/p_0 \simeq$ 30-50, typical for a laser plasma in air with $I_r \leqslant 10^7$ W/cm^2 [6].

For large radiation intensities ($I_r > 10^7$ W/cm^2), for which the change in the gas density in the flame during the pulse can be small, the absorbed energy is expended on increasing the internal energy of the plasma layer and not its enthalpy. However, in this case as well, in order to estimate $\varkappa_2$, relation (4) can be used with a closer value of the coefficient $k \simeq 1.8$ for the range $p/p_0 \simeq$ 30-100.

Thus, by measuring the parameters of the SW and using TPE, it is possible to determine the energy of the shock wave and, using relation (4), to estimate the energy absorbed by the laser plasma. The dependence of the coefficient of absorption of the plasma $\varkappa_2$ on Q_r, calculated with $k \approx 1.6$, is shown by the dashed line in Fig. 4.

As the measurements showed, the intensity of luminescence of the plasma in the spectral range $\lambda = 0.48$-0.62 μm, as well as the data in [5], where a laser pulse with a close shape was used, the threshold for formation of the flame on the graphite target constituted 4-5 J/cm². In addition, the plasma was always formed during the first peak, i.e., with a large instantaneous radiation intensity ($I_r \geqslant 3 \cdot 10^7$ W/cm²) [5]. It follows from the measurements of the gas dynamic parameters that when precisely this energy is attained, an intense shock wave forms and propagates in accordance with the theory of the point explosion, and the energy absorbed by the plasma flame also increases sharply. Thus the characteristic bend in the dependence of $\varkappa_1$ on Q_r, observed, in particular, for the graphic target with $Q_r \approx 4.5$ J/cm², can be used as an indicator of the presence of intense absorption of energy in the plasma near the target.

The energy of the shock wave Q_1, obtained on the graphite target with $Q_r > Q_{th}$, coincides within the errors in the measurements with the values of Q_1 observed on the anodized aluminum target. This is apparently due to the property of the material selected to absorb well the laser radiation passing through the plasma layer. Indeed, on the target with the high reflection coefficient, made of Al without deposition of an absorbing coating, the energy Q_1 was observed to increase by approximately a factor of 2. The absorption efficiency reached a magnitude $\varkappa_2 \approx 0.9$ with $Q_r \approx 8.8$ J/cm ($I_r \approx 1.1 \cdot 10^7$ W/cm²). This is apparently determined by the additional heating of the plasma at the stage of its development by the radiation reflected from the surface of the target.

Thus the investigations performed showed that the appearance of the laser plasma is accompanied by the formation of a shock wave, described by the theory of a point explosion, in the surrounding gas. The conditions of formation of the shock wave and the law governing its propagation permit determining the energy threshold for formation of plasma and estimating the magnitude of the radiation energy absorbed in the plasma flame. It was demonstrated that the efficiency of absorption $\varkappa_2$ is higher for targets made of materials with a high coefficient of reflection.

It was demonstrated experimentally that above the threshold of formation of plasma on the surface of the target, absorbing $\lambda = 10.6$ μm radiation well, the increase in the intensity of the laser pulse with duration $\tau \approx 0.8$ μsec in the range $I_r \approx 3 \cdot 10^6$-$1.5 \cdot 10^7$ W/cm² leads to an increase in $\varkappa_1$ from 0.08 to 0.28, respectively.

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NUMERICAL MODELING OF THERMAL SELF-FOCUSING OF ELECTROMAGNETIC WAVES IN A WEAKLY IONIZED PLASMA

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The results of numerical modeling of self-focusing of electromagnetic waves in the millimeter range in low-temperature weakly ionized plasma (coefficient of ionization less than or of the order of 0.01) are presented.

The system of equations describing self-focusing consists of the parabolic equation for the slowly varying envelope of the amplitude of the electric field intensity [1, 2] and the equations of two-temperature hydrodynamics for slow motions of the plasma [1-6]. In axially symmetrical geometry, the system of equations is written in the form

$$\begin{gathered}
\frac{\partial N}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rvN=0,\ \frac{\partial n}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rvn=0,\\
\frac{\partial Nv}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rv^2N=-\frac{1}{M}\frac{\partial}{\partial r}(P_e+P_h),\\
\frac{\partial W_e}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rv(W_e+P_e)=\sigma n|E|^2+\frac{3}{2}n\frac{T_e-T_h}{\tau_{eh}}+\frac{1}{r}\frac{\partial}{\partial r}rq_e\frac{\partial T_e}{\partial r},\\
\frac{\partial W_h}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rv(W_h+P_h)=-\frac{3}{2}n\frac{T_e-T_h}{\tau_{eh}},\\
2ik\frac{\partial E}{\partial z}+\Delta_\perp E+\frac{4\pi}{c^2}\sigma n\omega\left(i-\frac{\omega}{\nu}\right)E=0,
\end{gathered} \tag{1}$$

where n is the electron density, N is the density of atoms and ions v is the radial velocity of the plasma, ω and E are the frequency and amplitude of the intensity of the electromagnetic field

$$\mathscr{E}=\frac{1}{\sqrt{2}}(Ee^{-i\omega t}+E^*e^{i\omega t}),$$

W_e and W_h are the total energy of the electron and heavy components of the plasma and m and M are the mass of the electron and of an ion, respectively,

$$\sigma=\frac{e^2}{m}\frac{\nu}{\omega^2+\nu^2},\quad \tau_{eh}=\frac{M}{2m}\frac{1}{\nu},$$

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