Cooling and fragmentation of a spherical target heated by laser radiation

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The heating and explosion of a deuterated polyethylene target in a chamber with air are investigated. It is shown that an ionization wave is formed in the air and travels ahead of the shock wave. Estimation of the explosion energy in accord with the law of motion of the shock wave in air is shown to be applicable under strong radiation conditions.

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Heating of a deuterated polyethylene (C_nD_{2n}) target to temperatures ~1 keV by a laser pulse was investigated earlier in [1,2] Explosion of the target was accompanied by heating of the surrounding air (the residual air in the chamber) and by formation of a shock wave in the air. The photographs revealed in this case a complicated structure of the external zone. To determine the energy input to the target,[1] the self-similar law of motion of a shock wave from a point explosion is used. The finite mass of the target and the radiation lead to deviations from the picture of the point (self-similar) explosion. Therefore an estimate of the explosion energy (i.e., of that part of the laser energy which is transferred to the target) by using the self-similar law of motion of the shock wave calls for a verification.

To find the detailed picture of the motion and to explain the experimentally observed[1] structure, we use a numerical solution of the equations of radiation one-temperature gasdynamics.[3]

Under conditions close to the experiments of [1,2], we calculated the heating and also the subsequent cooling and expansion of a C_nD_{2n} target in a chamber with air. The chamber mass is 6.4×10^{-7} g. The air pressure in the chamber is 15 Torr. The laser pulse energy is 200 J. We assume that the laser emission is incident on the target with spherical symmetry. The waveform of the pulse is shown in Fig. 1. The reflection of the radiation is disregarded.

For the calculation, it is necessary to know the physical properties of the plasma that is produced when the polyethylene and the air are heated. The equations of state, the coefficient of the electronic thermal conductivity, and the absorption coefficient for air were taken from [4–7]. The equations of state and the coefficient of the electronic thermal conductivity for polyethylene were calculated by Kalitkin, Kuz'mina, and Rogov as a supplement to the data of [5]. The absorption coefficient was obtained in the hydrogenlike approximation with allowance for stagnation processes only.

Absorption of the laser radiation by the target leads to the natural picture of the heating, temperature propagation, and gasdynamic motion shown in Fig. 2.

One can see the front of the shock wave (I) propagating in the interior of the target, and also a shock wave (II) produced in the adjacent air layers.

The internal target layers are heated mainly on account of the gasdynamic-motion energy. The electronic thermal conductivity and the radiation exert a weak influence on the heating of the central zone. The energy fluxes due to the electronic thermal conductivity and the intrinsic radiation of the plasma turn out to be of the same order in the region of the transition from the hot shell to the cold central zone. We note that the character of the energy transfer to the internal zone should change with changing power and waveform of the laser pulse.

The radiation of the hot zone is absorbed in the cold air. This leads to heating of the air and to propagation of a temperature wave. The heated air loses transparency to the incident laser light. As a result, part of the incident laser light is absorbed in

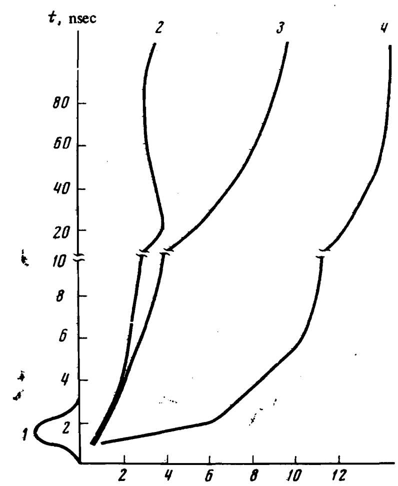

FIG. 1. Waveform of laser pulse (1), position of contact boundary (2), shock-wave front in air (3), ionization-wave front (4).

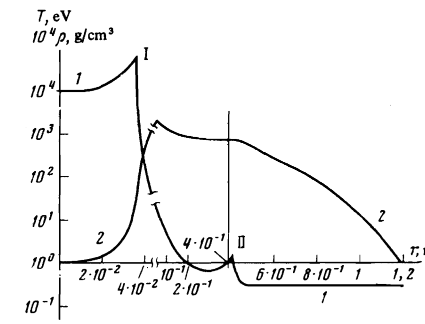

FIG. 2. Density (curve 1) and temperature (curve 2) vs. the radius for t = 1 nsec. The numbers I and II denote the positions of the shock waves, and the vertical line denotes the contact boundary.

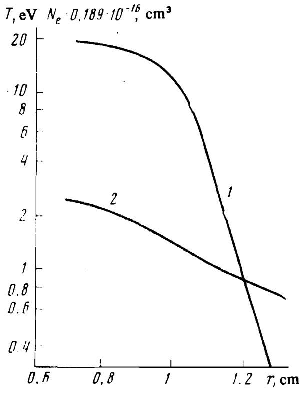

FIG. 3

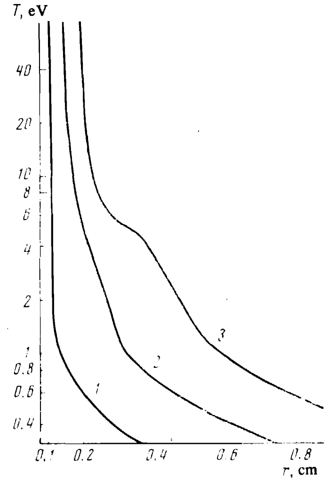

FIG. 4

FIG. 3. Electron concentration N_e (curve 1) and temperature (curve 2) in the region of the ionization wave at t = 20 nsec.

FIG. 4. Change of temperature with moving absorption wave: curve 1—for t = 1 nsec, 2—1.4 nsec, 3—2 nsec.

the heated air zone, accelerating the heating of the latter and the propagation velocity. Therefore the temperature wave becomes prior to the termination of the laser pulse an absorption wave with a radiative propagation mechanism.[8] Up to five per cent of the laser-pulse energy is absorbed in the heated-air zone.

The degree of ionization of the air increases abruptly (practically from 0 to 1) at T ~ 1 eV. Therefore the propagation of the temperature wave is accompanied by motion of an ionization wave (the regions of the steep gradient of the electron concentration, Fig. 3).

The high velocity of the absorption wave (Fig. 4) leads to detachment of the ionization wave from the shock wave (SW). This makes possible an experimental observation of the ionization wave (see Fig. 5 of [1]). We note that this wave, which accompanies the temperature wave, can be observed also in other situations (e.g., in strong-current radiating discharges).

During the expansion stage (t ~ 10–200 nsec), the law of motion of the SW front coincides with Sedov's self-similar law: $r_{SW} \sim t^{0.4}$. At t ~ 30 nsec, reverse motion (pulsations) occurs in the central zone (Fig. 1, curve 2).

An estimate of the initial energy input by means of the formula

$$r_{SW}(t) = [a(\gamma) E_0 t^2/\rho_0]^{1/5},$$

where $a(\gamma) \approx 1$, as used in [1], yields a value of 192 J at an initial value 200 J. It is quite possible that this determination of the energy gives satisfactory accuracy under conditions of explosion with strong radiation. As shown by the calculations, this result is stable to large variations in the plasma absorption coefficient.

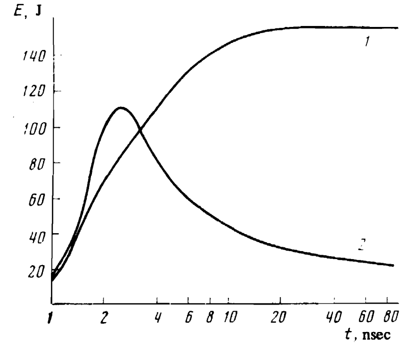

FIG. 5. Internal energy (curve 1) and kinetic energy (curve 2) as functions of the time.

It should also be noted that at t > 10 nsec the internal energy of the hot zone is constant (Fig. 5). The radiation in the transparency window is at the expense of the decrease of the kinetic energy.

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