Excitation of ultrastrong shock waves by a hot plasma piston

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The excitation of a shock wave in the residual gas by a hot laser plasma has been studied experimentally. The velocity of the shock wave has been found to remain constant. An "instantaneous" transition to free motion has also been found. A method is proposed for determining the amount of mass evaporated from the target from the dynamics of the shock wave.

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The so-called initial stage of the motion of spherical shock waves excited in the residual gas by a hot laser plasma is of much scientific and practical interest.[1–3] In this initial stage, which lasts for some tens of nanoseconds, energy is transferred from the target plasma (which is heated in ~1–2 ns) to a shock wave which moves at a velocity $\sim 10^7$–10^8 cm/s. This stage of the motion of the shock wave has previously been studied only theoretically.[4,5] The results derived in the different theoretical papers agree only qualitatively and may be summarized as follows. The motion of the shock wave in the initial stage occurs at a constant velocity D_0, which is determined by the ion temperature of the target plasma:

$$D_0 = \kappa'(T_i)^{1/2}. \tag{1}$$

Basov *et al.*[4] and Freiwald and Axford[5] predict different values for the coefficient $\kappa'(\gamma)$.

Two points should be kept in mind when making practical use of expression (1). First, it was assumed in the theoretical derivation that the target is heated instantaneously, so that T_i is the ion temperature of the plasma which is initially at rest. In reality, however, when a target is bombarded by a nanosecond laser pulse, the plasma actually begins to move even while it is being heated (in 1–2 ns), so that by the end of the laser pulse the greater part of the energy is in the form of the kinetic energy of the directed motion of matter.[6] In this case, therefore, T_i should be understood as the quantity $T_s \equiv (E_t + E_k)(\gamma - 1)/Nk$, where E_t and E_k are respectively the thermal and kinetic energies of the plasma, k is the Boltzmann constant, and N is the total number of particles.[1)]

Second, it has been found experimentally[3] that it is not possible for all the energy of the laser plasma, E_{pl}, to be converted into the energy of the shock wave, E_0 ($\beta \equiv E_0/E_{pl} < 1$). It has been shown that energy is lost because some of the ions making up the high-energy tail on the Maxwellian distribution escape from the plasma without interacting with the shock wave. Although the energy loss may be substantial, the number of plasma particles changes only slightly. Accordingly, if we describe the plasma by the standard equation of state

$$E_{pl} = \frac{NkT_s}{\gamma - 1}, \quad (2)$$

then the "temperature" of the plasma exciting the shock wave is lower than the initial temperature by a factor of β^{-1}, and expression (1) should be written

$$D_0 = \kappa(\beta T_s)^{1/2}. \quad (3)$$

Since the ratio of the thermal and kinetic energies of the plasma changes only slightly upon a change in conditions, and since this ratio is usually predicted by the calculations,[6] an experimentally tested expression (3) can provide a method for determining the ion temperature of the plasma.

The present experiments were carried out on the high-power Kal'mar laser apparatus[3] ($E_l \lesssim 250$ J, $q_0 \lesssim 2\times 10^{14}$ W/cm^2). The shock wave is excited in deuterium or air [$\rho_1 = (1-4)\times 10^{-6}$ g/cm^3] when the laser beam is focused on spherical targets of glass or polystyrene (70–250 μm in diameter).

By recording a Schlieren image of the shock wave with a "photoelectronic recorder"[3] (Fig. 1) we were able to follow the evolution of the shock wave under the various conditions over the time interval from 2 to 30 ns after the beginning of the bombardment. Figure 2 is a representative R-t diagram of the motion of the shock wave. The basic reproducible features of this diagram are a constant velocity of the shock wave in the initial stage (constant within ~5%) and an "instantaneous" transition to free motion ("instantaneous" in comparison with the duration of this stage, i.e., taking place in a few nanoseconds).[1]

The uniform motion of the shock wave in the initial stage agrees with the theoretical results of Refs. 4 and 5, but the experimental value $\kappa = (3.1 \pm 0.3)\times 10^7$ cm/(s$\times$keV$^{1/2}$) does not.

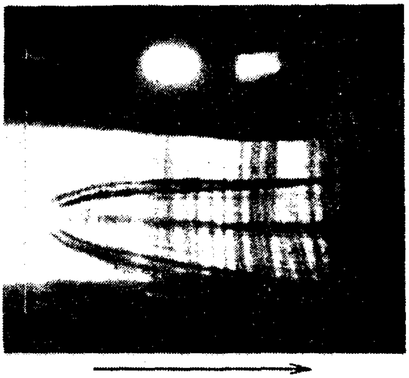

FIG. 1. Typical photograph of a Schlieren image of a shock wave in deuterium recorded with the "Photoelectronic recorder." Both the time and coordinate scales are nonlinear. The sweep time is ~30 ns; $p_1 = 16$ torr; $E_l = 177$ J; the target diameter is 174 μm. The double front at the beginning of the sweep is caused by electron thermal conductivity.[2]

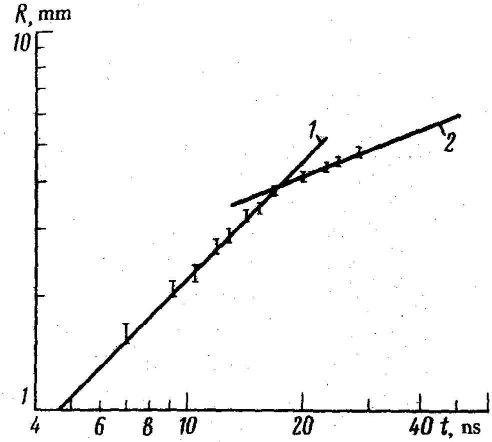

FIG. 2. Typical R-t diagram of the motion of the ion front of a shock wave in deuterium, plotted from the corresponding photograph of the type in Fig. 1. $E_{pl} \approx 7$ J; $T_i \approx 0.3$ keV; $m_0 = 5.4 \cdot 10^{-8}$ g.

The transition between the two regimes in the motion of the shock wave is determined by the instant at which the pressure of the target plasma becomes equal to the pressure of the plasma behind the shock front. With $D_0 \sim 3 \times 10^7$ cm/s and $R_{00} \sim 5$ mm, the pressure of the target plasma falls off by a factor of nearly two in $t \approx 2$ ns, causing the "instantaneous" change in the motion of the shock wave. This circumstance suggests a method for determining one of the basic properties of a laser plasma: the amount of target mass which is evaporated, m_0. Measurements of this quantity are intimately related to the solution of a problem which is presently of extreme importance to inertial fusion: determining the efficiency at which energy is transferred to the fuel, compressed to a high density.

Using the equation of motion of the shock wave in the initial stage along with the solution of the problem of an instantaneous point explosion, which gives a satisfactory description of the dynamics of the shock wave during the first part of the "free" expansion,[1] we can write the following equation at the transition between the two regimes (R_{00}, t_{00}):

$$\frac{(R_{00} - R_0)^2}{\kappa^2 \beta T_s} = \frac{R_{00}^5 \rho_1 \alpha}{\beta E_{pl}},$$

where α is a constant.[1] In the present experiments the condition $R_0 \ll R_{00}$ held, so that, using (2), we find

$$m_0 = (\gamma - 1) \rho_1 \alpha \kappa^2 \frac{\overline{m}_i}{(\overline{z} + 1)} R_{00}^3, \tag{4}$$

which unambiguously relates m_0 to the radius of the shock wave at the transition point. It should be noted that (in contrast with the methods for determining E_{pl} and T_i) expression (4) does not contain the quantity β, whose measurement presents defi-

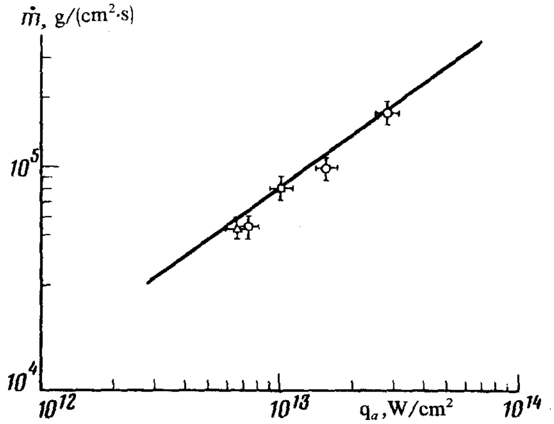

FIG. 3. Expenditure of target mass vs the absorbed laser power density. The line is the empirical dependence $\dot{m}(q_a)$ from Ref. 7. △—$(C_8H_8)_n$ target in air; □—$(C_8D_8)_n$ in D_2; ○—SiO_2 in D_2.

nite experimental difficulties; thus m_0 can be measured within a relative error $\sim 10\%$ (at an absolute error $\sim 30\%$). We might also note that expression (4) determines that mass of the gas caught up in the shock wave at which the "free" motion of the shock wave begins. For glass and polystyrene targets, we have $m_{00} \approx 8.5\ m_0$.

This method has been used to study m_0 under various conditions (Fig. 3). The results agree well with the empirical dependence[7] $\dot{m}(q_a)$ which has been found to successfully describe the results of nearly all experiments which have been carried out to date in the various laboratories. This agreement confirms the validity of this new measurement method, of expression (3), and of the value found experimentally for κ.

[1)]This point is obvious when we consider the plasma at the end of the laser pulse as having been instantaneously heated to the temperature T_s at a time $t \neq 0$, when part of the thermal energy has been converted into kinetic energy.

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