INITIAL STAGE OF OPTICAL EXPLOSION OF A MATERIAL PARTICLE IN AN INTENSE LIGHT FLUX

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The initial stage of optical explosion of a small material particle in an intense light beam is considered. The simplified model used leads to simple expressions for the time-dependent radius of the plasma cloud, expansion rate, and temperature, facilitating the selection of optimal conditions as compared to numerical results from the literature. It is shown that an exponential growth of radius and expansion rate occurs under certain conditions. The case of picosecond pulses is considered in greater detail. The ranges of optimal and non-optimal quantities determining the process are evaluated.

FOLLOWING the early work on laser heating of matter to high temperatures[1-3] particular attention was paid to the heating of small particles that permitted the attainment of very high temperatures. This problem was the subject of several papers[4-6], which failed, however, to investigate in a functional form the initial stage of the expansion during which the dimensions of the expanding material do not yet exceed the cross sectional area of the light beam. Numerical computations performed in[4-6] do not allow for a direct selection of optimal conditions, especially in the little known but most interesting case of ultrashort light pulses.

In this case the initial stage is of particular interest and is also the most dramatic since the increase of the absorbed power following the increase of plasma bunch dimensions results, as we show below, in an exponential growth of the dimensions and expansion rate of the bunch; such a growth is not known to the ordinary gas dynamics. For short pulses or short time periods of plasma opacity the initial stage is the controlling one, and is followed by the trivial stage of free expansion.

The present paper investigates the features of the initial expansion stage, using a simple model and assuming total absorption of light incident on the plasma bunch; this is usually the case because of the high plasma densities in the initial stage. Neglect of light reflection from dense plasma is justified not only for the expanded material (when $\omega_p \lesssim \omega$), but also for a denser plasma, owing to the presence of a strong nonlinear absorption of very intense radiation, especially in the case of picosecond pulses. (Nonlinear absorption is associated with collective processes and anomalous dissipation of light because of the presence of instabilities.)

We also assume that the absorbed heat is equalized throughout the volume; this is also justifiable because of the high electron thermal conductivity at high temperature and small dimensions of the bunch in the initial stage. The short time, small size, and large expansion velocities allow us to neglect radiation losses.

We obtain the expansion dynamics from the energy balance:

$$\frac{d}{dt}\frac{pV}{\gamma-1}+\frac{d}{dt}\frac{M\dot{a}^2}{2}=\pi a^2 I_0;$$

here p is gas kinetic (mainly electronic) pressure ($p \approx M\ddot{a}/4\pi a^2$), V is the volume of a bunch of radius a(t), M is its effective mass, and I_0 is the light flux density. The radius of the bunch is determined by the equation

$$\frac{1}{a^2}\frac{d}{dt}(a\ddot{a}+\dot{a}^2)=\frac{2\pi I_0}{M}=A$$

for the specific heat ratio $\gamma = 5/3$ usually chosen for high temperatures. Substituting $a = y^k$ and selecting k so as to simplify the equation, we obtain for $k = 1/2$ the equation $\dddot{y} = 2Ay$, whose solution is

$$y=C_1e^{\alpha t}+e^{-\alpha t/2}\left\{C_2\sin\frac{\sqrt{3}}{2}\alpha t+C_3\cos\frac{\sqrt{3}}{2}\alpha t\right\},\quad \alpha=\{2A\}^{1/3}.$$

We are also interested in the initial conditions $a = a_0$, $\dot{a} = 0$, and $\ddot{a} = 0$ for $t = 0$, i.e., $y = y_0$, $\dot{y} = 0$, and $\ddot{y} = 0$; hence

$$y=\frac{1}{3}y_0\left\{e^{\alpha t}+2e^{-\alpha t/2}\cos\frac{\sqrt{3}}{2}\alpha t\right\}=y_0f(x).$$

with the dimensionless quantity

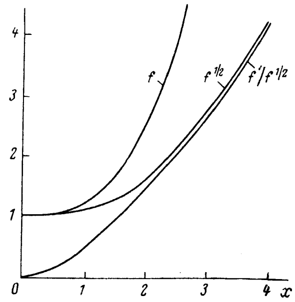
$$x=\alpha t=(2A)^{1/3}t=\left(\frac{4\pi I_0}{M}\right)^{1/3}t=\frac{v_0t}{a_0}.$$

Here $v_0 = a_0\alpha = (3I_0/\rho_0)^{1/3}$ is the characteristic expansion rate and depends only on the light flux density and the initial density of the material. For example, for a laser power $W \sim 10^{12}$ W and a focal spot dimension $\sim 10^{-2}$ cm we obtain $I_0 \sim 10^{23}$ erg/cm²sec and $v_0 \approx 10^8$ cm/sec, i.e., the expansion energy is of the order of 10 keV.

The figure shows the function f(x), which determines the dynamics of dimension growth, $a(t) = y^{1/2} = a_0f^{1/2}(x)$, and the expansion rate $\dot{a} = \frac{1}{2}v_0f'(x)/f^{1/2}(x)$. We see that for $x \gg 1$ ($v_0t \gg a_0$) the growth of dimension and velocity is exponential

$$a \approx a_0e^{\alpha t/2},\qquad \dot{a} \approx v_0e^{\alpha t/2}.$$

Such a fast increase is not typical of the usual gas dynamics involving heat emission.



Using the relationship

$$p = M\ddot{a}/4\pi a^2 \approx 3N(Z+1)kT/4\pi a^3$$

we obtain $kT = [m_i/3(Z+1)]a\ddot{a}$, where $m_i = M/N$ is the effective ionic mass and Z is its degree of ionization. Hence the ratio of the effective expansion energy to the effective thermal energy is

$$\frac{W_{\text{exp}}}{W_{\text{therm}}} \approx \frac{m_i\dot{a}^2}{2kT} \approx \frac{3}{2}(Z+1)\frac{\dot{a}^2}{a\ddot{a}} \approx \frac{3}{2}(Z+1)$$

for the developing expansion (when $a \sim e^{\alpha t}$).

For small $x = \alpha t \ll 1$ we have $a(t) = a_0(1 + 1/12x^3)$ and $\dot{a}^2/a\ddot{a} \approx 1/8x^3$, therefore in the initial stage the thermal energy is many times higher than the expansion energy.

We evaluate the opacity conditions for plasma: $\kappa a \gtrsim 1$, where κ is the absorption coefficient. Neglecting nonlinear absorption, the coefficient of collision absorption $\kappa \approx (\omega_p^2/\omega^2 c)\nu_s(T)$ and the condition $\kappa a_{cr} \approx 1$ are satisfied for

$$a_{cr} \approx a_0 \left\{\frac{10^3 Z^3 (Z+1)^{3/2} a_0 \rho_0^3 e^6}{m_e^{3/2}\omega^2 I_0 c m_i^{7/2}}\right\}^{1/8} \approx a_0 \left\{\frac{10^{61} Z^3 (Z+1)^{3/2} \rho_0^3 a_0}{\omega^2 I_0 A^{7/2}}\right\}^{1/8}.$$

For $\omega \approx 3 \times 10^{15}$ sec^{-1}, $Z/A = 1$, $\rho_0 \approx 1$ g/cm^3, $I_0 \approx 10^3$–10^4 GW/cm^2, and $a \approx 10^{-3}$–10^{-2} cm, we have $a_{cr} \approx 10\, a_0$.

The above formula shows the weak dependence of the ratio a/a_0 on the type of target and the laser power. Nonlinear absorption can increase the range of conditions under which absorption can be regarded as nearly total.

We use the obtained relations to evaluate the effectiveness of heating a particle with ultrashort pulses (this case was not considered in the cited literature) and the interactions between the quantities involved.

If the size of the particle is small and it does not exceed the transparency dimension $a(T) < a_{cr}$ and focal spot size $a(t) < a_f$ during pulse length T, the total energy absorbed by plasma is

$$Q = I_0 \int_0^T \pi a^2(t)\,dt \approx I_0 \pi a_0^2 \int_0^T f(\alpha t)\,dt = \frac{\pi a_0^3 I_0}{v_0} \int_0^{v_0 T/a_0} f(x)\,dx,\ v_0 = \left(\frac{3I_0}{\rho_0}\right)^{1/3}$$

The expression for Q shows that when $a_0 \to 0$ and $a_0 \to \infty$ this quantity increases. The extremum condition ($\partial Q/\partial a_0 = 0$) is satisfied for

$$3\int_0^{x_e} f(x)\,dx = f(x_e)\,x_e,$$

which occurs only for the value of x at the extremum point $x_e \gg 1$ (since for $x_e \ll 1$ the function $f(x_e) \to 1$); this simplifies the extremum condition and we find $x_e = v_0 T/a_0 = 3$.

In addition to the total plasma energy we are interested in the energy per unit mass $Q_1 = 3Q/4\pi a_0^3 \rho_0$. This quantity has no extremum and continuously increases as $a_0 \to 0$.

In the case of $v_0 T/a_0 \gg 1$ all relations are considerably simplified:

$$Q \approx \frac{\pi a_0^3 I_0}{v_0} \exp\left\{\frac{v_0 T}{a_0}\right\},$$

and the energy per unit mass

$$Q_1 = \frac{Q}{M} = \frac{3I_0}{v_0 \rho_0} \exp\left\{\frac{v_0 T}{a_0}\right\}.$$

We see an exponential growth of these quantities with increasing pulse length and decreasing a_0.

These formulas also show the advantage of the "stretched-out heating" regime, since for the same total pulse energy density $W = I_0 T$ the energy input increases to the limit whether I_0 decreases or increases. The extremal value of I_0 can be determined more exactly from the extremum of the expression

$$I_0^{2/3} \int_0^{W/I_0^{2/3}} f(x)\,dx,$$

that can be written in the form

$$\xi_e f(\xi_e) = \int_0^{\xi_e} f(x)\,dx.$$

Hence it follows from $f(0) = 1$ that $\xi_e \approx 1$, i.e., $I_e^{2/3} \approx W/a_0\rho^{1/3}$, or $v_0 T \approx a_0$. The optimal values $I_0 \neq I_0^{\text{extr}}$ can be selected by splitting the pulse and sending a pulse train with small intervals between the pulses.

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