Acceleration of material by a pressure pulse of radiative plasma

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A time-dependent analytical model is developed for radiative plasma formed by the action of a pulse of *x* radiation on matter. The model determines the parameters of the radiative plasma as functions of the intensity and length of the x-ray pulse and the properties of the target material. The problem of the acceleration of a planar or spherical target under the action of the pressure pulse from the radiative plasma is solved. Analytical expressions are found for the target velocity and the hydrodynamic coupling coefficient (the ratio of the target kinetic energy to the energy of the x-ray pulse). The parameters of the radiative plasma and of the plasma formed by direct action on the material by a laser pulse are compared, along with the properties of ablative acceleration using indirect and direct compression of a spherical target. It is shown that for x-ray intensities $\sim 10^{14}$ W/cm^2 which are of interest for inertial confinement fusion, the parameters of the radiative plasma from heavy elements (gold, iron, etc.) fall within the following ranges: density 0.1–0.3 g/cm^3, temperature 0.1–0.3 keV, pressure 20–40 Mbar; values of the final target material velocity and hydrodynamic coupling coefficient in excess of 300 km/s and 0.1 respectively (needed for ignition) can be achieved only if a substantial part of the target mass, 80–90%, is vaporized. These results imply that in indirect drive using targets with relatively thick shells (and therefore possessing enhanced hydrodynamic stability) the only way to achieve high hydrodynamic efficiency is to use heavy elements in a porous state with a microscopic density of 0.5–2 g/cm^3 as the target material.

1. INTRODUCTION

This work is aimed at the theoretical investigation of the physical properties of high-temperature radiative plasma formed by the action on matter of a pulse of x radiation. This problem is important for the study of the physics of x-ray absorption, energy transport processes, hydrodynamic motion, and optical properties of matter in nonstationary plasmas.

Furthermore, the hydrodynamic properties of radiative plasma have an important application in inertial confinement fusion (ICF). One of the concepts of current interest for ICF is based on the so-called indirect compression of a thermonuclear target.[1] By indirect compression (indirect drive) one means the compression of material by a plasma pressure pulse formed through the action of soft x rays, the energy of which is obtained by converting the energy of a driver (a laser or ion beam). The advantage of this approach in comparison with direct drive, in which the laser or ion-beam pulse is applied directly, is the high isotropy of the energy absorption process, which leads to more favorable conditions for the compression of a spherical shell target[2] from the standpoint of the development of the Rayleigh–Taylor hydrodynamic instability.

On the other hand, when one compares these two approaches one should take into account that indirect drive is a more complicated way of changing the driver energy into thermonuclear plasma energy. The energy conversion efficiency $\eta_p = E_p/E_d$ (where E_p is the internal energy of the thermonuclear plasma and E_d is the driver energy) in direct compression is determined first by the energy absorption coefficient of the driver in the vaporized part of the target, the corona: $\eta_{ab} = E_{ab}/E_d$ (here E_{ab} is the energy absorbed in the corona from the laser or ion beam) and secondly by the hydrodynamic coupling coefficient $\eta_h = E_h/E_{ab}$ (where E_h is the kinetic energy of the accelerated unvaporized part of the target), and finally by the efficiency with which kinetic energy of the target is converted into internal energy of the thermonuclear plasma, $\eta_i = E_p/E_h$:

$$\eta_p = \eta_{ab} \times \eta_h \times \eta_i .$$

In indirect drive, in addition to these processes we must also have conversion of the driver energy into x radiation and absorption of the x radiation in the target. These processes can take place in either one or several parts of the target, but in both cases they lead to considerable (more than 50%) driver energy losses in comparison with direct drive.[3]

In this connection, a key point in the energy balance problem for indirect drive is the hydrodynamic efficiency with which matter can be accelerated by the pressure pulse of the radiative plasma, since the processes by which the driver energy is absorbed and the kinetic energy is converted into internal energy of the thermonuclear plasma differ little from the analogous processes in direct drive, which have been studied in considerable detail (see, e.g., Refs. 4–7).

The criterion for efficiency in target acceleration in ICF is reaching a hydrodynamic coupling coefficient greater than 0.1 and a final shell velocity (at the instant when the target collapses in the center) of at least $(3–4)\cdot 10^7$ cm/s (Refs. 1 and 2).

The difference in the way material is accelerated in direct and indirect compression is due to the difference in the physics of the formation of the coronal plasma and the pressure pulse in the two cases. What is different is the transport mechanisms for the absorbed energy: in direct drive these mechanisms are the shock wave and electron thermal conductivity, while in indirect drive they are the shock wave and energy transport by the radiation of the plasma itself.

The physics of the conversion of laser radiation into x rays, the processes by which the radiative plasma is formed, and the acceleration of matter under the action of the pressure pulse of the radiative plasma are being actively studied at present both experimentally and theoretically. In experiments performed in various laser facilities (see, e.g., Refs. 7–9) a high degree of conversion into x rays has been achieved for short-wavelength laser radiation with $\lambda=0.27$–$0.53\ \mu$m: 70–90% for action on planar targets made of heavy elements (Au, Pb, etc.) for a laser pulse with intensity $I_L \simeq 10^{14}$–10^{15} W/cm^2 and length $t_L \simeq 3$–5 ns. In a series of experiments the electron temperature of the radiative plasma has been measured; for a laser pulse with the above parameters it is found to be in the range 150–400 eV (Refs. 8–10).

Theoretical studies of the properties of the radiative plasma are based primarily on numerical simulation. Using generalizations of the data from experiments and numerical calculations, scaling laws are proposed which describe the rate of vaporization of material under the action of the laser pulse on a planar target made from heavy elements, the temperature, and the ablative pressure of the resulting radiative plasma as functions of the intensity and length of the laser pulse.[11–13]

It is our view that it is useful to supplement these efforts with a self-consistent theory of the formation of the radiative plasma, which would provide a unified description of the properties of the plasma that forms when the laser pulse acts on a target made from various heavy elements. In the present work an analytical time-dependent theory is proposed for the formation of plasma in an equilibrium x-ray field, taking into account the hydrodynamic motion of the material. We find the temperature, density, and expansion velocity of the radiative plasma as functions of the x-ray pulse parameters, the atomic number of the elements, and the degree of ionization of the target material for a prescribed efficiency for conversion of the laser radiation into x rays. In addition, we solve the problem of the acceleration of a planar and spherical shell under the action of a pressure pulse from the radiative plasma. We have determined the rate of vaporization of material and the velocity of the unvaporized part of the target as functions of the x-ray pulse and target properties and calculated the hydrodynamic coupling coefficient for a spherical shell target. These results are compared with those from experiments and numerical calculations, showing not only the qualitative correctness of the theoretical models but also good quantitative agreement. We find the conditions under which the target is accelerated effectively by indirect drive and propose a means of achieving these conditions for low-aspect-ratio target shells with relatively small ratios of the shell radius to thickness, (~10–20), by virtue of which the stability against hydrodynamic perturbations is enhanced.

2. MODEL OF THE RADIATIVE PLASMA

Consider the formation of plasma under the action of an x-ray pulse under the following conditions. We assume that the x-ray pulse with constant intensity I_r and length t_r is incident on an unbounded slab of material with high atomic number A. We will assume that I_r and t_r are sufficiently large that the resulting plasma is in a state such that radiation and matter are in equilibrium. Such x-ray pulse parameters correspond to conditions in which the laser radiation is converted efficiently into x rays.[7]

We will look for the temperature, density, and velocity of the plasma material as functions of the x-ray pulse in the approximation in which the processes corresponding to plasma formation evolve self-consistently. This approach to the problem has been used successfully to derive a model of the target corona for direct drive resulting from absorption of the laser energy and transport of the absorbed energy by sound waves,[3,14] electron thermal conductivity,[15] or fast electrons.[3,16] In addition we will assume that the plasma parameters are uniformly distributed through the target mass.

The condition for a self-consistent state in a radiative plasma is that the Rosseland mean free path for the photons of the radiation in the plasma equal its size. In the calculations below we use the standard formula for the Rosseland path length:

$$L_r = C_r \frac{T^n}{\rho^m}; \quad C_r = \text{const},$$

where T and ρ are the plasma temperature and density respectively. The characteristic size of the expanding plasma is

$$L_h \cong v t,$$

where v is the average plasma velocity, t is time, and we assume $t < t_r$. Then the self-consistency condition can be written in the form

$$\frac{T^{n-1/2}}{\rho^m} = \sqrt{\frac{(Z+1)k}{A m_p}} \frac{v}{v_s} C_r^{-1} t. \tag{1}$$

Here Z is the average ionization state of the plasma, m_p is the proton mass, k is the Boltzmann constant, and v_s is the adiabatic speed of sound, $v_s^2 = P/\rho$. The second equation describing the state of the plasma is the energy equation:

$$I_r = \rho v \left[\varepsilon + \frac{P}{\rho} + \frac{v_s^2}{2} \left(\frac{v}{v_s} \right)^2 \right], \tag{2}$$

where $P = \rho B T$ and $\varepsilon = P/\rho(\gamma-1)$ are the pressure and internal energy of the plasma respectively; here $B = (Z+1)k/A m_p$ is the specific heat and γ is the adiabatic index. In the calculations below it is convenient to introduce the parameter $\beta \equiv v/V_s$ in Eqs. (1) and (2).

By solving Eqs. (1) and (2) we find the following expressions for the plasma parameters:

$$T = [\beta^{-2} B^{3m-1} C_r^2 C_1^{2m}]^{-k_1} [I_r^{2m} t^2]^{k_1}, \tag{3}$$

$$\rho = [\beta^3 B^{3n} C_r^{-3} C_1^{2n-1}]^{-k_1} [I_r^{2n-1} t^{-3}]^{k_1}, \tag{4}$$

$$P = [\beta B^n C_r^{-1} C_1^{k_2}]^{-k_1} [I_r^{k_2} t^{-1}]^{k_1}, \tag{5}$$

$$v_s=[\beta B^n C_r^{-1} C_1^m]^{k_1}[I_r^m t]^{k_1}, \tag{6}$$

where we have introduced the notation $k_1=1/(2n+3m-1)$, $k_2=2n+2m-1$, $C_1=\beta(\gamma/\gamma-1+\beta^2/2)$.

In consequence of the approximations we have made, this problem belongs to the class of problems involving hydrodynamic expansion of a material slab under the action of an energy source uniformly distributed through its mass. Because of this we can specify an approximate value of the parameter β which appears in the solutions from the well-known self-similar solution of this class of problems.[17] It yields the following expressions for the parameters of the plasma corona:

$$u=\frac{3}{2}\frac{x}{t}, \tag{7}$$

$$T=\frac{2}{3\gamma-1}\frac{\dot{E}_n}{Bm_k}t, \tag{8}$$

$$\rho=\rho(t)\exp\left[-\frac{3}{16}\left(\frac{3\gamma-1}{\gamma-1}\right)\frac{m_k}{\dot{E}_n}\frac{x^2}{t^3}\right], \tag{9}$$

where

$$\rho(t)=\sqrt{\frac{3}{4\pi}\frac{3\gamma-1}{\gamma-1}}\frac{m_k^{3/2}}{\dot{E}_p^{1/2}t^{3/2}}.$$

Here u, T, and ρ are the velocity, temperature, and density respectively of the plasma, x is the spatial coordinate, B is the specific heat, m_k is the total mass of the plasma, and $\dot{E}_n$=const is the absorbed power of the laser radiation. The average velocity v, corresponding to the average momentum, is

$$v=\frac{1}{m_k}\int_0^\infty u\rho dx.$$

Substituting the expressions for u and ρ into the integral we find

$$v=\sqrt{\frac{12}{\pi}}\sqrt{\frac{\gamma-1}{3\gamma-1}}\sqrt{\frac{\dot{E}_n t}{m_k}}.$$

Next, using expression (8) to determine the sound speed v_s, we find the following expression for β:

$$\beta=\sqrt{\frac{6}{\pi}}\simeq 1.38.$$

Note that the values of β obtained from numerical calculation[11,12] lie in the interval 1.3–1.5.

As an example we calculate the parameters of the radiating plasma for the case of a gold target. According to Ref. 18, for gold we have $n=2.5$, m=1.5, $C_r=0.1$ cm(g/cm^3)/keV$^{2.5}$. Then we have $k_1=0.12$, $k_2=7$ and expressions (3)–(6) assume the form

$$T\ [\text{keV}]=0.24I_r^{0.36}t^{0.24}\left(\frac{A}{Z+1}\right)^{0.4}, \tag{10}$$

$$\rho\ [\text{g/cm}^3]=0.057I_r^{0.48}t^{-0.36}\left(\frac{A}{Z+1}\right)^{0.9}, \tag{11}$$

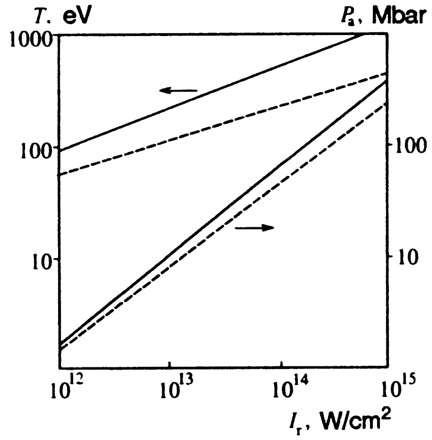

FIG. 1. Temperature T and pressure P_s of the radiative plasma of a gold target as a function of the intensity I_r of an x-ray pulse. The results of Ref. 13 are indicated by the dashed curve.

$$P_a\ [\text{Mbar}]=38I_r^{0.84}t^{-0.12}\left(\frac{A}{Z+1}\right)^{0.32}, \tag{12}$$

$$v_s\ [\text{cm/s}]=2.6\cdot 10^7 I_r^{0.18}t^{0.12}\left(\frac{A}{Z+1}\right)^{-0.3} \tag{13}$$

Here and in what follows I_r is given in units of 10^{14} W/cm^2 and the time t in ns; $P_a=(1+\beta^2)P$ is the ablative pressure.

Let us compare these results with those from numerical calculations and experiments. In Ref. 13, using experimental data, the following behavior was found for the temperature and ablative pressure of the plasma of a gold target as functions of the x-ray intensity:

$$T\ [\text{keV}]=0.2I_r^{0.3},\quad P_a\ [\text{Mbar}]=48I_r^{0.78}.$$

The scaling law for the ablative pressure of the plasma of a gold target obtained in Ref. 12 from numerical calculations takes the form

$$P_a[\text{Mbar}]=44I_r^{0.81}t^{-0.1}.$$

The temperature and ablative pressure of the plasma as functions of the x-ray intensity, Eqs. (10) and (12), together with the results of experiments[13] are shown in Fig. 1.

Comparison of the results shows good qualitative agreement with the present model of the radiative plasma. A calculation using Eqs. (10)–(12) for $I_r=10^{14}$ W/cm^2 and $t=3$ ns yields the following results for the parameters of a gold target corona: $T\approx 600$ eV, $\rho\approx 0.26$ g/cm^2, $P_a=36$ Mbar. Since the path length of x-ray photons corresponding to a plasma temperature of several hundred eV is considerably longer than the path length of the photons of laser radiation with wavelength $\lambda\approx 0.35-1.06$ μm, the average density of the radiative corona is much greater than the average density of the corona formed from the direct action of laser radiation on a target made of light elements, which is close to the critical density corresponding to the wavelength of the laser radiation: $\rho_{cr}=(0.3-3)\cdot 10^{-2}$ g/cm^3.

3. ACCELERATION OF MATERIAL BY THE PRESSURE PULSE OF THE RADIATIVE PLASMA

Now we will consider the problem of accelerating a thin layer of material in response to the pressure of the plasma formed when the x-ray pulse is absorbed at one of the surfaces of the layer.

3.1. Acceleration of a spherical layer

The vaporization of the outer part of a spherical shell in connection with the formation of the radiative corona and acceleration of the unvaporized part of the shell toward the center under the action of an ablative pressure is described by the following equations (see, e.g., Ref. 19):

$$\frac{dM}{dt}=-4\pi R^2\beta\rho v_s, \tag{14}$$

$$M\frac{dv}{dt}=4\pi R^2(1+\beta^2)P. \tag{15}$$

The initial conditions of the problem take the form $R|_{t=0}=R_0$, $M|_{t=0}=M_0$, $v|_{t=0}=0$, where M and R are the mass and radius of the unvaporized part of the shell, v is the velocity in the direction of the center, $M_0=4\pi R_0^2\cdot\Delta R\cdot\rho_0$ is the initial mass of the shell, and ΔR and ρ_0 are its thickness and density.

Using Eqs. (10)–(13) to introduce the time averages of the sound speed and coronal plasma pressure over the duration of the x-ray pulse, we transform Eqs. (14) and (15) into the dimensionless equations

$$\mu\frac{du}{d\tau}=(1-3k_1)(1+2k_1)(1+\beta^2)\vartheta\alpha x^2\tau^{-k_1}, \tag{16}$$

$$\frac{d\mu}{d\tau}=-\beta(1-3k_1)(1+k_1)\vartheta\alpha x^2\tau^{-2k_1}, \tag{17}$$

$$\frac{dx}{d\tau}=-\vartheta u,\quad x|_{t=0}=1,\quad \mu|_{t=0}=1,\quad u|_{t=0}=0, \tag{18}$$

where we have introduced the dimensionless variables $\mu=M/M_0$, $u=v/\bar{v}_s$, $x=R/R_0$, the parameter $\vartheta=\bar{v}_s t_r/R_0$ (the ratio of the time scale $R_0/\bar{v}_s$ of the collapsing target to the pulse length t_r), and the parameter $\alpha=(R_0/\Delta R)(\bar{\rho}/\rho_0)$. Here

$$\bar{\rho}=(1-3k_1)^{-1}\rho(t_r), \tag{19}$$

$$\bar{v}_s=(1+k_1)^{-1}v_s(t_r), \tag{20}$$

where $\rho(t_r)$ and $v_s(t_r)$ are the values of the density and sound speed at time $t=t_r$.

We solve this system by the method of successive approximations. As a first approximation we assume that the mass and radius of the shell are equal to their average values during the process of compression, $\bar{\mu}$ and $\bar{x}$. As a result we find the following solutions:

$$\mu=1-2C_2(1-k_1)\sqrt{\bar{\mu}\alpha}\xi\left(\frac{t}{t_c}\right)^{1-2k_1}, \tag{21}$$

$$u=C_3\sqrt{\frac{\alpha}{\bar{\mu}}}\sqrt[3]{\xi}\left(\frac{t}{t_c}\right)^{1-k_1}. \tag{22}$$

In these expressions t_c is the time for the target to collapse to the center:

$$\left(\frac{t_c}{t_r}\right)^{1-k_1/2}=C_4\frac{R_0}{\bar{v}_s}\sqrt{\frac{\bar{\mu}}{\alpha}\frac{1}{\bar{x}t_r}} \tag{23}$$

and $\xi=\sqrt{(t_r/t_c)^{3/2k_1}}$ is the parameter relating the x-ray pulse length to the target collapse time. The constants C_2, C_3, and C_4 take the form

$$C_2=\frac{\beta}{2}\bar{x}\sqrt{\frac{(1-3k_1)(1-k_1)(2-k_1)}{(1+\beta^2)(1+2k_1)}}\frac{1+k_1}{1-2k_1},$$

$$C_3=\bar{x}\sqrt{\frac{(1+\beta^2)(1-3k_1)(1+2k_1)(2-k_1)}{1-k_1}},$$

$$C_4=\sqrt{\frac{(2-k_1)(1-k_1)}{(1-3k_1)(1+2k_1)(1+\beta^2)}}.$$

Averaging the solution (21) and (22) in the first approximation over the time of target collapse we find the average values of the shell mass and radius:

$$\bar{x}=\frac{2-k_1}{3-k_1}, \tag{24}$$

$$\bar{\mu}=1+\frac{\alpha\xi^2C_2^2}{2}-\sqrt{\frac{\alpha\xi^2C_2^2}{2}\left(2+\frac{\alpha\xi^2C_2^2}{2}\right)}. \tag{25}$$

The range of variation of the parameter α is determined from the condition $\mu(\alpha)|_{t=t_c}>0$, and from (21), (24), and (25) is equal to

$$0<\alpha<[2C_2^2\xi^2(1-k_1)(1-2k_1)]^{-1}. \tag{26}$$

The upper limit of α corresponds to complete vaporization of the shell. At the instant the target collapses to the center ($t=t_c$) the general solution (21)–(23) for a gold target assumes the following form:

$$u=1.44\sqrt{\frac{\alpha}{\bar{\mu}}}, \tag{27}$$

$$\mu=1-0.73\sqrt{\alpha\bar{\mu}}, \tag{28}$$

$$t_c=\sqrt{\frac{\bar{\mu}}{\alpha}}\frac{R_0}{\bar{v}_s}, \tag{29}$$

where

$$\bar{\mu}=1+0.086\alpha-\sqrt{0.086\alpha(2+0.086\alpha)},\quad 0<\alpha<4.34.$$

The dependence of the velocity and mass of a gold shell on the parameter α is shown in Fig. 2.

3.2. Acceleration of a planar target

Experimental studies of the physics of material acceleration under the action of a laser pulse have been widely pursued with planar targets. Hence there is interest in solving the problem of accelerating a layer of material under the action of a pulse of radiative plasma. Assume that a thin layer of material has high atomic number and thickness Δ. In this case, in the initial equations of motion (14)–(15) we should omit the factor $4\pi R^2$ and the target mass M should

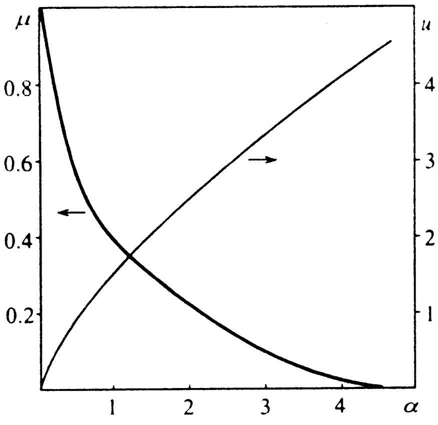

FIG. 2. Unvaporized mass $\mu = M/M_0$ and velocity $u = v/v_s$ of a gold target as functions of the parameter $\alpha = \bar{\rho} R_0/\rho_0 \Delta R$.

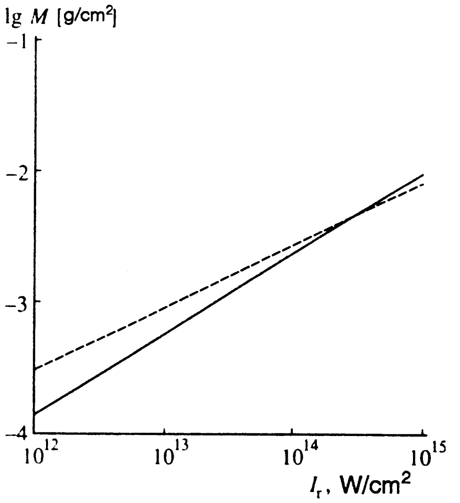

FIG. 3. Unvaporized mass M of a planar gold target as a function of the x-ray pulse intensity I_r. The result obtained from a numerical calculation in Ref. 13 is indicated by the dashed curve.

be understood as the mass per unit area (g/cm²). Using the average-mass approximation, we find the solution for a gold planar target:

$$M\ [\mathrm{g/cm^2}] = M_0 - 5.5 \cdot 10^{-3} I_r^{0.66} t^{0.76}, \tag{30}$$

$$v\ [\mathrm{cm/s}] = \frac{8.2 \cdot 10^4}{\bar{M}} I_r^{0.84} t^{0.88}, \tag{31}$$

where

$$\bar{M} = M_0 - 3.1 \cdot 10^{-3} I_r^{0.66} t^{0.76}. \tag{32}$$

This solution is valid for $t < t_{ev}$, where t_{ev} is the time at which the material is completely vaporized. We can determine t_{ev} by equating expression (30) to zero:

$$t_{ev} = 0.25 \Delta^{1.3} I_r^{0.87}.$$

If velocities 300–400 km/s for $I_r = 5 \cdot 10^{13}$ W/cm² and $t = 3$ ns are reached at time t_r, the initial target mass should be $M_0 = 7.5 \cdot 10^{10-3}$ (g/cm²).

This solution can be compared with the results of numerical calculations and experiment given in Refs. 12 and 13.

The dependence reported in Ref. 13 for the vaporized mass is

$$M_{ev}\ [\mathrm{g/cm^2}] = 3.8 \cdot 10^{-3} I_r^{0.5}.$$

In Ref. 12 the following result is given:

$$M_{ev}\ [\mathrm{g/cm^2}] = 4.7 \cdot 10^{-3} I_r^{0.63} t^{0.82}.$$

The exponents of the intensity and time in Refs. 12 and 13 in the expressions for the vaporized mass are close to those we obtain in our simple analytical model. Figure 3 shows the vaporized mass as a function of the x-ray intensity. The results of this work agree well with the numerical calculations of Refs. 12 and 13.

4. HYDRODYNAMIC COUPLING COEFFICIENT FOR INDIRECT DRIVE

We calculate the final hydrodynamic coupling coefficient for a spherical shell target accelerated by the momentum of the radiating plasma, using the results given above for the velocity of the unvaporized mass of the target together with the expression for the energy of the x-ray pulse:

$$E_r \simeq 4\pi \bar{R}^2 I_r t_c = 4\pi R_0^2 \left(\frac{2\gamma}{\gamma - 1} + \beta^2 \right) (1 - 3k_1)(1 + 2k_1) \times (1 + k_1) t_r \bar{x}^2 \rho \bar{v}_s^3.$$

Evaluating the kinetic energy $E_h|_{t=t_c}$ using Eqs. (27)–(28), we find a general expression for η_h:

$$\eta_h = \frac{(1+\beta^2)^2}{2\beta C_1} \frac{(1 - 4k_1^2)}{(1 - k_1^2)^2} \frac{D\xi\sqrt{\alpha\bar{\mu}}(1 - D\xi\sqrt{\alpha\bar{\mu}})}{\bar{\mu}^2}, \tag{33}$$

where we have introduced the notation $D = 2C_2(1 - k_1)$. Expression (33) is valid [cf. Eq. (26)] for

$$0 < \alpha < [2C_2^2 \xi^2 (1 - k_1)(1 - 2k_1)]^{-1}.$$

Using Eqs. (33) and (26) we can determine the optimum value of the consistency parameter

$$\xi = \sqrt{\left(\frac{t_r}{t_c} \right)^{3k_1}}.$$

First of all it is obvious that the parameter ξ should be less than unity, since only in this case is all of the x-ray pulse energy used for accelerating and compressing the target. Then, exactly as with α, the consistency parameter enters into the expression for the average mass (25) and into the hydrodynamic coupling coefficient in the combination $\alpha\xi^2$; consequently the form of the function $\eta_h(\alpha)$ for ξ=const and $\eta_h(\xi^2)$ for α=const is the same. From condition (26) it is clear that by reducing ξ we spread out the function η_h in α. This means that as ξ is reduced we can achieve the same value of the hydrodynamic efficiency for larger values of the parameter α. Increasing the parameter $\alpha = (\bar{\rho}/\rho_0)(R_0/\Delta R)$ implies either increasing the aspect ratio of the shell or the average density of the corona. However, neither of these is

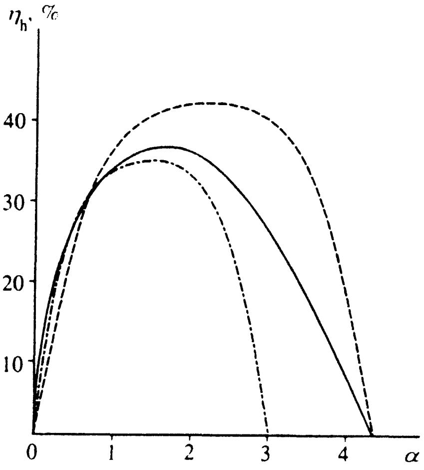

FIG. 4. Hydrodynamic coupling coefficient η_h as a function of α in the case of a radiating corona in the steady and unsteady cases (solid trace and dash-dot trace) and in the case of a "hydrodynamic" corona (dashed trace).[13]

desirable. When the aspect ratio is increased, i.e., for thin shells, the probability that the shell will be disrupted in the process of compression as a result of hydrodynamic instability increases. Raising the average density of the radiative corona requires the use of higher intensities of laser radiation, as a result of which the efficiency with which energy is converted into x rays drops. Thus, it is undesirable to increase the range of variations of the parameter α, and the optimum value of the consistency parameter ξ should be 1. For gold the expression for the hydrodynamic coupling coefficient assumes the form

$$\eta_{\mathrm{h}}=0.46(\alpha\bar{\mu})\bar{\mu}^{-2}(1-0.73\sqrt{\alpha\bar{\mu}}),\qquad(34)$$

where

$$\bar{\mu}\approx 1+0.086\alpha-\sqrt{0.172\alpha},\quad 0<\alpha<4.34.$$

The function (34) is displayed in Fig. 4, from which we see that the maximum hydrodynamic coupling coefficient $\eta_{\max}=36\%$ is achieved for $\alpha=1.6$. The nonmonotonic behavior of η_h is related to the increase in the final velocity and the decrease in the unvaporized mass of the shell as a function of α.

Note that the expressions for the mass and velocity of the shell in the dimensionless form (27), (28), as well as the hydrodynamic coupling coefficient (34) calculated for a gold target, have a universal character, and to within 5% can be used for targets of other heavy elements, although the sound speed and density of the radiating corona which enter into these quantities can vary considerably, depending on the atomic composition of the target material. This is related to the fact that the constants C_2,C_3,C_4 which determine the solution of the dimensionless equations of motion (21)–(23) depend only on the exponent k_1, which is determined by the exponents n of the temperature and m of the density in the expressions for the Rosseland path length, and do not depend on the constant C_{r} of the Rosseland path length. Since the exponents n and m differ little for various materials, and they are much greater than unity, the exponent in question satisfies $k_1\ll 1$ for all elements. As a result, the constants C_2,C_3,C_4 for different materials are close to the values

$$C_2\approx\beta/3\sqrt{1+\beta^2},\quad C_3\approx 2(1+\beta^2)/3,\quad C_4\approx\sqrt{2/(1+\beta^2)}\,.$$

On the other hand, the values of the sound speed and the density of the radiating corona depend on C_{r}, which varies considerably for different materials (for example, for Au, $C_{\mathrm{r}}\approx 10^{-2}$; for Fe, $C_{\mathrm{r}}\approx 0.3$; and for Al, $C_{\mathrm{r}}\approx 0.7$).

5. HYDRODYNAMIC EFFICIENCY FOR ACCELERATION OF A SPHERICAL TARGET BY THE IMPULSE OF A RADIATIVE PLASMA

We consider the conditions for efficient acceleration of a target shell by indirect drive (see Introduction) and compare the hydrodynamic efficiency of an indirect-drive target with that of a direct-drive target, evaluated at the wavelength of an Nd laser, the type most widely used in current experiments.

From Eqs. (20) and (27), in the case of indirect drive the final velocity of a gold shell and the parameter α of a matched target (a target whose time of collapse is equal to the pulse length) are equal to

$$v\approx 0.42\cdot 10^7 I^{0.46}\left[\frac{R_0/\Delta R}{\rho_0}\right]^{0.5}\left[\frac{A}{Z+1}\right]^{0.15}\bar{\mu}^{-0.5},\qquad(35)$$

$$\alpha\approx 1.4\cdot 10^{-2} I^{0.71}\left[\frac{R_0/\Delta R}{\rho_0}\right]^{1.12}\left[\frac{A}{Z+1}\right]^{0.94},\qquad(36)$$

where $\bar{\mu}\approx 1+0.086\alpha-0.41\sqrt{\alpha}$, $\alpha\leqslant 4.34$.

In the case of laser radiation acting directly on the target, the bulk of the radiation is absorbed near the plasma resonance, and for this reason the average density of the target corona in direct drive is close to the critical plasma density corresponding to the wavelength of the laser radiation, $\rho\simeq 1.7\cdot 10^{-3}\,(A/Z+1)\lambda^{-2}$, and the acceleration properties of the target shell are calculated from the following relations:[19]

$$v\approx 0.37\cdot 10^7 I^{0.33}\lambda^{-0.33}\left(\frac{A}{Z+1}\right)^{0.17}\left[\frac{R_0/\Delta R}{\rho_0}\right]^{0.5}\bar{\mu}^{-0.5},\qquad(37)$$

$$\alpha\approx 1.7\cdot 10^{-3}\left(\frac{A}{Z+1}\right)\lambda^{-2}\left[\frac{R_0/\Delta R}{\rho_0}\right],\qquad(38)$$

where

$$\bar{\mu}\approx\left(\sqrt{1+\frac{\alpha}{36}}-\sqrt{\frac{\alpha}{6}}\right)^2,\quad \alpha\leqslant 4.5.$$

Let us consider the results given above for the maximum radiation fluxes acting on a target with direct and indirect drive. From the physics of conversion of laser radiation into x rays given in the Introduction, the maximum x-ray flux should be taken to be the quantity 10^{14} W/cm^2. The maximum laser intensity at which the role of parametric processes in the interaction of the laser radiation with the plasma can still be disregarded is related to the wavelength by $I\approx 10^{14}\lambda^{-2}$ W/cm^2 (Refs. 1, 5).

First of all we note that for direct-drive and indirect-drive targets the functional dependence of the final velocity and the parameter α on all problem in the parameter, including the radiation intensity (if we take for the ratio $I^{0.33}/\lambda^{0.33}$ in direct drive the ratio of these quantities corresponding to the maximum intensity of the laser radiation) are similar.

The parameter $A/(Z+1)$ of the coronal plasma for indirect-drive targets is considerably greater than in direct drive. Specifically, the atoms of heavy elements in the corona of the indirect-drive targets are partially ionized; for gold, e.g., at the intensities we have assumed the charge state is $Z \approx 20-30$ (Ref. 18) and hence $A/(Z+1) \approx 7-9$. The corona in direct-drive targets is an essentially completely ionized plasma of light elements, so the ratio $A/(Z+1)$ in this case is close to 2.

Taking this into account we can easily see that for the same values of $(R_0/\Delta R)/\rho_0$ the value of α for indirect-drive targets is considerably greater than in direct-drive targets (by about a factor of 30 for laser wavelengths $\lambda \approx 1.06$ μm and a factor of 3 for $\lambda \approx 0.35$ μm). This difference in the values of α can be explained by the substantial increase in the density of the radiating corona above the density of the corona in a direct-drive target, which in turn is a consequence of the fact that the path length of an x-ray photon is greater than the absorption length of the laser radiation at these wavelengths. Under the same conditions, however, the difference in the final velocities with which the target shells move in the two designs is slight; when the third harmonic of an Nd laser is used, the final shell velocity in a direct-drive target is twice that in the case of indirect drive. This is due to the higher temperature and consequently the higher sound speed in the case of direct drive because of the behavior of the photon path lengths of x rays and laser radiation mentioned above.

Calculations using Eq. (36) reveal that in indirect drive final shell velocities $(3-4)\cdot 10^7$ cm/s can be achieved only if the relative mass of the vaporized part of the shell is large. For a gold target a final shell velocity $3\cdot 10^7$ cm/s is achieved for $\alpha \approx 2.5$ and a relative mass of the vaporized material of $1-\mu \approx 0.83$, while a velocity of $4\cdot 10^7$ cm/s is achieved for $\alpha \approx 3.5$ and $1-\mu \approx 0.93$. The maximum velocity, corresponding to the maximum possible value of α equal to 4.34, is $4.5\cdot 10^7$ cm/s. Thus, indirect drive has essentially no margin above the minimum (from the standpoint of hydrodynamic efficiency) shell velocity. An indirect-drive target can operate only in a narrow range of the parameter α, $2.5 \leqslant \alpha \leqslant 4$, the upper limit of which corresponds to the value of the hydrodynamic coupling coefficient $\eta_h \approx 0.1$ [see Fig. 4 and Eq. (34)], while the lower limit corresponds to a velocity $3\cdot 10^7$ cm/s.

The prospects for using the direct approach to compression in order to achieve large final velocities for the target shell are considerably broader. Specifically, as shown by the calculation using Eqs. (37) and (38), at the maximum value of the laser radiation for the third harmonic of an Nd laser the velocity $3\cdot 10^7$ cm/s is reached at $\alpha \approx 0.17$ and $4\cdot 10^7$ cm/s is reached at $\alpha \approx 0.3$, while the maximum velocity corresponding to the maximum possible value $\alpha \approx 4.5$ is $1.5\cdot 10^8$ cm/s.

Thus, the operating regime of a target in indirect drive differs from that of a target in direct drive. An indirect-drive target operates at large values of the parameter $\alpha \approx 2.5-3.5$ and hence at large values of the relative mass of the vaporized material $1-\mu \approx 0.8-0.9$ (see Fig. 2).

6. CONCLUSION

In conclusion we consider the important question of the maximum possible aspect ratios for indirect-drive targets satisfying the criterion for hydrodynamic efficiency of the target acceleration.

The values of the shell aspect ratio that are acceptable from the standpoint of hydrodynamic stability are less than 30 (Ref. 19). For the shell in an indirect-drive target made of gold, in the normal state with initial density $\rho_0 \approx 19$ g/cm^3 the parameters $\alpha \approx 2.5$ ($v \approx 3\cdot 10^7$ cm/s, $\eta_h \approx 0.32$) and $\alpha \approx 3.5$ ($v \approx 4\cdot 10^7$ cm/s, $\eta_h \approx 0.18$) correspond to very large aspect ratios, 310 and 420 respectively.

It is evident that for a given value of α (for a given hydrodynamic efficiency) the aspect ratio of the target can be chosen smaller if the initial density of the ablator is smaller ($R_0/\Delta R = \alpha\rho_0/\bar{\rho}$). The need to absorb x radiation imposes definite restrictions on the amount by which the initial density of the ablator can be reduced in indirect drive: specifically, the vaporized part of the ablator must be made of heavy elements.

One way to reduce the aspect ratio of a target in indirect drive may be the use of a combined ablator, consisting of an outer layer of heavy material with normal density, e.g., gold, whose mass would be equal to the mass of the radiating corona that forms, together with an internal layer made of material from light elements with a mass equal to the mass of the unvaporized part of the shell, which would not have to absorb x radiation. However, because of the requirement that the vaporized material have a large relative mass, i.e., that the mass of the radiating corona be large, corresponding to the effective operating regime of an indirect-drive target, this reduction is insufficient from the standpoint of hydrodynamic stability. In fact, in order that the bulk of the ablator kinetic energy pass into internal energy of the thermonuclear plasma when the target is compressed the initial density of the unvaporized part of the ablator should be at least 5–10 times greater than the density of the thermonuclear material ($\rho^0_{DT} \approx 0.2$ g/cm^3 for DT ice).[19] However, using material with a density $\rho_0 \approx 1$ g/cm^3 as the inner layer of a confined ablator (e.g., polyethylene) for $\alpha = 3.5$ ($\mu \approx 0.9$) reduces the aspect ratio of an indirect-drive target only to 140, while for $\alpha \approx 2.5$ ($\mu \approx 0.8$) it is reduced only to 70.

In this work we would like to propose a different (and in our opinion the only) way of efficiently reducing the aspect ratio of an indirect-drive target. This is to use an ablator consisting entirely of a low-density porous material of heavy elements with a microscopic density close to 1 g/cm^3. At present it is technically feasible to fabricate such a target, since the technology of preparing porous materials of heavy elements with macroscopic density from 10^{-2} to 1 g/cm^3 has achieved considerable success, e.g., in the case of porous copper and porous gold.[20] When $\alpha = 3.5$ is reached the aspect ratio of a target with an ablator made of porous gold is equal to 20, while for $\alpha = 2.5$ it is only 15.

Thus, the target parameters using an ablator made of porous material of heavy elements with a macroscopic density of 0.5–2 g/cm^3 can be chosen so as to ensure high hydrodynamic target acceleration efficiency under conditions favorable for stable compression.

[1] J. H. Nuckols, Phys. Today **9**, 28 (1982).
[2] Yu. V. Afanas'ev, N. G. Basov, P. P. Volosevich *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 150 (1975) [JETP Lett. **68** (1975)].
[3] Yu. V. Afanasiev and S. Yu. Gus'kov, in *Energy Transfer to the Plasma in Laser Targets, Nuclear Fusion of Inertial Confinement* (1993).
[4] N. G. Basov, P. P. Volosevich, E. G. Gamalii, S. Yu. Gus'kov, V. B. Rozanov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 135 (1978) [JETP Lett. **28**, 125 (1978)].
[5] Yu. V. Afanas'ev, N. G. Basov, B. L. Vasin *et al.*, Zh. Eksp. Teor. Fiz. **77**, 2539 (1979) [Sov. Phys. JETP **50**, 1229 (1979)].
[6] L. A. Bol'shov, I. N. Burdonskii, A. L. Velikovich *et al.*, Zh. Eksp. Teor. Fiz. **92**, 2060 (1987) [Sov. Phys. JETP **65**, 1160 (1987)].
[7] E. Storm, in *Proc. 11th Eur. IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research*, Vol. 3 (1987).
[8] W. C. Mead, E. M. Campbell, K. G. Estabrook *et al.*, Phys. Fluids **26**, 2316 (1983).
[9] P. Celliers and K. Eidman, Phys. Rev. A **41**, 3270 (1990).
[10] R. Sigel, G. D. Tsakiris, F. Lavarenne *et al.*, Phys. Rev. Lett. **65**, 587 (1990).
[11] N. A. Tahir and R. S. Arnolds, Phys. Fluids B **3**, 1717 (1991).
[12] M. Murasami and J. Meyer-ter-Vehn, Nuclear Fusion **31**, 1315 (1991).
[13] R. F. Schmalz, J. Meyer-ter-Vehn, and R. Ramis, Phys. Rev. A **34**, 2177 (1986).
[14] Yu. V. Afanas'ev, E. G. Gamalii, O. N. Krokhin, and V. B. Rozanov, Zh. Eksp. Teor. Fiz. **71**, 594 (1976) [Sov. Phys. JETP **44**, 311 (1976)].
[15] E. K. Storm, Report UCRL-50021-76, Lawrence National Laboratory, Sect. 5, p. 83 (1976).
[16] S. Yu. Gus'kov, V. V. Everev, and V. B. Rozanov, Kvantovaya Élektron. (Moscow) **10**, 802 (1983) [Sov. J. Quantum Electron. **13**, 498 (1983)].
[17] S. Yu. Gus'kov, V. V. Everev, V. Ya. Karlov *et al.*, Trudy FIAN **170**, 93 (1986).
[18] G. A. Vergunova and V. B. Rozanov, Kvantovaya Élektron. (Moscow) **19**, 263 (1992) [Sov. J. Quantum Electron. **22**, 239 (1992)].
[19] Yu. V. Afanasiev, E. G. Gamaly, S. Yu. Gus'kov *et al.*, Laser and Particle Beams **6**, 1 (1988).
[20] N. G. Borisenko and Yu. A. Merkul'ev, Trudy FIAN **220**, 28 (1992).

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