MODEL OF THE EXPANSION OF A LOW-TEMPERATURE LASER PLASMA IN A VACUUM

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UDC 523.529.56

Laser radiation acting on the surface of a solid target in an atmosphere at reduced pressure causes a plasma of target vapor to form and expand. It is known that at low pressures the background gas has little effect on the expansion. The model of expansion of a plasma in a vacuum [1-11] is a good approximation in this case. The main results here were obtained by considering a one-dimensional [1, 2, 4-8] or quasi-steady spherical [3, 5, 10, 11] expansion. For one-dimensional expansion self-similar solutions have been constructed for a completely [2, 4, 5] or partially [5, 8] ionized non-radiating plasma and computer simulations, taking the re-radiation of the plasma into account, have been carried out [6, 7]. For the spherical case the distribution of the plasma parameters is found numerically if the parameters at the Jouguet point are given [3, 5, 10].

The main results are found from numerical calculations (required even in self-similar solutions), which give a fairly detailed picture of the process. The principal characteristic features, however, should depend weakly on detailed knowledge of the exact absorption coefficients, the equations of state, and the transport equations; they are even more visible when the detailed is reduced and the model is simplified, naturally without losing the qualitative features of the process. Such an undetailed model makes it possible to see the main tendencies and occupies an intermediate position between numerical calculations and simple estimates. Self-similar solutions [2, 4, 5, 8] thus have given a relatively simple picture of the space—time distribution of the plasma parameters in one-dimensional expansion for a power-law (or constant) laser-radiation intensity.

It turns out that on the basis of the results of previous studies the examination of the expansion of a low-temperature laser plasma in a vacuum can be simplified further, which is what we have done here. This has made it possible to write the equation of one-dimensional expansion for any time dependence of the laser-radiation intensity, find its partial solutions, study the self-radiation of the plasma on the expansion, use the model of a two-dimensional expansion to estimate the time in which the self-consistent mode of expansion (plasma transillumination) is violated in the transition from the one-dimensional to the two-dimensional stage, and obtain approximate expressions for the time distribution of the plasma during the spherical or cylindrical stage of expansion. The model extends the class of problems encompassed by the analytical approach and can be used for the analytical investigation of other physical processes that accompany expansion: the study of a plasma, generation of electric and magnetic fields, interaction of a plasma with a background gas, etc.

1. Main Models. Equation of One-dimensional Expansion. The assumptions determining the model are based on the approximation of average charge for plasma ions [12] and generally concur with the assumptions of [8]. In this case only the external hot zone of the plasma, and not the internal heating zone, is considered.

Assume that there is a flat target in a vacuum. Laser radiation is incident on it along a normal and is absorbed by the expanding ablation plasma. If the expansion of heating times of the plasma exceed the characteristic ionization and recombination times, the ionization state is an equilibrium state. In such a plasma the charge distribution of the ions is in the form of a narrow sharp peak, mainly ions with one to three charges exist, which makes it possible to introduce an average ion charge (degree of ionization), which is assumed to be a continuous quantity [12, 8]: $Z = n_e/n$ (n_e and n are the electron and ion densities). One more simplification is associated with the replacement of the real dependence of the ionization potential $I(Z)$ by a power-law approximation [12, 8]: $I(Z) = I_1Z^{\alpha}$. The values of α for some elements, calculated for $I(Z) \lesssim 100$-300 eV, are given in Table 1. From the Saha equation of

Moscow. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 1, pp. 3-10, January-February, 1992. Original article submitted March 26, 1990; revision submitted September 19, 1990.

TABLE 1

Material	α
Carbon	1,2
Aluminum	1,7
Chromium	1,4
Iron	1,34
Copper	1,45
Silver	1,4
Lead	1,3

ionization equilibrium it follows [12, 8] that $I(Z) \simeq \beta T$ (T is the plasma temperature which is identical for electrons and ions, and β depends logarithmically on the plasma parameters and is assumed to be approximately constant).

The self-similar solutions were constructed [2, 4, 8] by using the linear dependence $v(x, t)$ of the plasma velocity on the coordinate x [13] with $v(0, t) \neq 0$. In most of the volume, however $v(x, t) \gg v(0, t)$ and it is more appropriate to take

$$v(x, t) = (x/x_f)dx_f/dt \tag{1.1}$$

[$x_f(t)$ is the coordinate of the plasma-vacuum boundary]. The laser radiation absorption coefficient decreases rapidly with increasing x. We can assume, therefore, that laser radiation is absorbed primarily near x = 0 and instead of the equation of local plasma heating [2, 4, 8] we can use the approximation of adiabatic expansion in the form [12]

$$(T^{3/2}/n)\exp(\gamma Z) = \mathrm{const}. \tag{1.2}$$

Substitution of (1.1) and (1.2) into the equation of motion with replacement of Z + 1 by Z at high Z [8] gives the distribution of plasma parameters in the one-dimensional stage of expansion:

$$\begin{gathered} Z(\xi, t) = Z_m(t)(1-\xi^2)^{1/(\alpha+2)}, \\ T(\xi, t) = T_m(t)(1-\xi^2)^{\alpha/(\alpha+2)}, \\ n(\xi, t) = n_m(t)(1-\xi^2)^{1,5\alpha/(\alpha+2)}\exp\{\gamma Z_m[(1-\xi^2)^{1/(\alpha+2)}-1]\}, \\ \xi = x/x_f \end{gathered} \tag{1.3}$$

[to obtain (1.3) it is sufficient that the entropy s depend weakly on the coordinate: $\gamma dZ/dx \gg ds/dx$]. The maximum parameters $Z_m(t)$, $T_m(t)$, and $n_m(t)$ with respect to coordinate are obtained at $\xi = 0$, taken to be the boundary of the inner and outer zones of the plasma:

$$\begin{gathered} Z_m(t) = \left(m\gamma_\alpha^{-1} I_\beta^{-1} x_f d^2x_f/dt^2\right), \quad T_m(t) = I_\beta Z_m^\alpha(t), \ \gamma_\alpha = 2\gamma/(\alpha+2), \\ I_\beta = I_1/\beta \end{gathered} \tag{1.4}$$

(m is the ion mass). The density $n_m(t)$ is found from the condition for a self-consistent expansion mode (SCEM) [1, 2, 4] in which the optical thickness of the plasma for laser radiation is $\theta_\ell = \mathrm{const}$ and is of the order of one. The absorption coefficient of laser radiation of frequency ν_ℓ in a rarefied plasma, where n_e is much smaller than the critical density for cutoff of laser radiation, with allowance for the photoeffect and stimulated emission at $h\nu_\ell \ll T$ has the form [12]

$$\varkappa_l = \varkappa_1 Z^3 n^2 T^{-3/2} \nu_l^{-2}, \quad \varkappa_1 = 2^{5/2} 3^{-3/2} \pi^{1/2} e^6 m_e^{-3/2} c^{-1}. \tag{1.5}$$

By means of (1.5), after approximate integration over x with allowance for the fact that the region near x = 0 makes the main contribution, we find from the SCEM condition that

$$n_m(t) = (4\gamma_\alpha/\pi)^{1/4} \nu_l \theta_l^{1/2} (\varkappa_1 x_f)^{-1/2} T_m^{3/4} Z_m^{-5/4}. \tag{1.6}$$

The plasma parameters (1.4) and (1.6) depend only on $x_f(t)$. The equation for $x_f(t)$ is obtained from the law of conservation of energy $E_1(t) + E_2(t) + E_3(t) = W_\ell(t) - W_r(t)$ (E_1, E_2, E_3 are, respectively, the kinetic energy of expansion, the thermal energy, and the energy of ionization of an atom to a Z ion per unit target surface area, $W_\ell(t)$ is the density of the laser radiation energy, and $W_r(t)$ is the plasma radiation loss). Approximate integration over x gives

$$\begin{gathered} E_1 = \frac{mN_s}{2\gamma_\alpha Z_m}\left(\frac{dx_f}{dt}\right)^2, \quad E_2 = \frac{3}{2} Z_m T_m N_s, \quad E_3 = \frac{I_1 Z_m^{1+\alpha}}{1+\alpha} N_s, \\ N_s = \left(\frac{\pi}{2\gamma_\alpha Z_m}\right)^{1/2} x_f n_m \end{gathered} \tag{1.7}$$

[$N_s(t)$ is the number of plasma atoms evaporating per unit area of the target]. The energy expended on evaporation of the surface can be disregarded. The equation of expansion is then written as

$$x_f^{1/2}\left(x_f\frac{d^2x_f}{dt^2}\right)^{(7\alpha-3)/(4\alpha+8)}\left[\frac{3}{\beta}+\frac{2}{\alpha+1}+\frac{(dx_f/dt)^2}{\beta x_f d^2x_f/dt^2}\right]=b\,(W_l-W_r),$$
$$b=2\,(\varkappa_1/\theta_l)^{1/2}\left(\gamma_\alpha^{8\alpha-1}I_\beta^{-17}m^{3-7\alpha}\right)^{1/(4\alpha+8)}/(\pi^{1/4}\beta\nu_l). \tag{1.8}$$

When the laser radiation is obliquely incident at an angle φ to the normal to the target θ_ℓ must be replaced by $\theta_l\cos\varphi$ in the formulas.

Thus, in constructing the model instead of the equations of continuity, energy and local absorption of laser radiation [2, 4, 8, 11] we used the SCEM condition, the equation of total energy balance, and the adiabatic equation, which simplified the discussion substantially. The SCEM condition made it possible, with the expansion velocity distribution (1.1), to obtain the time-dependent number of atoms $N_s(t)$, to which is related the flux of atoms into the outer zone of the plasma with velocity $v_n(t) = n_m^{-1}dN_s/dt$. It should be smaller than $v(x, t)$, which leads to the limitation $\xi > \xi_v = v_n/(dx_f/dt)$. With the condition $Z(x, t) > 1$ we have $T > I_\beta \sim 1$ eV and together with (1.3) we have $\xi^2 < \xi_Z^2 = 1 - Z_m^{-\alpha-2}$.

2. Two-dimensional Expansion. The equation of two-dimensional expansion (1.8) makes it possible to find analytical (exact or approximate) solutions in certain specific cases. Some of them are given below. An exact solution is obtained for $W_r = 0$, $W_\ell = W_\tau t^\delta/\tau^\delta$ [$W_\tau = W_\ell(\tau)$ and τ is the laser pulse length]. We call it the δ solution

$$x_f(t)=\frac{t}{(d^2+d)^{(7\alpha-3)/(16\alpha-2)}}\left(\frac{bW_l}{at^{1/2}}\right)^{(2\alpha+4)/(8\alpha-1)},$$
$$Z_m(t)=\left[\frac{m\,(d^2+d)\,x_f^2}{\gamma_\alpha I_\beta t^2}\right]^{1/(\alpha+2)},$$
$$d=\frac{(\alpha+2)\,(2\delta-1)}{8\alpha-1},\quad a=\frac{3}{\beta}+\frac{2}{\alpha+1}+\frac{d+1}{\beta d}, \tag{2.1}$$

$n_m(t)$, $T_m(t)$, and $N_s(t)$ are found from (1.4), (1.6), and (1.7). Comparison of the solution for the expansion of the aluminum plasma at $\delta = 1$, $\beta = 9$ with the known solution [5] indicates good agreement to within 20-30%.

Equation (1.8) is solved approximately for $W_r \ll W_\ell \sim t^\delta$, if we write

$$x_f(t) = x_{f\delta}(t)\,[1+\rho(t)],\ \rho \ll 1, \tag{2.2}$$

where the superscript δ denotes the δ solution (2.1). Linearization of Eq. (1.8) with respect to ρ leads to

$$\rho(t) = -W_r/[A_gW(t)],\ A_g = A_1 + A_2g + A_3(g^2-g),$$
$$A_1=\frac{8\alpha-1}{2\alpha+4},\ A_2=\frac{7\alpha-3}{2d\,(\alpha+2)}-\frac{2}{a\beta d^2},\quad A_3=\frac{7\alpha-3}{4d\,(\alpha+2)\,(d+1)}-\frac{1}{a\beta d^2} \tag{2.3}$$

[g is the exponent in $\rho(t) \sim t^g$, which is determined by the form of the thermal radiation of the plasma taken into account]. The plasma parameters linearized with respect to ρ have the form

$$\frac{dx_f}{dt}=\frac{dx_{f\delta}}{dt}\left[1+\left(1+\frac{g}{d+1}\right)\rho\right],\quad Z_m(t)=Z_{m\delta}\,(1+A_z\rho),$$
$$T_m(t) = T_{m\delta}(1+\alpha A_z\rho),\ n_m(t) = n_{m\delta}[1-(1-(3\alpha-5)A_z/2)\rho/2],$$
$$N_s(t) = N_{s\delta}[1+(1+(3\alpha-7)A_z/2)\rho/2],$$
$$A_z = [2+2g/d+(g^2-g)/(d^2+d)]/(\alpha+2). \tag{2.4}$$

Let us estimate the intensity of the plasma radiation in the continuous and linear parts of the spectrum. In the continuous spectrum the maximum intensity is reached at frequencies $h\nu \ll 3T_m$. The absorption coefficient decreases with increasing ν. Accordingly, while the optical thickness of the plasma is of the order of one at the frequency of the laser radiation, at $\nu > \nu_\ell$ the plasma is transparent to radiation and at $h\nu_\ell \ll 3T_m$ the loss for radiation of the continuous spectrum can be considered to be a volume loss. The formula for the energy loss per unit volume of plasma f_r is given in [12, 14]:

$$f_r = a_rZ^3n^2T^{1/2},\ a_r = 8\pi\varkappa_1(1+u)/hc^2 \tag{2.5}$$

[$u = E_4/T = \beta/4$ for a hydrogen-like atom in which the energy of the first excited level is $E_4 = I(Z)/4$]. Integration of (2.5) over the volume of the plasma with allowance for (1.3) gives the approximate intensity of the continuous radiation

$$q_{rc} = a_r\theta_l\nu_l^2 T_m^2/\varkappa_1, \quad W_{rc} = \int_0^t q_{rc}(t)\,dt.$$

The line radiation is absorbed resonantly and has a large absorption coefficient. We can assume, therefore, that the plasma radiates as a black body with intensity

$$q_{rd} = 2\sigma k_d T_m^4, \quad W_{rd} = \int_0^t q_{rd}(t)\,dt,$$

where σ is the Stefan–Boltzman constant; k_d is the average fraction over the spectrum occupied by lines. In a dense plasma the lines are broadened by the Stark effect. The width of the k-th level of the hydrogen-like atom is estimated as [14] $\Delta\varepsilon_k = 3\hbar^2 n^{2/3} k(k-1)/m_e$. The maximum number of levels which can still be considered discrete is found from the condition that $\Delta\varepsilon_k$ be equal to the distance between neighboring levels. This gives the estimate

$$k_d \simeq \left[\hbar^2 n^{2/3} m_e^{-1} I^{-1}(Z)\right]^{1/5}.$$

If in Eq. (2.3) W_r is taken for the unperturbed plasma parameters (2.1), then $g = g_c$ is obtained for continuous radiation and $g = g_d$ for line radiation, where $g_c = (\delta + 4\alpha - 1)/(8\alpha - 1) \approx 1/2$; $g_d = [(8\alpha + 1)\delta - 1]/(8\alpha - 1) \approx \delta$.

For calculations it is convenient to use practical units of measurement: x, cm; t, μsec; energy, J; velocity, cm/μsec; W, J/cm², q, MW/cm²; n, 10^{18} cm^{-3}; T_m, I(Z) and laser radiation quantum energy, $\varepsilon_l = h\nu_l$, eV. In these units Eq. (1.8) maintains its form with b replaced by

$$b_p = 10\left[\gamma_\alpha^{8\alpha-1}(1{,}6I_\beta)^{-17}(1{,}67A)^{3-7\alpha}\right]^{1/(4\alpha+8)}/(\beta\varepsilon_l\theta_l^{1/2})$$

(A is the atomic weight of the target material). The plasma parameters (1.4), (1.6), and (1.7) are written as

$$Z_m(t) = \left(A\gamma_\alpha^{-1}I_\beta^{-1}x_f d^2x_f/dt^2\right)^{1/(\alpha+2)}, \quad T_m(t) = I_\beta Z_m^\alpha,$$

$$n_m(t) = 2{,}1\varepsilon_l\gamma_\alpha^{1/4}\theta_l^{1/2}I_\beta^{3/4}Z_m^{(3\alpha-5)/4}x_f^{-1/2}, \quad N_s = 2{,}7\varepsilon_l\gamma_\alpha^{-1/4}\theta_l^{1/2}I_\beta^{3/4}Z_m^{(3\alpha-7)/4}x_f^{1/2};$$

the δ solution (2.1) transforms to

$$x_f(t) = \gamma_\alpha^{1/2}t\left\{[1{,}67A(d^2+d)]^{3-7\alpha}\left(10W_l\varepsilon_l^{-1}\beta^{-1}a^{-1}t^{-1/2}\theta_l^{-1/2}\right)^{4\alpha+8}(1{,}6I_\beta)^{-17}\right\}^{1/(16\alpha-2)}, \tag{2.6}$$

$$Z_m(t) = \left(\frac{A}{I_\beta\gamma_\alpha}\right)^{1/(\alpha+2)}\left[\frac{b_p^4(d^2+d)W_l^4}{a^4t^2}\right]^{1/(8\alpha-1)} = \left[\frac{2\cdot 10^4 A(d^2+d)W_l^4}{\theta_l^2\beta^4(1{,}6I_\beta)^8 a^4\varepsilon_l^4 t^2}\right]^{1/(8\alpha-1)}.$$

The intensity of the plasma radiation is

$$q_{rc} = 0{,}2\varepsilon_l^2T_m^2, \quad q_{rd} = 0{,}2k_dT_m^4, \quad k_d = n^{2/15}I^{-1/5}(Z)/6.$$

3. Two-dimensional Expansion, Round Radiation Spot. In [3, 5, 10] Nemchinov used the assumption, derived from general principles, that when plasma moves away from the target to a distance exceeding the size of the laser radiation spot, its expansion becomes spherical and the plasma parameters correspond to the end of the two-dimensional stage of expansion. We consider an approximate model of axisymmetric expansion to more fully substantiate the possibility of such a transition to a model of spherical expansion for the round laser radiation spot and to estimate the plasma transillumination time. We introduce r, the distance from the axis of the laser radiation. The adiabatic equation (1.2) and the linear distribution of the velocity with respect to x (1.1) and with respect to r: $v_r(r, t) = (r/r_f)dr_f/dt$ (r_f is the coordinate of the plasma boundary at x = 0). From the equation of motion and the requirement that the distribution $Z_m(x, r, t)$ so determined be compatible we find that the plasma boundary has the shape of a half-ellipsoid of rotation with semiaxes x_f and r_f, which are related by

$$x_f d^2x_f/dt^2 = r_f d^2r_f/dt^2,$$

and the spatial distribution of the plasma parameters has the form (1.3) with $1 - \xi^2$ replaced by $1 - \xi^2 - \xi_r^2$ ($\xi_r = r/r_f$). Formulas (1.4) and (1.6) also remain valid.

The condition for SCEM clearly is not satisfied over the entire laser-radiation spot of radius r_l, but a requirement that it be satisfied on the axis of the laser radiation is introduced. The model, therefore, is exact only for $r_f \gg r_\ell$, when the plasma parameters are almost constant along the radius inside the spot. In view of the above-mentioned methodological nature of the model this approximation is not fundamental. The equation of expansion is determined from the energy balance

$$r_f^2 x_f^{1/2}\left(x_f\frac{d^2x_f}{dt^2}\right)^{7(\alpha-1)/(4\alpha+8)}\left[\frac{3}{\beta}+\frac{2}{\alpha+1}+2\frac{(dx_f/dt)^2+2\,(dr_f/dt)^2}{\beta x_f d^2x_f/dt^2}\right]=b_1 r_l^2\,(W-W_r), \tag{3.1}$$

$$b_1=(\varkappa_1/\theta_l)^{1/2}\beta^{-1}\pi^{-1/4}\nu_l^{-1}\left(\gamma_\alpha^{12\alpha+3}I_\beta^{-21}m^{7-7\alpha}\right)^{1/(4\alpha+8)}.$$

In the two-dimensional stage of expansion, when $x_f \ll r_\ell$, for $W_r = 0$ we have a δ solution, similar to (2.1):

$$r_f/r_l = 1 + (x_f/r_l)^2 d/(4d + 2).$$

When $x_f = r_\ell$ we find that r_f exceeds r_ℓ by no more than 20-40% if δ = 1-3 and α = 1.2-1.7. In the two-dimensional stage, therefore, the plasma moves mainly along the laser beam, $x_f = r_\ell$ can be assumed to be the boundary of the two-dimensional stage, and the spherical expansion approximation can be used when $x_f > r_\ell$ [3, 5, 10].

Analysis showed that the expansion velocity of the plasma boundary grows very slowly in the spherical stage and can be assumed to be a constant, corresponding to the end of the two-dimensional stage. Then from the solution of Eq. (3.1) it follows that the number of atoms in the plasma, N(t) and dN/dt increase rapidly with time. This means that a time t_c should be reached when the laser radiation intensity is insufficient to evaporate such a large number of atoms. This indicates violation of the SCEM and supports the results of [3, 9] about the transillumination of the plasma upon transition to the two-dimensional stage of expansion. The time t_c is estimated from the condition $\pi r_l^2 q_l \varkappa_s = \varepsilon_s dN/dt$, where ε_s is the binding energy of an atom on the surface, $\varkappa_s$ is the coefficient of absorption of laser radiation by the surface,

$$t_c/t_l = \exp\{7(\alpha-1)\theta_l/[3\alpha+17-(11-3\alpha)\delta]\} \tag{3.2}$$

[t_ℓ is the time when the two-dimensional stage of expansion ends, $x_f(t_\ell) = r_\ell$]. In the case θ_ℓ = 0.3 for two-dimensional expansion with δ = 1 [2, 4, 8] at α = 1.2-1.7 we obtain t_c/t_ℓ = 1.03-1.1. As δ increases t_c/t_ℓ increases because of the increase in θ_ℓ [8], but remains of the order of one. The SCEM is violated and the plasma is transilluminated, therefore, almost immediately after the transition to the spherical stage. In the process the laser radiation reaches the target surface, where it evaporates a new portion of material, which heats up, is ionized, and gradually catches up to the portion evaporated previously. An oscillatory mode with period $\sim t_c \sim t_\ell$ arises. These oscillations should be most pronounced for the density and less for the temperature. Such a mode was observed in the computer simulations of Bergel'son, as communicated in [5]. The oscillations can be recorded experimentally if the electrical potential of the target is measured.

With time the oscillations should be damped and a model of quasi-steady spherically symmetric expansion should be established [3, 5, 10, 11]. This stage is characterized by the presence of a dense laser-radiation absorbing plasma core, a distance r_ℓ from the target, and peripheral layers that are transparent to the laser radiation. It is reasonable to assume that not all parameters of the plasma core correspond to the end of the two-dimensional stage, but only the temperature and velocity do, since they are least subject to change under transition to spherical expansion. At δ = 1 and $W_\ell = q_\ell t$ formula (2.6) gives (in practical units)

$$T_l=T_m(t_l)=I_\beta Z_l^\alpha,\quad Z_l=Z_m(t_l)=\left[\frac{A\,(d^2+d)\,r_l}{I_\beta\gamma_\alpha t_l^2}\right]^{1/(\alpha+2)},$$

$$V_l=\frac{dx_f\,(t=t_l)}{dt}=\frac{(d+1)\,r_l}{t_l}, \tag{3.3}$$

$$t_l=\left\{\left(\frac{r_l^2}{\gamma_\alpha}\right)^{8\alpha-1}\left(\frac{\theta_l^{1/2}a\beta\varepsilon_l}{10q_l}\right)^{4\alpha+8}(1{,}6I_\beta)^{17}\,[1{,}67A\,(d^2+d)]^{7\alpha-3}\right\}^{1/(18\alpha+2)}.$$

The density at the core boundary $r = r_\ell$ can be conveniently determined by using the condition that the laser-radiation energy flux $\pi r_\ell^2 d_\ell$ be equal to the plasma energy flux from the core, which gives (in practical units)

$$n\,(r_l)=10q_l V_l^{-1}\{1{,}6\,[3/\beta+2/(\alpha+1)]\,I_1 Z_l^{1+\alpha}+1{,}67AV_l^2\}^{-1}. \tag{3.4}$$

After a plasma layer leaves the core, its expansion velocity increases slightly with the distance (logarithmically) and can be assumed to be equal to V_ℓ. If the laser radiation intensity varies rather slowly with time, so that the plasma flow manages to build up, then

$$n(r,t)=n(r_l)r_l^2/r^2,\ Z(r,t)=Z_l-2\gamma^{-1}\ln(r/r_l).$$

In order to take the radiation energy loss into account it is necessary to introduce $q_r = dW_r/dt$ and replace q_ℓ with $q_\ell - q_r$ in (3.3) and (3.4), the result being algebraic equations for the plasma parameters with a known energy loss q_r on them. For example, if the main contribution comes from line radiation and the surface of the plasma core can be taken to be the radiating surface (this holds at $r_\ell \gtrsim 0.1$ cm in contrast to the quasi-volume loss [10] at $r_\ell \lesssim 0.03$ cm), then in practical units $q_{rd} = 0.06n^{2/15}(r_\ell)T_\ell^{3/8}$. The substitution of $q - q_{rd}$ into (3.3) and the substitutions $9\alpha + 1 \approx 9\alpha$, $T_\ell^{9/4} \approx T_\ell^2$ lead to

$$T_l^2=\frac{(B^2+2Dq_l)^{1/2}-B}{D},\quad B=\frac{2{,}8\varepsilon_l a\gamma_\alpha^{1/4}\theta_l^{1/2}}{[1{,}67A(d^2+d)r_l]^{1/2}},\quad D=\frac{0{,}13n^{2/15}(r_l)}{T_l^{1/5}}\approx\text{const.}$$

4. Radiation Spot Elongated in One Direction. Suppose that the width of such a spot is y_ℓ. The model of a two-dimensional expansion is built as in Sec. 3. If the plasma boundary is at a distance $x_f < y_\ell$ from the target, the model of two-dimensional expansion is applicable. At $x_f > y_\ell$ cylindrical expansion occurs, in which the plasma is transilluminated at the time $t_c/t_l = \exp\{(7\alpha-5)\theta_l/[11-\alpha-3(3-\alpha)\delta]\}$. This occurs later than in the case of spherical expansion (3.2) because of the weaker effect of the lateral flow of the plasma. At $\delta = 1\times$ $(\theta_\ell \approx 0.3)$ and $\alpha = 1.2$-1.7 we obtain $t_c/t_\ell = 1.3$-1.4. Transillumination of the plasma should, as in the case of spherical expansion, result in oscillations of the plasma parameters. But they should be less distinct and should have a longer period than that for a round laser-radiation spot of the same size. The parameters of the plasma core are determined by (3.3) and the density differs slightly from (3.49: $n(y_\ell) \approx 1.3n(r_\ell)$. For the peripheral layers we have the distribution

$$n(r,\ t)=n(y_l)y_l/r,\ Z(r,\ t)=Z_l-\gamma^{-1}\ln(r/y_l).$$

The energy loss for plasma radiation is taken into account, as in Point 3, by replacing q_ℓ by $q_\ell - q_r$.

5. Second Version of the Model. One more version of the model can be constructed if an adiabatic equation different from (1.2) is used. To define it we write the specific internal energy of the plasma in the form $\varepsilon = I_\beta Z^{1+\alpha}[3/2 + \beta/(1+\alpha)]/m$ and we find the heat capacities at constant volume c_V or constant pressure c_p. They are proportional to Z, but their ratio remains constant:

$$\gamma_a=c_p/c_V=[5(1+\alpha)+2\beta]/[3(1+\alpha)+2\beta].$$

Although an ionizable plasma is not an ideal gas in the classical sense, many expressions for an ideal gas do hold. Thus,

$$T=\text{const}\,\rho^{\gamma_a-1},\quad \varepsilon=p/((\gamma_a-1)\rho),\quad w=\gamma_a p/((\gamma_a-1)\rho) \tag{5.1}$$

(w is the specific enthalpy and ρ is the density). The expression $p \sim \rho^{(\alpha\gamma_a+\gamma_a-1)/\alpha}$ however, does differ from the usual expression $p \sim \rho^{\gamma_a}$, although not by much, while $\varepsilon \sim \rho^{(\alpha+1)(\gamma_a-1)/\alpha}$ does differ substantially from $\varepsilon \sim \rho^{\gamma_a - 1}$. The use of (5.1) instead of (1.2), after some simplifications of the coefficients, leads to the space–time distribution

$$Z(\xi,t)=Z_m(t)(1-\xi^2)^{1/(\alpha+1)},\ n(\xi,t)=n_m(t)(1-\xi^2)^{\gamma_b/(1+\alpha)},\ \gamma_b=\alpha/(\gamma_a-1),$$

$$Z_m(t)=\left(\frac{mx_f}{\gamma_b I_\beta}\frac{d^2x_f}{dt^2}\right)^{1/(\alpha+1)},\quad n_m(t)=\left(\frac{4\gamma_b}{\pi}\right)^{1/4}\frac{\nu_l I_\beta^{3/4}\theta_l^{1/2}}{(\varkappa_1 x_f)^{1/2}Z_m^{3(2-\alpha)/4}}.$$

The equation of a two-dimensional expansion is written as

$$x_f^{1/2}\left(x_f\frac{d^2x_f}{dt^2}\right)^{(7\alpha-2)/(4\alpha+4)}\left[\frac{3}{2\beta}+\frac{1}{1+\alpha}+\frac{(dx_f/dt)^2}{2\beta x_f d^2x_f/dt^2}\right]=b_2(W_l-W_r),$$
$$b_2=(\varkappa_1/\theta_l)^{1/2}\left(\gamma_b^{8\alpha-1}I_\beta^{-9}m^{2-7\alpha}\right)^{1/(4\alpha+4)}/(\pi^{1/4}\beta\nu_l). \tag{5.2}$$

Then (5.2) is solved in much the same way as in Sec. 2. The solution does not differ markedly (to within the accuracy of the model) from formulas (2.1)-(2.4). The discussion for two-dimensional expansion virtually agrees with that in Secs. 3 and 4.

In summary, the proposed theoretical model makes it possible to find simple expressions for the parameters of a laser plasma expanding in a vacuum over a wide range of parameters of the laser radiation and the target material.

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