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МОДЕЛЬ МЕХАНІЗМУ ГАЛЬМІВНОГО ПОГЛИНАННЯ ЛАЗЕРНОГО ВИПРОМІНЮВАННЯ

Проведена теоретична і експериментальна робота з встановлення параметрів плазми при наносекундній тривалості лазерного імпульсу та умові існування розвинутого газодинамічного руху плазми. Авторами отримано розв'язок задачі з опису поглинання лазерного випромінювання в щільному шарі гарячої плазми. Авторами встановлено аналітичні залежності, які досить добре відповідають реальним умовам і визначають геометричну і аналітичну товщини плазми. Ці результати співпадають з строгим розв'язком газодинамічних рівнянь для процесу випаровування у "самоузгодженому" режимі. В реальних умовах при фокусуванні випромінювання сильне бокове розширення плазми призводить до квазісферичного характеру розльоту і густина плазми зменшується значно швидше, ніж в одновимірному випадку. Автори порівняли вирази для внутрішньої енергії плазми і оцінили час переходу плоскої течії в двовимірну. Це дало змогу виявити, що як у випадку плоскої течії, так і у випадку двовимірної течії внутрішня енергія плазми зростає за схожими законами.

Ключові слова: *плазма, режим плазми, фокусування, випромінювання, густина плазми, одномірна та двомірна течії плазми.*

Yu. Zhiguts, V. Rudj

MODEL OF MECHANISM OF BRAKING LASER RADIATION ABSORPTION

Theoretical and experimental work was carried out on establishing the parameters of the plasma with a nanosecond duration of the laser pulse and the condition of the existence of the developed gas-dynamic movement of the plasma. The authors obtained a solution to the problem of describing the absorption of laser radiation in a dense layer of hot plasma. The authors have established analytical dependencies that correspond quite well to real conditions and determine the geometric and analytical thickness of the plasma. These results cooperate with the rigorous solution of the gas-dynamic equations for the evaporation process in the "self-consistent" regime. In real conditions, when the radiation is focused, the strong lateral expansion of the plasma leads to the quasi-spherical nature of the spread and the plasma density decreases much faster than in the one-dimensional case. The authors compared the expressions for the internal energy and estimated the transition time of a planar flow into a two-dimensional one. This made it possible to discover that both in the case of a planar flow and in the case of a two-dimensional flow, the internal energy of the plasma grows according to similar laws.

Keywords: *plasma, plasma regime, focusing, radiation, plasma density, one-dimensional and two-dimensional plasma flow.*

Introduction. The unique properties of laser radiation: coherence, high pulse power, and small angular divergence make it relatively easy to focus optical systems while obtaining extremely high power densities. The first studies of the effect of such a laser on the surface gave an unexpected result - the kinetic energy of the emitted components at a laser power of up to 10^6 W was hundreds of electron volts. Most laser-plasma parameters depend nonlinearly on the power density of laser radiation. On the other hand, the idea of heating a substance to thermonuclear temperatures by laser radiation [1-4] stimulated a number of analytical studies of plasma associated with high-intensity irradiation of condensed substances [5-11].

The aim of the study. Develop analytical dependencies to establish the main plasma parameters (density, thickness, and others), and compare them with those calculated by the rigorous solution of gas-dynamic equations and with practical data. Assess the adequacy and appropriateness of the developed analytical dependencies.

Formulation of the problem. In modern plasma physics, the problem of estimating the main plasma parameters occupies an important place. Therefore, the study of a simplified method of their definition acquires relevant and significant importance. The results of this problem can be used in the laser deposition of films to obtain soft X-ray mirrors and gratings.

Theoretical and practical studies. Consider the case when the vaporized substance is ionized to a large extent. At the same time, the steam begins to intensively absorb laser radiation, which leads to an increase in the temperature of the substance and significantly affects the dynamics of the entire process. Since, in the considered case, the times for establishing thermodynamic equilibrium in a dense hot plasma are significantly shorter than the characteristic duration of a laser pulse, the radiation absorption coefficient can be calculated on the basis of the equilibrium theory in a highly ionized absorption gas.

That is, it is mainly determined by transitions in the continuous energy spectrum of electrons with their simultaneous scattering in the Coulomb field of ions. Absorption occurs both due to free-free and due to free-bound transitions (bremsstrahlung and photoeffect). The problem is solved entirely by the quantum mechanical method only for a water-like system. Assuming a Maxwellian distribution of electrons according to velocities with temperature T, it is possible to obtain an expression for the bremsstrahlung absorption coefficient [12] (Kramer-Heisenberg's formula):

$$K_v = \frac{4}{3}\left[\frac{2\pi}{3mkT}\right]^{\frac{1}{2}} \frac{z^2 e^6}{hcmv^2} N_t N_e, \tag{1}$$

where Z is the nuclear charge of the hydrogen-like system.

Taking forced reradiation into account, relation (1) takes the form:

$$K_v = \frac{4}{3}\left(\frac{2\pi}{3kt}\right)^{\frac{1}{2}} \text{x} \frac{e^6 (Z-1)\hat{Z}N_0^2}{hcm^{\frac{3}{2}}v^3}\left(e^{\frac{kv}{kT}} - 1\right), \tag{2}$$

where N_0 is the initial density of atoms, and Z is the average charge of plasma ions.

The value $\frac{hV}{kT}$ at h7 kT can serve as an estimate of the share of the contribution to the absorption coefficient of free-bound transitions in relation to free-free ones. In this case, the absorption coefficient will look like this:

$$K_v = 1{,}75 \cdot 10^{-2} \cdot \frac{r(\hat{Z}-1)\hat{Z}N_0^2}{v^2 T^{3/2}}, \tag{3}$$

For a weakly ionized gas, the interaction of an electron with radiation is mainly carried out in the field of a neutral atom or molecule. In this case, the absorption coefficient will be expressed

$$K_v = 3{,}2 - 10^{-39}(\lambda, mkm)^2 \cdot (kt, eV)^{\frac{1}{2}} \cdot n_0 \cdot n_{e,} \tag{4}$$

With a nanosecond duration of the laser pulse, the condition for the existence of developed gas-dynamic plasma motion is fulfilled. The characteristic time of its acceleration during evaporation from the surface is 10^{-10} s, and formally the problem can be described by the system of gas-dynamic equations (5)-(8) [11]:

$$\frac{d\rho}{dt} + \frac{d}{dz}(\rho v) = 0, \tag{5}$$

$$\frac{dv}{dt} + \text{v}\frac{dv}{dx} = 0, \tag{6}$$

$$\frac{d}{dt}\left(\rho c - \rho\frac{v^2}{2}\right) = \frac{d}{dx}\left[\rho v\left(c + \frac{v^2}{2} + \frac{P}{\rho}\right) - q\right], \tag{7}$$

$$q(z,t) = q_0 \, exp\left[-\int_x^{\infty} K(z`,t)dz`\right] \tag{8}$$

Consider the behaviour of the integral under the sign of the exponent of the system equation (9):

$$I = \int_x^{\infty} K\langle z',t\rangle \; dz'^1. \tag{9}$$

In this formulation of the problem, expression (3) describes the absorption of laser radiation in a dense layer of hot plasma. Let the initial optical thickness of the layer be small and a significant part of the light flux reaches the surface. At the same time, as a result of intensive evaporation, the vapor density increases. Therefore, according to (5), the optical thickness also increases. Conversely, if the initial optical thickness is large, the evaporation rate will decrease and the energy of the laser radiation will be spent on heating the plasma, and this, together with the gas-dynamic expansion, will lead to a decrease in the optical thickness and a subsequent increase in the evaporation rate. Thus, there must be some optimal optical thickness of the plasma heated by laser radiation. This indicates the existence of a stable asymptotic behavior of the plasma generated by laser radiation near the surface of a dense substance, i.e. the so-called "self-consistent regime". In this mode, the value:

$$I = \int_0^{\infty} K\langle z`\rangle dz` \quad = 1. \tag{10}$$

Though that the system (5)-(9) in the general case, taking into account the absorption in pairs, can be solved only by numerical methods, under the above assumptions it is possible to obtain an analytical solution that corresponds quite well to real conditions. Let's write the absorption coefficient (3) in a slightly different form:

$$K = K_0 \rho^{\alpha} c^{\beta}, \tag{11}$$

where ρ is the density, c is the internal energy, proportional to T.

The geometric thickness of the plasma is equal to the speed of sound multiplied by time t.

The geometric thickness of the plasma is equal to the speed of sound $c = [(\xi - 1)7c]^{1/2} \sim c^{\frac{1}{2}}$ multiplied by time t. For the optical thickness, we get the ratio:

$$K\rho^{\alpha} c^{\beta - 1/2} t = 1, \tag{12}$$

from the law of conservation of energy we obtain

$$M\ (c + v^2/2) = q_0 t, \tag{13}$$

Considering $M = c^{\frac{1}{2}} \rho t$, from (12) and (13), it follows:

$$c = \ (k_0 t q^{\alpha})^{2/(3\alpha - 2\beta - 1)}, \tag{14}$$

$$\rho = \left[(k_0 t)^3 q^{2\beta - 1}\right]^{-1/(3\alpha - 2\beta - 1)}, \tag{15}$$

$$M = \left(k_0^{-2} q_0^{\alpha - 2\beta - 1}\ \ t^{3\alpha - 2\beta - 2}\right)^{1/(3\alpha - 2\beta - 1)}, \tag{16}$$

In the case of fully ionized gas α=2, β=-2/2:

$$c = k_0^{1/4} q_0^{1/2} t^{1/4}, \tag{17}$$

$$\rho = k^{-3/9} t^{-3/8} q^{1/4}, \tag{18}$$

$$M = k_0^{-1/4} q_0^{1/2} t^{3/4}, \tag{19}$$

These results, obtained by relatively simple considerations, coincide with the strict solution of gas-dynamic equations (5)-(8) for the evaporation process in the "self-consistent" regime.

However, from simple physical markings, it is clear that in real conditions when radiation is focused, the strong lateral expansion of the plasma leads to a quasi-spherical spread, as a result of which the plasma density decreases much faster than in the one-dimensional case. The outer region of the plasma clot will be transparent to radiation, which will be absorbed only in a surface layer of the order of the focusing spot size, where the motion will be close to one-dimensional. In general, the problem is two-dimensional and its solution presents significant mathematical difficulties. Therefore, a one-dimensional spherical model was investigated in [13], which corresponds well to evaporation when radiation is focused on the surface. In this case, there is also a self-consistent mode of evaporation. However, the constancy of the optical thickness refers already to a layer of fixed thickness r_0:

$$K\ (\rho, e) r_0 = 1, \tag{20}$$

The solution of the system of gas-dynamic equations (5)-(8) within the one-dimensional spherical model for a fully ionized gas has the following form:

$$t = 0{,}45 K_0^{2/9} r_0^{2/3} Q^{1/9}, \tag{21}$$

$$\rho = 0{,}53 K_0^{1/4} r_0^{-1} Q^{1/3}, \tag{22}$$

$$M = 1{,}1 K_0^{2/9} r_0^{2/3} Q^{5/9} t, \tag{23}$$

where Q is the total radiation flux.

By comparing the expressions for internal energy in formulas (5)-(8), it is possible to estimate the time t' of the transition of a planar flow into a two-dimensional flow:

$$t` = K_0^{-1/9} r_0^{8/9} q_0^{-2/9}, \tag{24}$$

As can be seen from (5)-(8), both in the case of a planar flow and in the case of a two-dimensional flow, the internal energy of the plasma increases according to similar laws of $c \sim q^{1/2}$ and $c \sim q^{4/9}$. However, in the case of a two-dimensional flow, the internal energy also depends on the focusing conditions.

Conclusions. The authors obtained a solution to the problem of describing the absorption of laser radiation in a dense layer of hot plasma in the form of analytical dependencies and determining the geometric and analytical thickness of the plasma. These results coincide with the rigorous solution of the gas-dynamic equations for the evaporation process in the "self-consistent" regime. The authors compared the expressions for the internal energy and estimated the transition time of the planar flow to the two-dimensional flow. This made it possible to discover that both for the planar flow and for the two-dimensional flow the internal energy of the plasma increases according to similar laws.

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