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INTERACTION OF LASER RADIATION WITH MATTER. LASER PLASMA

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Energy transfer in a volume-structured medium

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***Abstract*. A study was made of the physical properties of the so-called foam – a low-density (the average density is ~ 1 μg cm^{-3}) microstructured medium. Foams of different type were classified according to the specific features of their internal structure. The propagation of high-power laser radiation through these media was considered and the relationships for the depth of radiation penetration for differently structured foams were obtained. Based on a self-similar solution describing the expansion of a film (filament) with its simultaneous heating by the law $T = At^{\alpha}$, a model of the heat propagation through a porous medium was proposed and a relationship for the hydrothermal wave velocity $v_{ht} = [4K/\alpha(\alpha + 2)]^{1/2} c_T$ was obtained (c_T is the isothermal sound velocity in the bulk of the heated material and K is a constant determined in the context of the model). The hydrothermal wave velocity was shown to be substantially determined by the processes occurring on a foam microstructure scale. The velocity dependence on the parameters of these processes was analysed within the framework of the proposed model.**

***Keywords*:** *smoothing of ununiformity of laser target irradiation, microstructured medium (foam), hydrothermal wave velocity*.

Providing a large degree of compression uniformity of nuclear fuel-bearing targets is crucial to inertial confinement fusion (ICF). This problem is especially pressing for direct-drive targets (DDTs). At present, there are two main approaches to the solution of this problem. The first involves the development of special techniques of optical smoothing, such as induced spatial incoherence (ISI) [1], smoothing by spectral dispersion (SSD) [2], etc., with the aim of improving the uniformity of laser target irradiation. An alternate approach is the development of target designs optimal as regards employing the thermal smoothing in the energy transfer from the region of absorption of the laser radiation (LR) to the ablation region owing to the electron heat transfer (see, e. g., Refs [3 – 5]).

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The use of a low-power LR prepulse with a high degree of uniformity of DDT irradiation to produce a plasma cloud around the target was proposed in Ref. [3]. Then, by the time of arrival of the main pulse, the region of energy release would be separated from the ablation surface by a distance Δ and the smoothing of the nonuniformity $\delta I/I$ of target irradiation would take place due to the electron thermal conduction. The degree of smoothing is determined by the characteristic spatial nonuniformity wavelength $\lambda_{\perp}$: $\delta p/p \approx \delta I/I \exp(-2\pi\Delta/\lambda_{\perp})$, where p and δp are the pressure and its variation caused by the intensity variation δI.

The prepulse-assisted thermal smoothing was experimentally demonstrated in Ref. [4]. A disadvantage of this technique is that a very high degree of irradiation uniformity should be provided during the action of a LR prepulse on the target. Otherwise the irradiation nonuniformities would be 'imprinted' on the target and would set the stage for the efficient development of gas dynamic instabilities.

From this point of view the employment of an additional thick-layered outer shell made of a material with about a critical density holds more promise for smoothing the nonuniformities. As shown by the calculations of Ref. [6], it is possible to select the parameters of this layer (the initial density ρ_f and the layer thickness Δ_f) in such a way that, on the one hand, there should be no reduction of the hydrodynamic efficiency, and on the other hand, the existence of a spacing between the region of energy release and the ablation region $\Delta \sim \Delta_f$ at the onset of the laser pulse would favour a more efficient thermal smoothing of the irradiation nonuniformities. This is the reason why great interest has been expressed by researchers in the use of materials of this kind (see, e. g., Refs [7 – 9]).

The materials with a very low density mentioned above are microstructured media made of randomly oriented polymer fibres or thin films of solid-state density separated by vacuum gaps. In the general case, this 'foam' may consist of both fibre and film fragments. The average density of a porous medium (foam) ρ_f may vary over a wide range, depending on the characteristic spacing d and the fibre (film) thickness. For a foam dominated by filamentary structures, the average density is

$$\rho_f = \rho_0 \pi \left(\frac{d_0}{d}\right)^2, \qquad (1)$$

where d is the average distance between the fibres; d_0 is the average fibre thickness; and ρ_0 is the fibre density.

In foams produced primarily by film fragments, the latter will evidently form three-dimensional polyhedrons of

an arbitrary configuration. The cavities bounded by such polyhedrons can be either closed or in communication with each other. Generally speaking, a foam can contain variously configured cavities of different size. However, in the consideration of a foam of a film structure we will proceed from the average characteristics of the porous medium: specifically, the foam will be assumed to contain pores with some characteristic radius R_0 in which the openings occupy a relative area p (the case where $p \to 0$ corresponds to the situation of closed pores). The average density of a porous structure

$$\rho_f = 3\rho_0 w(1-p)/R_0\,, \tag{2}$$

where w is the density of a pore wall.

The LR transfer in a porous medium was investigated in several experimental and theoretical papers (see, e.g., Refs [10, 11]). The propagation of LR in a foam depends substantially on its internal structure, and the propagation will therefore be considered starting from the proposed classification of the porous media. As will be seen from the subsequent discussion, the knowledge of only the average foam density proves to be insufficient and the specific feature of its structure should also be taken into account. For a foam of purely filamentary structure, the LR propagation length is determined by the geometrical shadow produced by the fibres in the bulk of the material:

$$l = \frac{d^2}{d_0 k}, \tag{3}$$

where k is the average absorption coefficient for the LR incident on a fibre.

The penetration of LR into a porous medium with closed pores is limited by the non-vaporised surfaces of the pore walls. In a foam with open pores, the situation is different: by multiple internal reflection (which is typical for the absorption of high-power radiation with a wavelength of the order of 1 μm), the LR can propagate through the holes in the pore walls to relatively large depths. To estimate the depth of its penetration into the foam in this case, we consider a single pore. Let the LR with an energy E_L be delivered to the pore through the holes. Then, assuming that E_L is fairly uniformly distributed over the internal surface of the pore, we conclude that a fraction pE_L of this energy will escape through the holes immediately and a fraction $(1-p)kE_L$ will be absorbed. Accordingly, an energy $(1-p)(1-k)pE_L$ will leave through the holes after the first reflection, etc. Summing over the members of this series gives an estimate of the LR energy emerging from the pore:

$$E = E_L p \sum_{n=0}^{\infty} (1-p)^n (1-k)^n = \frac{pE_L}{1-(1-p)(1-k)}. \tag{4}$$

One can see from (4) that upon the multiple internal reflection of the LR from the internal surface of the pore walls, the fraction E_L that escapes absorption by the walls, can be quite large (it proves to be out of proportion to the area of the holes in an averaged elementary cell). Assuming that the absorption occurs over a distance $2R_0$ and that half the unabsorbed energy E_L is reflected backwards after multiple internal reflection, we obtain the LR penetration depth

$$l = R_0 \frac{1-(1-p)(1-k)}{k(1-p)}. \tag{5}$$

Note that for small absorption coefficients k, the length l can substantially exceed the pore diameter, whereas in the case of closed pores, it is evident that $l \approx 2R_0$.

Let us estimate the depth of LR penetration into foams with a different internal structure and an average density $\rho_f \approx 5$ μg cm^{-3}. In a foam consisting of fibres of thickness $d_0 = 1.2$ μm spaced at $d = 30$ μm, $l = 1.5 \times 10^3$ μm for $k \leqslant 1$, according to formula (3). For a rather 'porous' foam with a relative area of the holes $p = 0.5$, the depth is $l \approx 45$ μm for pore diameters $d = 2R_0 = 30$ μm and a wall thickness $w = 0.05$ μm. Accordingly, for a foam consisting closed pores, l is still lower and is evidently equal to the pore diameter: $l \approx d \approx 30$ μm. Therefore, the internal foam structure significantly affects the LR penetration depth.

The heat is transferred from the region of intense absorption of the high-power LR to the bulk of a colder material. The transfer of thermal energy in a homogeneous material has been much studied to date (see, e.g., Ref. [12]). In the initial stage of laser irradiation, the velocity of propagation of the thermal wave (TW) exceeds the sound velocity, and the material motion can be neglected at this stage. The velocity of the thermal wave decreases during its propagation, and at some point in time t_0 the shock wave catches up with the thermal one. Thereafter the gas dynamic motion should be taken into account to describe the heat transfer.

Let us estimate the characteristic time t_0. According to Ref. [10], the velocity of the TW front propagation through an immobile material for a fixed LR intensity Q_0 is

$$v_{hw} \approx \frac{7}{9}\kappa_0^{2/9} \frac{Q_L^{5/9}}{(c_V\rho)^{7/9}} \frac{1}{t^{2/9}}, \tag{6}$$

where κ_0 is the thermal conductivity coefficient; c_V is the heat capacity of the material; and Q_L is the LR intensity. Equating v_{hw} to the sound velocity gives

$$t_0 \approx \left(\frac{7}{9}\right)^3 \frac{Q_L \kappa_0}{[c_V(\gamma-1)]^{1/2}(c_V\rho)^2}. \tag{7}$$

It follows from Eqn (7) that the time t_0 depends rather strongly on the material density. For instance, for $Q_L \approx 10^{14} - 10^{15}$ W cm^{-2} and a material density $\rho_f \sim 1$ μg cm^{-3}, $t_0 = 20 - 200$ ns, which far exceeds the typical LR pulse duration in ICF experiments. To estimate t_0, we adopted a plastic-like material with parameters $\gamma = c_p/c_V = 5/3$, $c_V = 7.8 \times 10^7$ J g^{-1} K^{-1}, $\kappa_0 = 7.9 \times 10^{-11}$ W cm^{-1} K$^{-7/2}$. Therefore, in the range of LR pulse duration ($\tau_L \sim 1$ ns) of interest and for homogeneous media with densities corresponding to the average foam density, the energy transfer is supersonic.

However, the heat transfer in porous materials differs from that in a homogeneous medium. Initially, there occurs the heating of the foam media by the LR (through its penetration depth) and then the heat transfer is effected by the expanding plasma of the heated material volume. In this case, the heating takes place in the so-called hydrothermal wave mode, when the cold material is heated in contact with a hot low-density plasma. In Ref. [13], the propagation of a hydrothermal wave through a porous medium was studied under the assumption that its velocity was constant and equal to the local sound velocity in the medium. It is our belief that the processes occurring on the foam microstructure scale should essentially affect the velocity of a hydro-

thermal wave. In this connection the aim of our consideration is to establish the dependence of the wave velocity on the parameters describing the microdynamics of the material.

During the foam heating, the films (or fibres) of the cold material heat up and expand on contact with the hot low-density plasma, which acts as a thermal reservoir and does not exert any noticeable effect on the film (fibre) expansion dynamics owing to its extremely low density. We assume, on these grounds, that the gas-dynamic film (fibre) expansion takes place autonomously and the expanding material heats up in the process. In view of the latter circumstance, the microdynamics of the foam heating cannot be described in the context of the model of adiabatic or isothermal expansion of its microstructure components. Nevertheless, the description of the microdynamics of the wall (fibre) expansion proves to be possible by taking advantage of the self-similar solution that represents the gas dynamic film (fibre) expansion with its simultaneous heating by the $T(t) = At^{\alpha}$ law. In the case of a plane, cylindrical, or spherical geometry of the problem (i. e., in the expansion of a plane wall, fibre, or sphere), the material expansion takes place with a linear profile of the mass material velocity and a characteristic Gaussian density profile [14]:

$$\rho(x,t) = \left[\frac{\alpha(\alpha+2)}{4\pi}\right]^{n/2} \frac{M}{R^n(t)} \exp\left[-\frac{\alpha(\alpha+2)}{4}\xi^2\right], \qquad (8)$$

where $\xi = x/R(t)$ is the self-simulated variable; $R(t) = [(\gamma - 1)c_V T(t)]^{1/2} t$ is the characteristic spatial scale; $n = 1$, 2, or 3 respectively for a plane, cylindrical, or spherical geometry of the problem. The energy of the expanding material is

$$E(t) = Mc_V T(t)\left(1 + \frac{\gamma-1}{2}\frac{\alpha+2}{\alpha}\frac{n}{2}\right). \qquad (9)$$

To analyse the heat transfer, we will use the following model: the porous medium is represented as a multitude of thin plane parallel walls of a material of solid-state density and thickness w spaced at a distance d (Fig. 1). This porous medium is heated by high-power LR. When the hot rarefied plasma reaches a cold wall, the latter heats up (by the heat accumulated in the volume of the hot material) and begins to dump in response to this heating. Neglecting the inertial action of the incident plasma (because of its low density), we assume that the expansion of the material wall takes place according to the law given by expression (8).

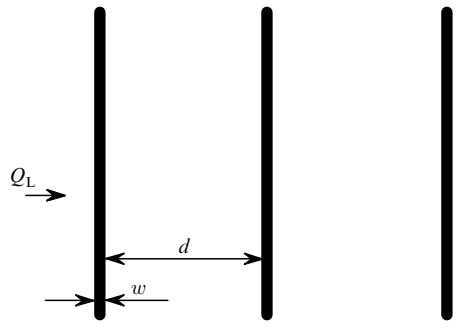

Figure 1. One-dimensional model, which represents the foam as a set of plane-parallel films, employed in the gas dynamic calculations.

Expression (8) defines a very steep density profile, and a relatively well-defined instant of the 'onset' of heat conduction is therefore bound to exist. Therefore, the time t_* it takes a hydrothermal wave to travel a distance d can be determined from the relationship

$$\frac{\alpha(\alpha+2)}{4}\frac{d^2}{R^2(t_*)} = K, \qquad (10)$$

where K is a constant. Then, the velocity of propagation of a hydrothermal wave is

$$v_{\mathrm{ht}} = \frac{d}{t_*} = \left[\frac{4K(\gamma-1)}{\alpha(\alpha+2)} c_V \bar{A}\right]^{\frac{1}{\alpha+2}} d^{\frac{\alpha}{\alpha+2}}, \qquad (11)$$

where $\bar{A}$ is the average atomic weight (atomic number) of the particles in the foam.

A number of calculations of the dynamics of heating porous media were performed in the context of the model proposed above. The thickness of the plane films w was taken to be equal to 0.05 μm and their separation was set to $d = 30$ μm. A hydrocarbon with a solid-state density $\rho = 1$ g cm^{-3} (the average density $\rho_{\mathrm{f}} \approx 1.7$ mg cm^{-3}), an atomic number $\bar{A} = 6.5$, an average charge $Z = 3.5$, and $\gamma = 5/3$ was selected as the film material. The electron and ion heat capacities in this plasma are as follows: $c_{V_{\mathrm{e}}} = 7.8 \times 10^7$ J K^{-1} g^{-1}, $c_{V_{\mathrm{i}}} = 2.2 \times 10^7$ J K^{-1} g^{-1}.

The system was exposed to high-power LR with an intensity $Q_{\mathrm{L}} = 1.45 \times 10^{13}$ W cm^{-2} and a wavelength $\lambda = 1.315$ μm (the critical density for this wavelength is $\rho_{\mathrm{cr}} \approx 2$ mg cm^{-3}). The calculations were conducted in the framework of a one-dimensional two-temperature gas dynamic model with the inclusion of thermal conduction and LR absorption. At the instant the plasma of heated material layers filled the free space to the next layer, a new material layer was added. Each material layer contained 150 Lagrangian points.

The results of gas-dynamic calculations in the context of so simple a model allow an understanding of the principal processes occurring when a foam material is heated by high-power LR. Figs 2 and 3 show the profiles of the density, the velocity, the electron and ion temperatures after the impact of the first material layer on the second one. The times it takes the hydrothermal wave to travel from the second layer to the third one and from the third one to the fourth are virtually the same and equal to 40 ps. One can see the regions of self-similar motion [the density is described by expression (8)], which form early in time after the commencement of heating each successive layer of material. The regions of self-similar flow are separated by the shock waves that originate after the discontinuity decay at the instant the plasma stream strikes a cold dense wall: a weak shock wave originates in the cold dense material of the pore wall, which does not lead to noticeable compression or heating, whereas a strong shock wave originates in the incident rarefied plasma, resulting in the heating of ions up to a temperature of ~ 10 keV.

One can see from Figs 2 and 3 that the region of ion heating advances beyond the domain enclosed by the shock waves due to the ion thermal conduction for such ion temperatures. For material densities of the order of the average plasma density, the electron–ion relaxation times far exceed the time it takes a hydrothermal wave to travel from one material layer to another:

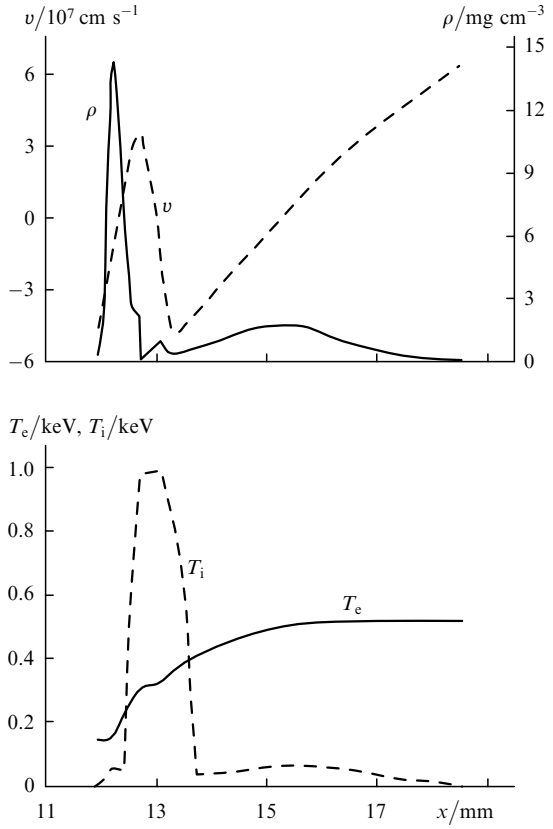

Figure 2. Density (ρ), velocity (v), ion (T_i) and electron (T_e) temperature profiles within $\Delta t = 11$ ps after the first layer strikes the second one.

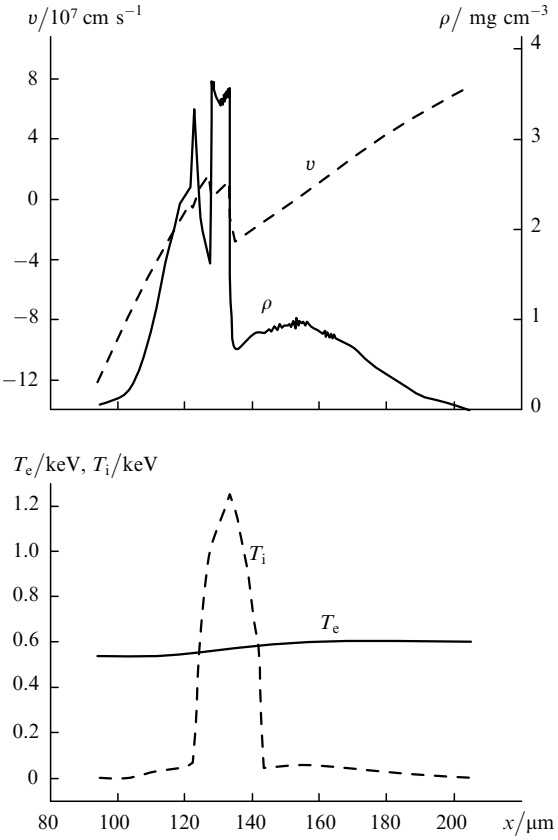

Figure 3. Density (ρ), velocity (v), ion (T_i) and electron (T_e) temperature profiles within $\Delta t = 39$ ps after the first layer strikes the second one.

$$\tau_{ei} = 45\frac{\bar{A}T_e^{3/2}}{Z^3\rho\Lambda_{ei}} \approx 500\,\text{ps},$$

where T_e is expressed in kiloelectronvolts, ρ in g cm^{-3}, and τ_{ei} in picoseconds; Λ_{ei} is the Coulomb logarithm.

Hence, the regions of higher ion temperature will exist in the plasma for some time after the passage of a hydrothermal wave. We emphasise that the origination of shock waves and the consequential formation of hot-ion domains when a foam material is exposed to high-power LR is caused by the foam structure. In particular, no appreciable ion heating is observed in the calculations where the pores are filled with a material with a density comparable to the average foam density.

Thus, one can see from Figs 2 and 3 that the microdynamics of the hydrothermal wave propagation through a porous medium can be described using the self-similar solution (8). In this case, however, the parameters A and α remain undefined. We will find them relying on the data of numerical calculations. To this end, we write, in addition to relationship (10), the condition for the energy balance (9) during the period of heating the next layer:

$$Q_L t_* = Mc_V A t_* \left(1 + \frac{\gamma - 1}{2}\frac{\alpha + 2}{2\alpha}\right). \tag{12}$$

Since the intensity of electron-ion heat exchange is low (the characteristic relaxation times τ_{ei} are long), the thermal capacity of the electron component should be used as the thermal capacity of the matter. The incident plasma stream heats the layer material to a temperature T_0, i.e., $T(t_*) = T_0 = At_*^{\alpha}$. Note that the entire thin material layer is assumed to heat up by the power law everywhere over the volume from the very beginning. This assumption involves in essence two assumptions: (i) the initial heating of the entire layer to some initial temperature (which is far lower than T_0) takes place in a time much shorter than t_*; (ii) subsequently there occurs a relatively uniform heating of the entire volume of the layer material.

The first assumption is legitimate for the length scale of the order of the layer thickness, which is easy to verify (see the estimates given in the foregoing text). The second assumption is justified for a time comparable with t_* (while the layer temperature is comparable with T_0). We extend it to all the instants of time since the commencement of layer heating. The legitimacy of this assumption is suggested by the characteristic self-similar flow profiles (8) formed in the calculations immediately after the beginning of the layer heating. We resolve expressions (9), (11), and $T(t_*) = T_0$ for A, α, and t_* to obtain

$$t_* = \frac{Mc_V T_0}{Q_L}\left(1 + \frac{\gamma - 1}{2}\frac{\alpha + 2}{2\alpha}\right), \tag{13}$$

$$A = T_0 \Big/ \left[\frac{Mc_V T_0}{Q_L}\left(1 + \frac{\gamma - 1}{2}\frac{\alpha + 2}{2\alpha}\right)\right]^{\alpha} \tag{14}$$

and the equation for determining the α parameter

$$\left(1 + \frac{\gamma - 1}{2}\frac{\alpha + 2}{2\alpha}\right)^2 = \frac{\alpha(\alpha + 2)}{4K(\gamma - 1)}b, \tag{15}$$

where the dimensionless parameter is

$$b = (Q_L d/M)^2/(c_V T_0)^3.$$

In the calculations, the moment at which the incident plasma collides with the pore wall is determined by the constant $K \approx 4.1$. For positive α, Eqn (15) has only one root. Substitution of the calculated K, Q_L, d, $M = 5$ μg cm^{-2}, and $T_0 \approx 0.5$ keV in formulas (13)–(15) gives $b = 127$. For the above values of these quantities, the root of Eqn (15) is $\alpha = 0.25$. This gives us the hydrothermal wave velocity $v_{ht} = 8.7 \times 10^7$ cm s^{-1}, whereas our gas dynamic calculations yield 7.5×10^7 cm s^{-1}.

Here, we do not analyse the mechanisms of heat exchange between the incident plasma stream and the pore wall. Referring to Fig. 2, a considerable volume of the near-wall plasma experiences cooling immediately after the plasma contact with the pore wall. This is indicative of a high intensity of the heat exchange between the plasma and the wall material, which exceeds the intensity of absorbed LR at the initial instants of time. Later, when the temperature of the pore wall material becomes comparable with the temperature of the plasma of the heated material volume, the intensity of the heat exchange falls off.

These two circumstances determined the parameter value $\alpha = 0.25$ obtained in our estimates (which is in essence some average over the whole time of heating and expansion of the wall). Note that the potential and kinetic energies of the expanding layer prove to be comparable for this α-parameter value [according to formula (9), the kinetic energy of the plane layer exceeds its internal energy by a factor of 1.5].

Relationship (11) can be recast to more compact and clear form if we introduce $c_T = [(\gamma - 1)c_V T_0]^{1/2} = [(\gamma - 1)c_V A t_*^{\alpha}]^{1/2}$ – the isothermal sound velocity in a heated material. We then obtain the hydrothermal wave velocity

$$v_{ht} = [4K/\alpha(\alpha + 2)]^{1/2} c_T.$$

Therefore, in our model the velocity of propagation of the hydrothermal wave from the source of high-power energy release in a porous medium is proportional to the isothermal sound velocity, with the proportionality factor far exceeding unity; i.e., the heat propagation in a foam is essentially supersonic.

The constant K was found from a fit to the calculated data. In reality, owing to the steepness of the density profile, account should be taken of the thermal flux limitation in the rarefied incident plasma stream. That is why the 'onset' of heat exchange with the pore wall governed by the K parameter will occur at quite a certain point in time, when the heat flux attains some threshold value.

Since the density profile in the incident plasma is Gaussian, the dependences of the K parameter on the temperature of the expanding layer, the heat flux due to the absorption of LR, and the characteristic dimension of the plasma layer at the instant of the 'onset' of thermal conduction will be logarithmic (i.e., very weak). Hence the K parameter can be treated as a constant in our model consideration. The gas dynamic calculations of foam heating with the inclusion of thermal flux limitation were also performed for the model considered above: it was assumed that the electron heat flux S cannot exceed

$$S_{lim} = f n_e (T_e/m_e)^{1/2} T, \qquad (16)$$

where $f = 0.1$; n_e is the electron density; and m_e is the electron mass.

The heat flux limitation permits calculating the hydrothermal wave propagation through a foam medium with a low-density filling of the inner pore volume (with a density of the material in the space far lower than the average foam density ρ_f). In this case, there is no appreciable heat exchange between the pore walls to the point of filling the inner pore space with the plasma.

In the calculation of material heating by high-power LR with the inclusion of heat flux limitation, the LR-absorption region (in a subcritical plasma) has a higher temperature than the adjacent higher-density plasma layers. As is easily seen, this kind of 'heat blocking' in the low-density plasma corona heated by LR is bound to occur up to coronal plasma temperatures $T_c \approx 1$ keV in the conditions of our calculations. In our calculations, the electron temperature proves to be lower than T_c throughout the time period under consideration. A consequence of this circumstance is that Q_L exceeds the heat flux transferred to the next material layer. For a near-wall plasma temperature $T_0 \approx 0.5$ keV, in particular, the limiting heat flux transferred to the pore wall is $S_{max} \approx 0.28 Q_L$.

Our calculations suggest that the heat flux limitation in the space between the pores acts throughout the period of heating of the next plasma layer. In this connection the heat transfer to the pore wall will be considered to obey formula (16) and the incident heat flux taken to be equal to S_{max} in order to find the K constant. We take advantage of the self-similar relationship (8) for the density ρ to obtain

$$K = \ln\left\{68 \frac{T^{3/2}}{S_{max}} \left[\frac{\alpha(\alpha + 2)}{4\pi}\right]^{1/2} \frac{d}{R(t_*)}\right\}. \qquad (17)$$

The first factor in the expression under the logarithm sign is a large number, and it is precisely this quantity that determines the K constant. The remaining two cofactors are two orders of magnitude lower and can therefore be discarded as small corrections. It follows that the K constant with a logarithmic accuracy is determined by the expression

$$K \approx 4.2 + \ln\left(T^{3/2}/S_{max}\right)$$

[here and in formula (17), T is expressed in kiloelectronvolts and S_{max} in W cm^{-2}]. In particular, for the case under consideration we have $K \approx 8.6$. To determine the α parameter and the hydrothermal wave velocity, we take advantage of formula (13) once again. In our case, $b = (S_{max} d/M)^2/(c_V T_0)^3 \approx 10$ and $\alpha \approx 1.36$. In the hydrodynamic calculation, the hydrothermal wave velocity determined by these values of K and α is $v_{ht} = 2.74 c_T \approx 4.5 \times 10^7$ cm s^{-1}; in our calculation, $v_{ht} = (4.3 - 5.5) \times 10^7$ cm s^{-1}. Note that the velocity of TW propagation through a homogeneous medium with an average density ρ_f will, after traversing a distance of 120 μm (which corresponds to four layers in our model), amount to 8.2×10^7 cm s^{-1}.

Therefore, the investigations carried out in this work allow us to draw the conclusion that, first, the heat propagation through a porous medium (foam) takes place much differently than through a homogeneous medium with a density equal to the average foam density. Second, the hydrothermal wave velocity is substantially determined by the processes occurring on the microstructure scale of a porous medium (in particular, the hydrothermal wave velocities in the above calculations with and without thermal flux limitation are significantly different).

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