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Low-density absorber–converter in direct-irradiation laser thermonuclear targets

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***Abstract*. A version of a thermonuclear target for direct irradiation by a laser pulse is proposed, which ensures a virtually arbitrary laser-to-soft X-ray radiation conversion efficiency. The key target element is the external spherical layer of a low-density composite material with a density close to the critical plasma density. The layer material is a porous medium of light elements (porous beryllium, porous plastics) with clusters of heavy elements (gold, copper) distributed inside it. This layer fulfils the dual function of absorbing laser radiation and converting the laser radiation to X-rays. A theory is developed to describe the plasma production and the generation of intrinsic radiation in composite materials of this kind irradiated by a high-power laser pulse. The efficiency of X-ray energy deposition for targets with a low-density absorber–converter is shown to be higher than for direct-irradiation targets with a solid converter and indirect-irradiation targets. Also discussed are the technological possibilities of producing low-density composite media containing clusters of heavy elements and having parameters that provide efficient operation of the absorber–converter in laser thermonuclear targets.**

Keywords: *laser thermonuclear fusion, interaction of laser radiation with matter, absorber – converter.*

1. Introduction

It is known that the conversion of the driver (laser or ion beams) energy to soft X-ray radiation energy is one of the most efficient ways of uniform heating of a spherical inertial-fusion target [1]. It is reasonable that, from an energy viewpoint, this technique should provide the highest possible driver-to-X-ray radiation energy conversion efficiency and the maximum energy utilisation efficiency of the generated X-ray radiation to compress and heat the fusion plasma.

The conversion efficiency achieved upon irradiation of a plane solid target by a laser pulse depends on the intensity and the wavelength of laser radiation, the target material and its thickness. The highest conversion efficiency is achieved with 'thick' targets, which are many times thicker than the ablation depth. The energy of a laser radiation beam is then converted to the unidirectional counter flux of intrinsic plasma radiation. In this case, the conversion efficiency increases with decreasing the laser wavelength. For wavelengths of 0.25 – 1.06 μm, the highest conversion efficiency was achieved for laser radiation intensities of 10^{14} – 10^{15} W cm^{-2} and amounted to 60 – 80 % of the laser output energy [1 – 3].

A special feature of the conversion of the 'thin' targets of thickness comparable with the ablation depth is that upon one-sided irradiation of these targets by a laser beam, bidirectional X-ray fluxes can be produced: the counter flux from the target surface under irradiation and the flux passing through the rear side of the target. However, because of the large losses due to the hydrodynamic motion of the material, the total conversion in 'thin' targets proves to be 2 – 3 times smaller than in 'thick' ones [4]. In this case, the fraction of energy of transmitted X-ray, which can generally be as high as 50 % of the total energy of the X-ray pulse for thin targets (fractions of a micrometer for gold foils), depends strongly on the target thickness.

For these reasons, the modern concept of an indirect-compression X-ray target (the so-called indirect target) involves a one-sided conversion of laser radiation to the counter X-ray radiation flux in a 'thick' target. An indirect-compression target contains two main elements: an external massive shell–converter (cylindrical [3] or spherical [5]) and a spherical fuel-bearing capsule inside it. The laser beams are injected into the converter through special openings and are focused on its inner surface, where the laser radiation is converted to the counter X-ray radiation flux.

Although this method of laser-to-X-ray radiation conversion provides a highly efficient and reliable conversion, it has several drawbacks. They stem primarily from the complexity of target irradiation procedure, which allows reducing the converter dimensions to only a certain limit. For instance, in an indirect-irradiation target designed for experiments on the National Ignition Facility (Lawrence Livermore National Laboratory, USA), the ratio between the area of the fusion capsule and the inner surface area of the converter is ~1:20, so that only 20 % of the X-ray radiation energy affects the thermonuclear capsule. For an expected conversion efficiency of 60 – 80 %, only 12 – 18 % of the laser energy will be utilised to heat and compress the working thermonuclear target.

That is why the search for reliable and efficient ways of converting laser radiation to the transmitted X-ray radiation flux acceptable for use with direct-irradiation thermonuclear targets is a task of exceptional importance for laser thermonuclear fusion (LTF).

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One of the lines of this search is based on the use of a low-density extended converter. Indeed, the conditions required for the efficient conversion of the internal energy of a heated body to the energy of thermal radiation are, first, the thermodynamically equilibrium state of radiation at which the free photon path is close to the smallest converter dimension, and, second, the smallness of energy losses due to the hydrodynamic motion of the material compared to the radiation loss.

For the plasma of heavy elements (gold, copper, and some other) at a temperature of several hundred electron-volts corresponding to the coronal temperature of a laser thermonuclear target, the condition of the thermodynamic radiation equilibrium in a plasma with dimensions close to the target dimensions is achieved for a material density of $10^{-2} - 10^{-1}$ g cm^{-3} [6]. This is well below the densities of the above materials in the normal state, but is higher than the critical plasma density, for instance, for the wavelength of a neodymium laser.

Due to the latter circumstance, in the case of a continuous material, the method of heating the converter by laser radiation, which would allow one to avoid significant energy losses caused by the hydrodynamic motion (which always appears upon absorption of laser radiation in a supercritical-density material due to ablation), remains uncertain.

In this paper, we present a physical substantiation of the employment of a composite material with a density of $\sim 10^{-3} - 5 \times 10^{-2}$ g cm^{-3} as the material for a low-density extended converter. This material is a porous medium of light elements with clusters of heavy elements distributed inside it [7]. The proposal to use such media as an efficient converter is based on modern studies [8–13]. According to these studies, laser radiation is efficiently absorbed in a porous material with a density several times the critical plasma density without significant excitation of hydrodynamic motion.

An important advantage of a composite converter is the possibility to change the laser-to-X-ray radiation conversion efficiency over a wide range by varying the relative content of heavy elements. A wide-range converter makes it possible to involve in the conversion not the entire laser energy incident on the target, but only that part of the energy which is required to smooth out the nonuniformity of target irradiation by the laser beams.

2. Generation of intrinsic radiation in a laser plasma of porous media

From the standpoint of the physics of LTF targets and the fabrication technology, porous polymers, porous beryllium, and porous beryllium hydride hold the greatest promise among the porous media of light elements. The technological methods of obtaining porous polymers with a density of $0.003 - 0.02$ g cm^{-3} [14, 15] and beryllium-based porous media with a density of $0.02 - 0.05$ g cm^{-3} have already been elaborated [16]. As shown below, the concentration of heavy elements in the composite material required for the efficient operation of the absorber–converter should provide a density of the heavy component in the range from 0.1 to 1 of the light-component density.

At present, the fabrication technology of solid-density composite materials with clusters of heavy elements in a wide range of their concentration, including copper-containing polymers [17] and beryllium with gold [16] is rather well developed. The fabrication of similar materials with a density of less than 0.06 g cm^{-3}, at comparable weight fractions of the light and heavy components is an intricate task. One of the lines of its solution is the use of beryllium hydride as the porous material [16]. Pilot samples of porous beryllium hydride have been fabricated, which contain distributed gold and copper clusters ranging from several tens to hundreds of angstroms in dimension.

Depending on the structure, the porous media are usually divided into two classes: foams (the structures with closed pores) and three-dimensional networks (the structures with open pores). Given a density ρ_0 of the solid pore elements and the average density ρ of the porous medium, and also assuming all the cells to be identical (with the edge size equal to a), we evaluate the second dimension b of the structure (the face thickness for foams or the fibre diameter for three-dimensional networks). It is equal to $a(\rho/\rho_0)$ for cubic closed cells and to $a(4\rho/3\pi\rho_0)^{1/2}$ for open cells, the number n of cells in a unit volume being equal to a^{-3}. The numerical coefficients in the above formulas are somewhat different for cells of different shapes, but the form of the functions remains invariable.

The porous structure of composite media is formed by solid particles, which are extended objects of a light material containing clusters of a heavy material of significantly smaller size. The clusters are nearly spherical in shape, their size d ranges from several tens to several hundreds of angstroms. The number of structure-forming elements per unit volume is

$$n_{\mathrm{f}} = \frac{\rho_{\mathrm{L}}}{\Omega_{\mathrm{s}}\rho_{\mathrm{L0}}}. \tag{1}$$

Here, ρ_{L0} and ρ_{L} are the density of the light material in the initial state and the average density of the light material in the medium; and Ω_{s} is the volume of a structure-forming element.

The technological methods of producing the porous materials under study involve foaming the composite material prepared in advance, and therefore the cluster distribution over the volume of structure-forming elements is uniform enough. Taking into account (1), the number of clusters per element is:

$$N_{\mathrm{c}} = \frac{3}{4\pi}\frac{\Omega_{\mathrm{s}}}{d^3}\frac{\rho_{\mathrm{H}}}{\rho_{\mathrm{H0}}}\frac{\rho_{\mathrm{L0}}}{\rho_{\mathrm{L}}}. \tag{2}$$

Here, ρ_{H0} and ρ_{H} are the density of the cluster material in the initial state and the average density of the heavy material in the medium, respectively. The average densities of the medium and the composite material of the solid element are

$$\rho_{\mathrm{a}} = \rho_{\mathrm{L}}\left(1 + \frac{\rho_{\mathrm{H}}}{\rho_{\mathrm{L}}}\right), \quad \rho_{\mathrm{s0}} = \rho_{\mathrm{L0}}\left(1 + \frac{\rho_{\mathrm{H}}}{\rho_{\mathrm{L}}}\right), \tag{3}$$

respectively. It follows from (2) that the cluster separation in a solid element is:

$$\Delta_{\mathrm{c}} \approx \left(\frac{\Omega_{\mathrm{s}}}{N_{\mathrm{c}}}\right)^{1/3} = d\left(\frac{4\pi}{3}\frac{\rho_{\mathrm{H0}}}{\rho_{\mathrm{L0}}}\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{H}}}\right)^{1/3}. \tag{4}$$

As an example, consider the parameters of porous beryllium containing gold clusters. For the average medium density $\rho_a = 10^{-2}$ g cm^{-3}, dimensions of a structure-forming element $a = 50$ μm and $b = 1$ μm, and a cluster dimension $d = 0.01$ μm, the parameters of a solid element of the composite porous medium are as follows. For equal densities of beryllium and gold $\rho_H/\rho_L = 1$, the element density of the light material elements (beryllium) is $n_f \sim 10^6$ cm^{-3}, the number of clusters in a structure-forming element is $N_f \sim 2 \times 10^8$, and the average cluster separation is $\Delta_c \sim 0.025$ μm. For the density ratio $\rho_H/\rho_L = 0.1$, we have $n_f \sim 2 \times 10^6$ cm^{-3}, $N_f \sim 4 \times 10^7$, and $\Delta_c \sim 0.05$ μm.

According to expression (4), in the 0.1–1 range of variation of the heavy-to-light material density of interest to us, the separation between the clusters of the heavy material in a structure-forming element of the composite porous material does not exceed four–six cluster dimensions, i.e., it is no greater than 0.1 μm. Hence, we can assume that the laser radiation with wavelengths down to the near-UV range will interact with such a composite solid element of the porous medium as with a continuous material having the average density $\rho_{s0} = \rho_{L0}(1 + \rho_H/\rho_L)$ in the initial state.

To date, several important results have been obtained in the field of laser radiation interaction with a porous material. The high (80 – 90 %) absorption efficiency was experimentally recorded for the laser radiation with wavelengths of 1.06 and 0.53 μm and an intensity of $10^{14} - 10^{15}$ W cm^{-2} in a porous material with a density of 0.001 – 0.02 g cm^{-3} close to the critical plasma density and exceeding it [10, 12]. The high absorption coefficients in a supercritical-density porous material are explained by a rather long homogenisation period (several nanoseconds) during which there exist stochastically distributed subcritical-density domains in the plasma [8, 13]. As a result, the radiation is absorbed in a volume at the so-called geometrical transparency depth L_a of a partially homogenised material (measured in centimetres):

$$L_a \approx 15b\left(\frac{\rho_{s0}}{\rho_a}\right)^{1/2}. \qquad (5)$$

For the above wavelengths and intensities of laser radiation, the penetration depth of the laser radiation in a porous material with a density of $10^{-3} - 10^{-2}$ g cm^{-3} and with structure-forming elements of small size $b \sim 0.5 - 1$ μm lies in the range between 600 and 150 μm. Another important feature of the interaction of laser radiation with a porous material is that no intense external hydrodynamic material flows are produced during the long initial interaction phase, whose duration is close to the period of total homogenisation of the porous material [9, 11, 12]. Up to the moment of completion of the homogenisation of the porous material, the major part of the absorbed laser energy is likely to represent the energy of colliding internal flows and shock waves.

Finally, note the high rate of transfer of the absorbed laser energy in a porous medium. The velocity of the energy transport wave measured in Refs [9, 12] for the porous media of light elements with a density of $10^{-3} - 10^{-2}$ g cm^{-3} was $(2 - 1) \times 10^7$ cm s^{-1} and that for porous media of the same density containing copper powder distributed inside it was $(5 - 2) \times 10^7$ cm s^{-1}.

Consider the action of laser radiation with an intensity $I \leqslant \lambda^{-2} 10^{14}$ W cm^{-2} (the wavelength λ is measured in micrometres) on the layer of a porous two-component material with densities of the light component ρ_L and the heavy component ρ_H. Under these conditions, the results outlined above allow us to formulate the model for the laser plasma of a composite porous material and for the generation of intrinsic radiation.

The radiation is absorbed over the geometrical transparency depth (5), its absorption by an individual structure-forming element taking place due to the inverse bremsstrahlung, without generation of fast electrons. In the initial stage of plasma production there occurs a medium homogenisation, which is accompanied by the transformation of the energy of hydrodynamic flows and shock waves, which appear upon heating and expansion of solid elements of the porous material, to the thermal plasma energy, as well as by the energy transfer between the ions of light and heavy components of the medium. This results in the production of a quasi-homogeneous plasma with a uniform distribution of the ions of heavy and light components and a uniform temperature distribution.

In the context of our approximate model, we will not take into account the effects of macrohomogenisation of the structure-forming elements and the microhomogenisation of the heavy and light components of the material on the radiative plasma properties. This approximation is justified for the following reasons. The clusters of the heavy component responsible for the radiative processes are heated under laser irradiation and expand within the solid element of the light component to retain for some time a high density ($\sim 10 - 20$ g cm^{-3}) close to their initial density. This time is the time of cluster expansion over a distance of several initial cluster dimensions and is equal to 0.2 – 0.5 ps. The expansion time of a structure-forming element during which the heated clusters of the heavy component retain a relatively high density close to the density of the light component (~ 1 g cm^{-3}) is 5 – 10 ps.

In this paper, we study the physics of an absorber–converter for high-gain thermonuclear targets to which there corresponds a laser pulse no less than 5 – 10 ns in duration. The lifetime of dense heated clusters of the heavy component is negligible compared to this duration. Because most of the absorbed laser energy during the homogenisation stage is in the form of energy of plasma density macro-oscillations, the average plasma temperature will be low (no higher than several tens of electronvolts [8, 12]) until the kinetic energy of chaotic material flows transforms to the thermal energy. In addition, the duration of the homogenisation stage is far shorter than that of the laser pulse.

In the general case, the description of the radiative properties of a multicomponent high-temperature plasma is an intricate problem whose solution involves numerical simulations. However, in the context of the problem under study, when the material is a two-component medium with the light component only insignificantly exceeding the heavy one in density, we can use an approximate approach to the calculation of the radiation paths. Indeed, the emissive power of a material is

$$J \propto n_e \sum Z_{ki}^2 n_{ki},$$

where Z_{ki} and n_{ki} are the charge and the density of the ions of the kth medium component, respectively; and n_e is the electron density.

The temperature of a laser plasma produced when a material is subjected to laser irradiation at an intensity of $10^{13} - 10^{15}$ W cm^{-2} ranges from several hundred to several thousand electron volts. At such temperatures, light elements are completely ionised, whereas the ion multiplicities of heavy elements, such as gold, are equal to 20–30. Under these conditions, we may approximately assume that the sum $\sum Z_{ki}^2 n_{ki}$ for the two-component material with the ratio $\rho_H/\rho_L \leqslant 1/4$ is determined by the charge and the density of the ions of the heavy component of the medium.

Therefore, the argument of the dependence of the radiation path on the degree of ionisation and the density of the two-component medium with the parameters under consideration is the product of two factors:

$$n_e \sum \left(Z_H^2 n_{Hi} + Z_L^2 n_{Li}\right) \approx \frac{n_e}{n_{Hi}} (Z_H n_{Hi})^2$$

$$= \left[Z_H \left(1 + \frac{Z_L}{Z_H} \frac{\mu_H}{\mu_L} \frac{\rho_H}{\rho_L}\right)\right] (Z_H n_{Hi})^2 .$$

The second factor contains only the parameters related to the heavy component of the medium (the ion multiplicity Z_H and the ion density n_{Hi}), while the first one takes into account the contribution of ionisation of the atoms of the light component the medium to the total number of plasma electrons.

With an 'ionisation' argument of this form, we can approximately calculate the radiation path in a two-component medium by using the known approximate expressions for the radiation paths for several heavy materials corrected to take into account the electron density of the composite medium. The simplest approximation formula is a power law $L = L_* T^n/\rho^m$. We proceed from a formula of this kind and retain a ratio of 2 between the exponents with which the factors containing the degree of ionisation of the heavy component and the correction for the degree of ionisation of the light component appear in the 'ionisation' argument. The expression for the radiation path in the two-component medium can then be written as

$$L_r \approx L_* \frac{T^n}{\rho_H^m} \left(1 + \frac{Z_L}{Z_H} \frac{\mu_H}{\mu_L} \frac{\rho_L}{\rho_H}\right)^{-m/2} . \quad (6)$$

Here, $Z_{H,L}$ and $\mu_{H,L}$ are the charge and the atomic weight of the ions of the heavy- and light-element materials, respectively. We consider gold as the heavy material with the approximation parameters $L_* = 10^{-2}$, $n = 5/2$, $m = 3/2$ [6].

We will analyse the conversion of laser radiation in a low-density absorber–converter of an LTF target by using the energy balance equation for the spherical layer of the two-component plasma, which is heated uniformly over its thickness by a laser pulse incident on its outer surface:

$$\left[\frac{(1+\alpha)K_B}{m_p(\gamma-1)} \left(\frac{Z_H}{\mu_H} \rho_H + \frac{Z_L}{\mu_L} \rho_L\right) T + \beta(\chi)\sigma T^4\right] \Omega$$

$$+ \frac{c}{4} \beta(\chi)\sigma T^4 (S_i + S_e)\tau = I S_e \tau , \quad (7)$$

Here, T is the plasma temperature; K_B is the Boltzmann constant; m_p is the proton mass; γ is the adiabatic index; $\sigma = 1.37 \times 10^{14}$ erg cm^{-3} keV^{-4}; c is the velocity of light; I and τ are the intensity and duration of the laser pulse; $\Omega = S_e^{3/2}[1 - (S_i/S_e)^{3/2}]/3(4\pi)^{3/2}$ is the converter volume; $S_e = 4\pi R_e^2$ and $S_i = 4\pi R_i^2$ are the outer and inner converter surface areas; $\beta = 2\chi$ for $\chi \leqslant 1/2$; $\beta = 1$ for $\chi \geqslant 1/2$; $\chi = \Delta/L_r$; L_r is the Rosseland photon path; $\Delta = R_e - R_i$ is the converter thickness; α is the hydrodynamic-to-thermal energy ratio. According to the self-similar solution for the isothermal expansion of a material of a finite mass [18], during the action of the energy source this ratio can be written in the form $\alpha = 3(\gamma - 1)(\nu + 1)/2$ for plane, cylindrical, or spherical geometries of the problem ($\nu = 0, 1, 2$).

The total conversion and the conversion to the transmitted flux are described by the formulas:

$$\eta = \frac{1}{4} \frac{c\beta(\chi)\sigma T^4}{I} \left(1 + \frac{S_i}{S_e}\right)$$

$$\equiv \frac{1}{4} \frac{c\beta(\chi)\sigma T^4}{I} \left[1 + \left(1 - \frac{\Delta}{R_e}\right)^2\right], \quad (8)$$

$$\eta_f = \eta \left(1 + \frac{S_e}{S_i}\right)^{-1} \equiv \eta \left(1 - \frac{\Delta}{R_e}\right)^2 \left[1 + \left(1 - \frac{\Delta}{R_e}\right)^2\right]^{-1} . \quad (9)$$

Eqn (7) describes the conversion of laser radiation energy absorbed in the converter (the right-hand side of the equation) to the energy contained inside the converter (the first term in the left-hand side of the equation), including the thermal ion and electron energies, the hydrodynamic energy of the material, and also to the energy of thermal radiation which escapes the converter (the second term in the left-hand side of the equation).

Note that the approximation of a uniformly heated converter substance, which was used in deriving expression (7), assumes rapid energy transfer, at which the thermal wave heats the converter over its entire thickness for the time shorter than the laser pulse duration: $\Delta/V_E < \tau$. We will show below that the range of the optimal thickness of the converter is $\sim 200 - 800$ μm. For energy transfer rates $V_E \sim (2 - 5) \times 10^7$ cm s^{-1}(see above), the uniformly heated converter approximation, with the above thickness, is valid for laser pulses of duration no less than 2–3 ns, i.e., it is valid for the conditions of the problem under study.

3. 'Equilibrium' converter of a composite porous medium

A necessary condition for a high efficiency of conversion of the plasma energy to the energy of intrinsic radiation is the equilibrium radiation state, and therefore we first of all determine the parameters and investigate the radiative properties of an optically dense converter with a thickness exceeding L_r: $2\Delta > L_r$. We will assume the converter to be thin compared to the target radius: $\Delta < R_e$. Under these conditions, Eqn (7) takes the form

$$\left[\frac{2K_B}{m_p(\gamma-1)} \left(\frac{Z_H}{\mu_H} \rho_H + \frac{Z_L}{\mu_L} \rho_L\right) T + \beta(\chi)\sigma T^4\right] \frac{\Delta}{\tau}$$

$$+ \frac{c}{2} \beta(\chi)\sigma T^4 = I. \quad (10)$$

In accordance with the definition of conversion efficiency (8), it is easy to obtain the following expression for the temperature of a geometrically thin 'equilibrium' converter:

$$T_* = \left(\frac{2I}{c\sigma\beta(\chi)}\right)^{1/4} \eta^{1/4} . \quad (11)$$

It follows from (11) that the plasma temperature of an 'equilibrium' converter depends only slightly on the conversion efficiency. In the case of an optically dense converter ($\beta = 1$), which corresponds to a high conversion efficiency ($\eta \sim 1$),

$$T_* = \left(\frac{2I}{c\sigma}\right)^{1/4} \approx 0.148 I_{14}^{1/4}. \quad (12)$$

Here, T_* is measured in kiloelectronvolts and I_{14} is the laser radiation intensity measured in units of 10^{14} W cm^{-2}. When the intensity is varied in the $10^{14} - 10^{15}$ W cm^{-2} range, the plasma temperature of an 'equilibrium' converter varies between 125 and 240 eV.

According to expressions (6) for the radiation path and (12) for the converter temperature, the condition for an optically dense converter has the form

$$\rho \frac{\rho_H}{\rho_L}\left(1+\frac{\rho_H}{\rho_L}\right)^{-1}\left(1+\frac{\mu_H}{Z_H}\frac{Z_L}{\mu_L}\frac{\rho_L}{\rho_H}\right)^{1/2} > \frac{I_{14}^{5/12}}{\Delta^{2/3}}\, 4\cdot 10^{-4} \text{ g cm}^{-3}, \quad (13)$$

where the converter thickness is measured in centimetres. Furthermore, by comparing the items in the first term of Eqn (10) and using expression (12) for the plasma temperature of an 'equilibrium' converter, one can readily see that the energy inside the converter resides primarily in the form of a 'material' energy if

$$\rho \frac{\rho_H}{\rho_L}\left(1+\frac{\rho_H}{\rho_L}\right)^{-1}\left(1+\frac{\mu_H}{Z_H}\frac{Z_L}{\mu_L}\frac{\rho_L}{\rho_H}\right) > I_{14}^{3/4}\, 2.3\cdot 10^{-3} \text{ g cm}^{-3}. \quad (14)$$

Otherwise, for an opposite sign in expression (14), it is in the form of radiative energy.

As a specific example of the converter material, we consider porous beryllium hydride BeH_2 containing gold clusters. In this case, we assume for the calculations that $Z_L/\mu_L = 1/2$ and $Z/\mu = 1/8$. For this composite material, when the densities of the light and heavy converter components are equal ($\rho_H/\rho_L = 1$), the condition for an optically dense converter of thickness, say, $\Delta = 500$ μm for a laser radiation intensity $I = 10^{14}$ W cm^{-2} is fulfilled for $\rho > 1.5 \times 10^{-3}$ g cm^{-3}. For $I = 10^{15}$ W cm^{-2}, this condition is fulfilled for $\rho > 4 \times 10^{-3}$ g cm^{-3}. For $I = 10^{14}$ W $\times$cm^{-2}, the condition that the 'material' energy exceeds the radiant energy in an 'equilibrium' converter is fulfilled for $\rho > 5 \times 10^{-4}$ g cm^{-3} and for $I = 10^{15}$ W cm^{-2} for $\rho > 2.5 \times 10^{-3}$ g cm^{-3}.

Therefore, the state of the laser plasma of a composite porous material with a density varying over a wide range, whose lower bound is close to $\rho \sim 10^{-3}$ g cm^{-3}, and a thickness is close to the absorption depth for the radiation of a neodymium laser and its harmonics, corresponds to the equilibrium state of the intrinsic plasma radiation. In this case, a characteristic feature of the distribution of internal plasma energy is that the 'material' energy significantly exceeds the radiative one.

Consider the conversion efficiency of a relatively dense composite material with a density exceeding the limit specified above, bearing in mind that the radiation path decreases sharply with plasma density. That is why the possibility of designing a more compact converter involves the use of a converter material with a relatively high density. By neglecting the radiative component of the internal energy of the converter in Eqn (10) and using relation (11), we obtain the equation for the determination of the conversion efficiency of a relatively dense and geometrically thin converter depending on the converter and laser pulse parameters:

$$\varphi \frac{\rho\Delta}{\tau I_{14}^{3/4}}\eta^{1/4} + \eta = 1. \quad (15)$$

Here, the laser pulse duration τ is measured in nanoseconds, ρ – in g cm^{-3}, Δ – in cm, and

$$\varphi = 4.2\times 10^2\left(\frac{Z_H}{\mu_H}+\frac{Z_L}{\mu_L}\frac{\rho_L}{\rho_H}\right)\left(1+\frac{\rho_L}{\rho_H}\right)^{-1}.$$

It follows from Eqn (15) that a nearly 100 % efficiency of conversion of laser radiation to the intrinsic plasma radiation in a converter of porous beryllium with an equal-weight content of gold clusters takes place when

$$\rho\Delta < \tau I_{14}^{3/4} 7\times 10^{-3} \text{ g cm}^{-2}. \quad (16)$$

According to (16), the optical thickness $\rho\Delta$ of an efficient beryllium converter with an equal-weight content of gold clusters should not exceed $\sim 10^{-2}$ g cm^{-2} for nanosecond laser pulses with an intensity of $10^{14} - 10^{15}$ W cm^{-2}. For the converter thickness of several hundred micrometres, a converter density of $10^{-3} - 10^{-2}$ g cm^{-3}, which provides efficient absorption of laser radiation, satisfies this condition with a large safety margin.

4. Efficiency of conversion by a porous composite absorber

Now let us find the range of variation of the parameters of a porous composite converter which corresponds to different laser-to-X-ray radiation conversion regimes and calculate the conversion efficiency for a specific laser pulse whose parameters are close to those of the output pulse of future megajoule laser facilities. The calculations were performed for a converter of porous beryllium with an equal-weight content of gold clusters and a 5-ns neodymium laser pulse with an intensity of 10^{14} W cm^{-2}.

Fig. 1 shows the regions of converter parameters corresponding to different laser-to-X-ray radiation conversion regimes calculated on the basis of Eqn (10). Curve *1* corresponds to the equality of the converter layer thickness and the absorption depth of laser radiation in the porous medium, $\Delta = L_a$. The absorption depth was calculated by formula (5) taking into account expressions (3) for the densities of the composite converter with a small dimension of the structure-forming element $b = 1$ μm. Curve *2* corresponds to the equality of a doubled converter thickness and the radiation path length calculated for a plasma temperature of the 'equilibrium' converter (12).

In the region above curve *2*, where $\chi = \Delta/L_r > 1/2$, the converter radiation can be treated as equilibrium with an effective temperature equal to T_*. In the domain below curve *2*, the ratio $\chi = \Delta/L_r < 1/2$ and the radiation is not equilibrium, its effective temperature is lower than the

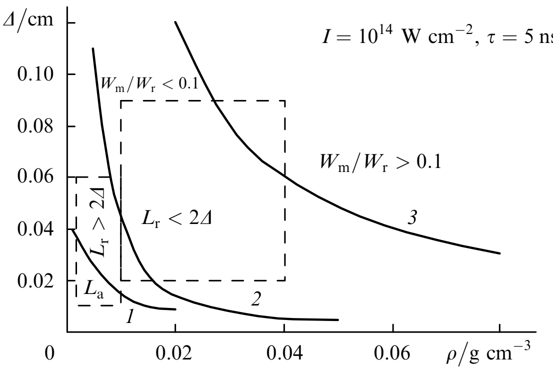

Figure 1. Regions of converter parameters corresponding to different regimes of conversion of laser radiation to the intrinsic plasma radiation: (*1*) converter layer thickness is equal to the depth of laser radiation absorption $\varDelta = L_a$; (*2*) boundary of the region of an optically dense converter; (*3*) ratio between the material energy W_m and the energy converted to the flux of intrinsic plasma radiation W_r is equal to 0.1.

plasma temperature. The parameter domain located above curve *3* corresponds to a ratio $W_m/W_r > 0.1$ between the material energy (thermal and hydrodynamic) and the energy converted to the flux of intrinsic plasma radiation. The parameter domain located below this line corresponds to a ratio $W_m/W_r < 0.1$.

An analysis of the data given in Fig. 1 allows one to determine the boundaries of two characteristic parameter domains for a porous composite converter which correspond to different regimes of laser-to-X-ray radiation conversion. The first parameter domain ($10^{-2} < \rho < 4 \times 10^{-2}$ g cm^{-3}, $0.02 < \varDelta < 0.1$ cm) corresponds to a high laser-to-X-ray radiation conversion efficiency of no less than 0.9. This parameter domain corresponds to the equilibrium radiation of an optically dense converter plasma.

The increase in the density and thickness of the converter compared to the upper boundaries of the regions results in the decrease in the conversion degree due to the increase in the thermal and hydrodynamic energy of the converter material. The decrease in the density and thickness of the converter compared to the lower boundaries of the regions reduces the conversion degree due to the increase in the converter transparency. Note that the excess of the converter thickness over the absorption depth of laser radiation in this region of parameters should not strongly affect the dynamics and degree of conversion because the radiative heat conductivity in an optically dense plasma results in a rapid transfer of the absorbed laser energy over the entire converter mass.

The second region with parameters $10^{-3} < \rho < 10^{-2}$ g cm^{-3}, $0.01 < \varDelta < 0.06$ cm lies outside the region of optically dense plasma and corresponds to a lower conversion efficiency, which may vary within wide limits under changes of the converter parameters.

Fig. 2 gives the total conversion efficiency (8) calculated on the basis of Eqn (10) for the above parameters of the laser pulse as a function of the converter thickness for different average densities of porous beryllium with an equal-weight content of gold $\rho_a = 5 \times 10^{-3}$, 10^{-2}, and 5×10^{-2} g cm^{-3}. For a converter thickness above 500 μm, the conversion efficiency is high, over 0.8, and is weakly sensitive to density variations. For a converter thickness above 800–1000 μm, the conversion efficiency is close to unity. Below $\varDelta = 400 - 500$ μm, the conversion efficiency lowers as the converter thickness decreases, and the faster, the lower the converter material density. When the converter density and thickness are varied over the limits $5 \times 10^{-3} < \rho < 5 \times 10^{-2}$ g cm^{-3} and $200 < \varDelta < 400$ μm, the conversion efficiency varies from ~ 90 to ~ 60 %.

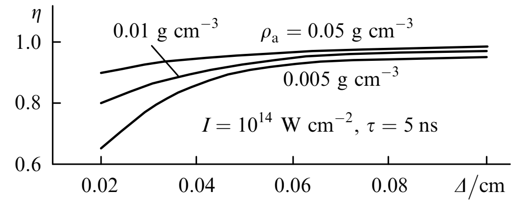

Figure 2. Dependences of the total conversion efficiency η on the thickness of a porous beryllium converter with an equal-weight gold content for different average converter densities ρ_a.

The results outlined above allow the following conclusion about the prospects of using thermonuclear targets with a low-density absorber–converter in ignition experiments. Spherical thermonuclear capsules with a radius of about 1 mm are contemplated for use in indirect-irradiation ignition experiments on the NIF facility [3]. According to the data of Fig. 1, the absorber–converter of porous beryllium with gold clusters which affords a high efficiency of conversion of laser radiation to the transmitted X-ray radiation flux should have a thickness smaller than the specified radius of the thermonuclear capsule for a density of no less than 10^{-2} g cm^{-3}. According to the data of Fig. 2, the absorber–converter with a density of 10^{-2} g cm^{-3} and a thickness of 600–800 μm is capable of providing total conversion, close to 100 %, and an efficiency of conversion to the transmitted X-ray radiation flux [see expression (9)] of about 30 %. For a simpler, direct irradiation method, this involves target exposure to laser pulses 2–3 times higher in energy than in the case of an indirect target.

5. Conclusions

Therefore, the use of a wide-range absorber–converter made of a composite material, which is a porous medium of light elements with clusters of heavy elements distributed inside it, allows the conditions of material compression in LTF targets to be varied over a wide range – from 'direct' compression to the 'indirect' one. In the latter case, this opens up the possibility to significantly reduce the laser radiation energy required for the ignition of the thermonuclear reaction.

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