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Two-dimensional energy transfer and plasma formation under laser beam irradiation of a subcritical-density material

S Yu Gus'kov, N V Zmitrenko, I V Popov, V B Rozanov, V F Tishkin

Abstract. Based on two-dimensional numerical simulations, a study was made of the radiation absorption, the energy transfer, and the plasma formation upon the interaction of a laser beam with a homogeneous medium consisting of light elements with a density not exceeding the critical plasma density, which corresponds to the plasma resonance for the wavelength of the driving laser radiation. The calculations were performed by the HEAT-3D code, which involved the solution of a two-dimensional heat conduction equation with an energy source describing the absorption of laser radiation due to inverse bremsstrahlung in the material. The simulations were performed of the interaction of laser beams of radii $10^{-2} - 6 \times 10^{-2}$ cm, $10^{14} - 5 \times 10^{15}$ W cm^{-2} in intensity, and with wavelengths of 1.053 and 0.527 μm with materials composed of light elements with densities of 1 – 10 mg cm^{-3}. An analysis of the simulations showed that the spatial temperature distribution of the resultant plasma is determined by the anisotropy of energy transfer. In its turn, the degree of anisotropy depends on the relation between the beam radius and the laser radiation absorption length, which is a function of the density and the temperature of the resultant plasma. The results of simulations are compared with the findings of experiments on laser irradiation of targets composed of low-density materials.

1. Introduction

The interest in the subject of our investigation is primarily due to the recent proposals to use low-density materials having a near-critical density in inertial confinement fusion targets. These proposals imply, in particular, employing these media as absorbers of the radiation of laser beams, which irradiate a spherical target, to smooth out the nonuniformity of the target heating [1, 2].

The smoothing effect of these media is associated with several factors. One of them is related to the bulk absorption of a laser beam over the inverse bremsstrahlung depth in a subcritical-density material [2, 3]. Compared to the case of a solid material, the radiation absorption in a subcritical-density material takes place in substantially larger volumes of the material, with the effect that the energy losses through hydrodynamic motion are relatively low [2].

Another significant circumstance is associated with the known fact that the propagation velocity of the front of the electron thermal conduction wave increases with a lowering of the density of the medium. As a consequence, when a material with a near-critical density is exposed to a beam of laser radiation with an intensity of $10^{14} - 10^{15}$ W cm^{-2}, the electron thermal conduction can provide a fast heat transfer (in several nanoseconds) through appreciable distances (several hundred micrometres) for the har-monics of Nd-laser radiation [2].

Here, we present and analyse the results of numerical solution, afforded by the HEAT-3D code [4], of a two-dimensional heat conduction equation for an immobile material with an energy source, which describes the inverse bremsstrahlung of the radiation of a laser beam of a given radius in a subcritical-density material composed of light elements. The calculations were performed for the laser beam parameters corresponding to the experiments with low-density media conducted in different laboratories: radiation energy $E_{\rm L} = 50 - 5000$ J, wavelengths $\lambda = 1.06$ and 0.527 μm, and radiation intensity $I_{\rm L} = 10^{14} - 5 \times 10^{15}$ W cm^{-2}. The density of the target material was varied from 1 to 10 mg cm^{-3}. Under the conditions being considered, the temperature of the plasma produced upon the exposure of a low-density homogeneous material to high-power fluxes of laser radiation proves to be rather high – above 1 keV. In this hot and low-density plasma, the time during which the thermal wave velocity exceeds the sound velocity is $t \leqslant \chi / c_V T$ (T is the plasma temperature; c_V and χ are the heat capacity and the thermal diffusivity of the plasma, respectively), amounts to 8 – 10 ns and exceeds the duration of the laser pulses under consideration, $\tau_{\rm L} = 1.1$ and 5 ns. This permits the heat transfer in this problem to be treated in the immobile material approximation.

The physics of the interaction of a laser beam with low-density media is extensively investigated in experiments pursued in different laboratories. Several experiments were conducted on gas media [5] and aerogels [5], but most of them were conducted on porous materials [5 – 10]. The physics of laser radiation absorption and the energy transfer are significantly different from those in homogeneous gas media. This distinction is primarily associated with the homogenisation of porous media, which accompanies the absorption of laser radiation and energy transfer inside them [3, 7, 9]. As a result, the energy transfer in such media is effected by a 'hydrothermal' wave [6, 7, 11, 12]. The propagation velocity of the front of this wave is close to the sound velocity while

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S Yu Gus'kov, V B Rozanov P N Lebedev Physics Institute, Russian Academy of Sciences, Leninskii prospekt 53, 117924 Moscow, Russia
N V Zmitrenko, I V Popov, V F Tishkin Institute of Mathematical Modeling, Russian Academy of Sciences, Miusskaya pl. 4a, 125047 Moscow, Russia

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the temperature distribution behind the front is nearly uniform.

In this work, a comparison is made between the results of numerical simulations and experiments on low-density media, including porous ones, because this comparison allows us to study the difference between energy transfer in a porous medium and the thermal conduction wave.

2. Formulation of the problem

The mathematical formulation of the problem is as follows. Consider a semi-infinite medium with density ρ at the surface of which the laser radiation intensity q_{L} is specified as a function of time in the range $0 \leqslant r \leqslant R_{\mathrm{L}}$. The laser radiation is transferred and absorbed along the normal to the medium surface xy over a depth equal to the inverse bremsstrahlung length [2]

$$L = 9.2 \times 10^{-8} \left(\frac{A}{Z} \right)^2 T^{3/2} \frac{1}{\rho^2 \lambda^2 Z} \ . \qquad (1)$$

Here, A and Z are the atomic number and the degree of ionisation of ions in the medium; T is the temperature of the resultant plasma in kiloelectronvolts; and λ is the laser radiation wavelength in centimetres.

The heat transfer along and across the direction of laser beam incidence on the medium is effected by the electron thermal conduction. The HEAT-3D code treats the three-dimensional heat conduction equation in a simply connected region in the Cartesian coordinate system

$$\rho c_V \frac{\partial T}{\partial t} = -\mathrm{div}\boldsymbol{W} + Q_{\mathrm{L}}, \qquad (2)$$

where Q_{L} is the source function;

$$\boldsymbol{W} = -\kappa \,\mathrm{grad} T \qquad (3)$$

is the heat flux vector; and $\kappa = 1.3 \times 10^{19} T^{5/2}/Z$ is the Spitzer electron heat conductivity in units of erg keV$^{-5/2}$ s^{-1} cm^{-1}.

The boundary condition

$$\left(-\kappa \frac{\partial T}{\partial \boldsymbol{n}} \right) \Bigg|_{\mathrm{S}} = 0 \qquad (4)$$

is prescribed at the boundary S of the simply connected region ($\boldsymbol{n}$ is the external normal to the surface S). The laser radiation absorption was modeled as follows:

$$Q_{\mathrm{L}} = I_{\mathrm{L}}/V_{\mathrm{L}} \,,$$

where V_{L} is the volume of the region of laser radiation absorption; $I_{\mathrm{L}} = I_0 \exp(-k_{\mathrm{L}} z)$ is the intensity of laser radiation; I_0 is the laser radiation intensity at the target surface; and $k_{\mathrm{L}} = L^{-1}$ is the absorption coefficient for the laser radiation. As applied to the problem under consideration, the volume was $V_{\mathrm{L}} = \pi R_{\mathrm{L}}^2 L$, the material was assumed to be fully ionised, $A \approx 7$, and $Z = 3.5$.

In the construction of a discrete model, the initial continuous region was replaced by a discrete grid, with triangle xy-plane partitioning and quadrangle zx-plane (or, which is the same, zy-plane) partitioning. The grid pitch may be nonuniform. Therefore, an elementary cell volume is a prism; the temperature, the density, and the heat conductivity are specified at the centre of the prism and the heat fluxes at its faces.

3. Results of simulations and discussion

The first series of calculations was performed for the conditions realised in the experiments conducted on the Nova Nd laser at the Lawrence Livermore National Laboratory [5]. In these experiments, the dynamics of energy transfer was studied in a plane target made of a porous agar-agar material with densities $\rho = 9$ and 4 mg cm^{-3} exposed to the beam of the second harmonic radiation of a Nd laser ($\lambda = 0.523$ μm). The laser pulse energy was $E_{\mathrm{L}} = 4200$ J and the pulse length $\tau_{\mathrm{L}} = 1.1$ ns; for a beam radius of $R_{\mathrm{L}} = 300$ μm, this provided an average irradiation intensity of about 1.5×10^{15} W cm^{-2}.

The method of stroboscopic x-ray photography was used to measure the time dependence of the coordinate of the plasma region with an electron temperature $T_{\mathrm{e}} \approx 800$ eV along the beam axis. The above coordinate was measured from the initial position of the illuminated target surface. Koch et al. [5] attempted to describe the experimental results using numerical calculations of the interaction of a laser beam (with the parameters corresponding to the experimental ones) with a homogeneous medium corresponding to agar-agar in chemical composition and to the experimentally studied targets in average density. The calculations were carried out employing a two-dimensional (cylindrical) version of the well-known LASNEX code. The code incorporates the computation of the hydrodynamic equations with inclusion of the electron thermal conduction, the transfer of intrinsic emission, the absorption of laser radiation, and other processes.

Koch et al. [5] presented the results of computations by the LASNEX code for the initial stage of the interaction, for the

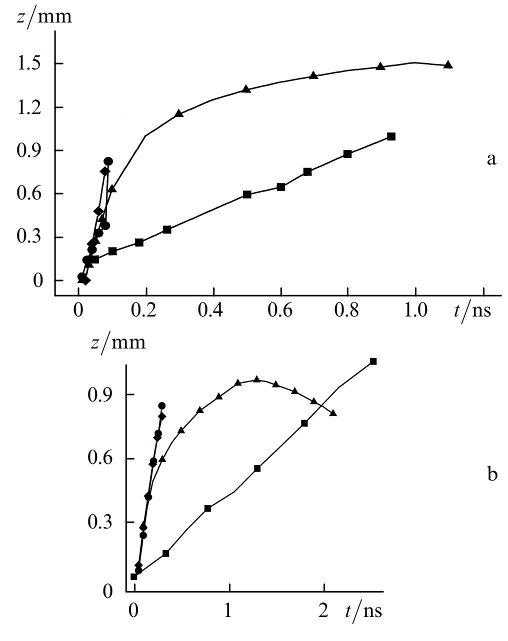

Figure 1. Time dependence of the dimension z of the region occupied by the plasma with a temperature $T_{\mathrm{e}} \geqslant 800$ eV measured from the initial location of the target surface in the direction of the beam axis for materials with densities $\rho = 4$ (a) and 9 mg cm^{-3} (b) in the experiments of Ref. [1] (■) and in the calculations by the LASNEX (●), HEAT-3D (▲), and DIANA (◆) codes.

$0 \leqslant t \leqslant 0.2$ ns time period. The results of computations given in Fig. 1 correspond to the location of the plas-ma region with $T_e \approx 800$ eV (as do the experimental data symbols).

First of all, an analysis of the results reported shows that energy transfer in a porous material proceeds, all other factors being equal, considerably slower (by a factor of 1.5 – 2) than in a homogeneous gas medium. The computations by the LASNEX and HEAT-3D codes yield close results in the time period for which the calculations by the LASNEX code were carried out. However, compared to the LASNEX computations, the HEAT-3D computations yield an earlier commencement of the reduction of heat transfer along the laser beam axis, which is associated with the effect of lateral heat spreading and the passage from a planar to two-dimensional propagation of the thermal conduction wave.

Moreover, the results of the LASNEX calculations agree well with the numerical calculations performed using the one-dimensional DIANA code (the code description is given in Ref. [13]). The latter are also shown in Fig. 1. The propagation of the thermal conduction wave described by the LASNEX code is one-dimensional in character even though the wave front travels a distance comparable with the diameter of the laser beam. This fact suggests that the solution obtained employing this code corresponds to a later manifestation of two-dimensional effects in comparison with the real situation.

As shown by the HEAT-3D simulations, at the initial stage of the process, for $t \leqslant 0.1 - 0.2$ ns, while heat propagates longitudinally (along the beam axis) through a distance of 600 – 800 µm, the dynamics of heat transfer corresponds to a plane wave of the electron thermal conduction. The plasma temperature at this stage of the process, when the lateral heat spreading does not reveal itself yet, turns out to be high, and therefore the depth of heat propagation is largely determined by the extent of the energy source caused by the absorption of laser radiation in the medium.

The energy transfer rate at the initial stage of the process is $(3 - 4) \times 10^8$ cm s^{-1}. The two-dimensional character of heat transfer in the gas medium is clearly demonstrated by the HEAT-3D calculations, beginning from the point in time $t = 0.2 - 0.3$ ns. From this point on, the velocity of the electron thermal conduction wave begins to fall off. By the time of termination of the laser pulse, the wave velocity is about 4×10^7 cm s^{-1} for the medium with a density $\rho = 4$ mg cm^{-3} and 2.5×10^7 cm s^{-1} for the medium with $\rho = 9$ mg cm^{-3}. As a result, the average (over the laser pulse duration) velocities of the electron thermal conduction wave are 1.5×10^8 cm s^{-1} for the gas medium with a density $\rho = 4$ mg cm^{-3} and 9×10^7 cm s^{-1} for the medium with $\rho = 9$ mg cm^{-3}.

The experimental average rates of energy transfer in porous media measured in Ref. [5] were 10^8 cm s^{-1} for the medium with a density $\rho = 4$ mg cm^{-3} and 4.5×10^7 cm s^{-1} for the medium with $\rho = 9$ mg cm^{-3}. Therefore, a comparison of the numerical HEAT-3D calculations with the experimental findings confirms the conclusions of Refs [6, 7, 11, 12] that the energy transfer in porous media is determined not by the electron thermal conduction but by the hydrodynamic process, which proceeds slower under these conditions.

Fig. 2 shows isotherms in the (z, R)-coordinates at the time $t = 1$ ns, close to the termination of the laser pulse, which were obtained by the HEAT-3D calculations for gas media with densities $\rho = 4$ and 9 mg cm^{-3}. Analysis of these data reveals a pronounced anisotropy of propagation of the electron thermal conduction wave for the lower-density gas medium. For a density $\rho = 4$ mg cm^{-3}, the dimension of the heated region in the direction of laser beam incidence far exceeds that in the lateral dimension. This is explained by the fact that the length of the inverse bremsstrahlung absorption in a subcritical plasma increases with decreasing plasma density [see formula (1)].

Fig. 2 also gives the positions of the fronts of the region of laser radiation absorption, which were determined as plasma regions where the laser radiation intensity is attenuated by a factor of e. For a density $\rho = 4$ mg cm^{-3}, the absorption depth is 450 µm and is close to the diameter of the laser beam, whereas for a density $\rho = 9$ mg cm^{-3}, this depth is equal to 150 µm.

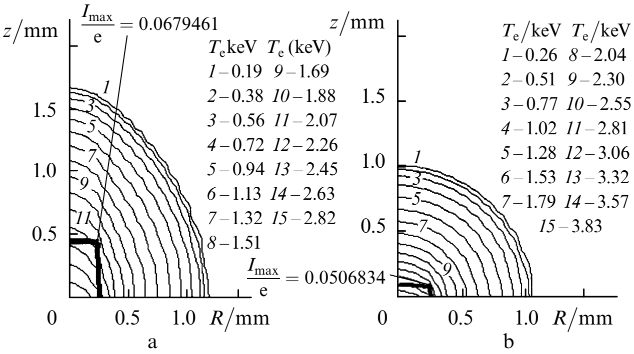

Figure 2. Isotherms in the (z, R) coordinates at the time $t = 1$ ns for the gas media with densities $\rho = 4$ (a) and 9 mg cm^{-3} (b).

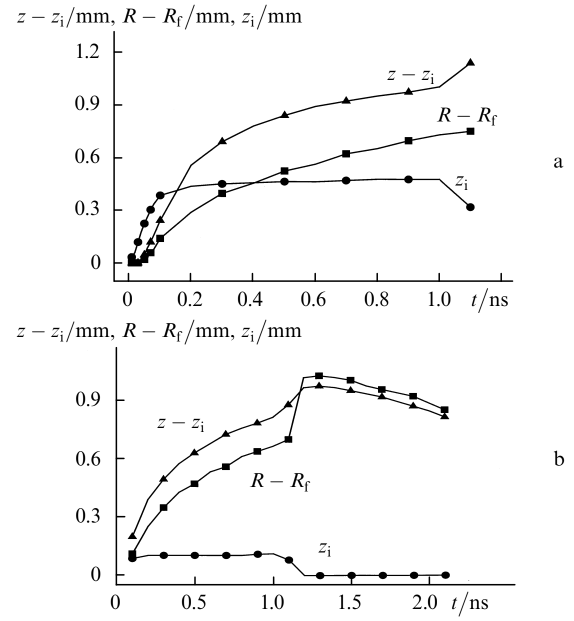

Figure 3. Time dependences of the longitudinal coordinate of the front of the laser radiation absorption region z_i and the dimensions of the heated plasma region in the longitudinal ($z - z_i$) and lateral ($R - R_f$) directions for $\rho = 4$ (a) and 9 mg cm^{-3} (b).

Fig. 3 depicts the time dependences of the longitudinal coordinate z_i of the front of the region of laser radiation absorption, where the laser radiation intensity drops by a factor of e. Also depicted are the dimensions of the heated plasma region in the longitudinal and lateral directions, which are defined respectively as the difference of the longitudinal coordinate of the thermal wave front and the coordinate of the absorption domain $z - z_{\rm i}$ and the difference of the radial coordinate of the thermal wave front and the radius of the focal spot of the laser beam $R - R_{\rm f}$.

The dynamic properties of the front propagation of the absorption region are similar for both of the medium densities. Initially ($t = 0.1 - 0.15$ ns), because of the increase in the temperature behind the wave front, the front of the absorption region propagates inward from the target surface. Then, up to $t = 1 - 1.2$ ns, it settles at a distance of ~ 100 μm from the irradiated target surface for $\rho = 9$ mg cm^{-3} and at ~ 450 μm for $\rho = 4$ mg cm^{-3}. The excess of the longitudinal velocity of thermal wave propagation over the radial one is greater in the case of a lower medium density. This is associated with stronger temperature gradients in the longi-tudinal direction, in particular, owing to a higher depth of the source action.

Consider now the results of simulations of the propagation of an electron thermal conduction wave through a homogeneous low-density medium upon irradiation of a target by the laser beam of the Mishen' facility. The HEAT-3D calculations were performed for medium densities $\rho = 0.5$ and 10 mg cm^{-3} and the following parameters of the laser beam: energy $E_{\rm L} = 100$ J, maximum intensity $I_{\rm m} \approx 5 \times 10^{13}$ W cm^{-2}, pulse duration $\tau_{\rm L} = 5$ ns, focal spot radius $R_{\rm f} = 100$ μm, and $\lambda = 1.06$ μm.

Fig. 4 shows the time dependences of the longitudinal and radial coordinates of the thermal-wave front (corresponding to the electron temperature 400 eV) and coordinates of the front of the absorption region of laser radiation. Note first of all that the material density in the calculations for the Mishen' facility was 4–8 times lower than that in the experiments on the Nova facility. As a result, as shown by numerical simulations, the distributed absorption of laser radiation substantially affects the character of heat transfer.

The ratio between the inverse bremsstrahlung length, which is inversely proportional to the square of the plasma density ($L \approx \rho^{-2}$), and the longitudinal dimension of the thermal wave front is equal to $\sim 0.32 - 0.4$ for the medium with a density $\rho = 1$ mg cm^{-3} and to 0.5–0.8 for the medium with a density $\rho = 0.5$ mg cm^{-3}. The average calculated velocities of the propagation of a thermal wave front are 2.5×10^7 cm s^{-1} for the medium with a density of 1 mg cm^{-3} and 5×10^7 for the medium with a density of 0.5 mg cm^{-3}.

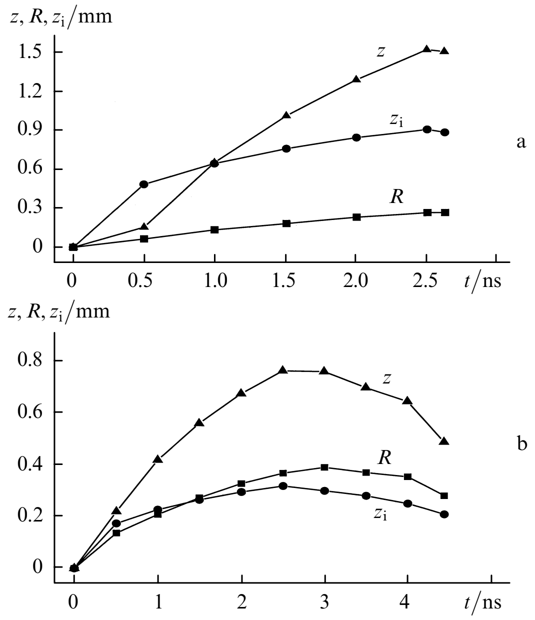

Figure 4. Time dependences of the longitudinal (z) and radial (R) coordinates of the thermal wave front as well as of the coordinates $z_{\rm i}$ of the laser radiation absorption region for $\rho = 0.5$ (a) and 1 mg cm^{-3} (b).

Fig. 5 shows the isotherms for the above densities at the time $t \approx 2.5$ ns corresponding to the middle of the laser pulse. These data clearly demonstrate the increase in the degree of heat transfer anisotropy (with a prevailing propagation of the thermal wave along the laser beam axis) in media with a lower density, which is explained by the increase in the length of laser radiation absorption due to inverse bremsstrahlung. The energy transfer rates measured for porous materials with the above densities in the experiments on the Mishen' facility were found to be close to the hydrodynamic rates and were equal to $(1 - 1.5) \times 10^7$ cm s^{-1} for a density $\rho = 1$ mg cm^{-3} and $(2 - 3) \times 10^7$ cm s^{-1} for $\rho = 0.5$ mg cm^{-3}.

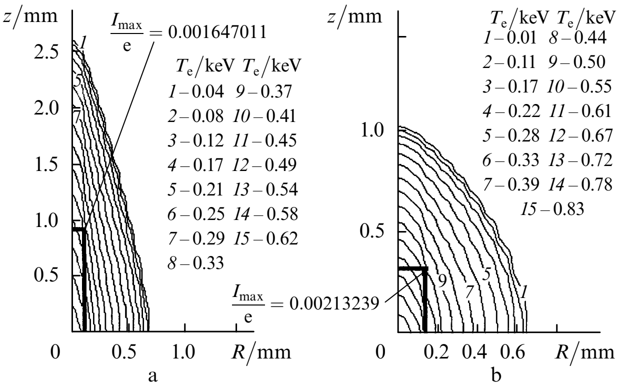

Figure 5. Isotherms for $\rho = 0.5$ (a) and 1 mg cm^{-3} (b) at the time $t = 2.5$ ns.

Therefore, for the conditions of low-density target irradiation on the Mishen' facility, the numerical simulations of the electron thermal conduction wave also yield higher rates of energy transfer, which exceed the experimental ones by a factor of 1.5–2. This suggests that the electron thermal conduction wave is not the dominant mechanism of energy transfer in porous targets exposed to laser radiation.

4. Conclusions

Our calculations of the propagation of a two-dimensional thermal wave in a homogeneous low-density material with a subcritical density of 0.5–1.0 mg cm^{-3} irradiated by a laser beam at intensities of $10^{14} - 10^{15}$ W cm^{-2} showed the feasibility of initiating supersonic thermal waves with velocities in the $(3 - 10) \times 10^7$ cm s^{-1} range. Note that absorption of laser radiation distributed over the inverse bremsstrahlung length makes, along with the electron thermal conduction, a significant contribution to the dynamics of a thermal wave. Such high energy transfer rates are sufficient for smoothing out the nonuniformities of plasma heating when reactor-scale fusion targets are irradiated by a relatively small number of laser beams (6–12) when the characteristic scale of spatial nonuniformities is 1000–600 μm [2].

The calculations confirmed the conclusion made in Refs [6, 7, 11, 12] that the energy transfer in a laser-produced plasma of low-density porous media is governed by a slower process than the electron thermal conduction.

References

1. Gus'kov S Yu, Rozanov V B, Zmitrenko N V, in *Laser Interaction with Matter (Proceedings of the XXIII European Conference on Laser Interaction with Matter, Oxford, UK, 1994)* (Bristol: IOP Publishing, 1995) p. 275
2. Gus'kov S Yu, Zmitrenko N V, Rozanov V B *Zh. Eksp. Teor. Fiz.* **108** 548 (1995) [*J. Exp. Theor. Phys.* **81** 296 (1995)]
3. Gus'kov S Yu, Rozanov V B *Kvantovaya Elektron. (Moscow)* **24** 715 (1997) [*Quantum Electron.* **27** 696 (1997)]
4. Popov I V, Zmitrenko N V, Tishkin V F, et al. *Advances in Laser Interactions with Matter and Inertial Fusion (Proceedings of the XXIV European Conference on Laser Interaction with Matter, Madrid, 1996)* (Singapore: World Scientific Publishing, 1997) p.172
5. Koch J A, Estabrook K J, Bauer J D, et al. *Phys. Plasmas* **2** 3820 (1995)
6. Bugrov A E, Burdonskii I N, Gavrilov V V, et al. *Zh. Eksp. Teor. Fiz.* **111** 903 (1997) [*J. Exp. Theor. Phys.* **84** 407 (1997)]
7. Bugrov A E, Burdonskii I N, Gavrilov V V, et al. *Zh. Eksp. Teor. Fiz.* **115** 805 (1999) [*J. Exp. Theor. Phys.* **88** 441 (1999)]
8. Caruso A, Gus'kov S Yu, Demchenko N N, Rozanov V B, Strangio C *J. Russ. Laser Res.* **18** 464 (1997)
9. Andreoli P L, Caruso A, Cristofary G, et al. *Preprint No. 35* (Moscow: Lebedev Physics Institute, Russian Academy of Sciences, 1998)
10. Batani D, Benuzzi A, Koenig M, et al. *Plasma Phys. Controlled Fusion* **40** 1576 (1998)
11. Gus'kov S Yu, Rozanov V B, in *Advances in Laser Interactions with Matter and Inertial Fusion (Proceedings of the XXIV European Conference on Laser Interaction with Matter, Madrid, 1996)* (Singapore: World Scientific Publishing, 1997) p.142
12. Gus'kov S Yu *Preprint No. 49* (Moscow: Lebedev Physics Institute, Russian Academy of Sciences, 1998)
13. Samarskii A A, Gaifullin S A, Zakharov A V, et al., in *Voprosy Atomnoi Nauki i Tekhniki. Problemy Yadernoi Fiziki i Inzhenerii* (Problems of Nuclear Science and Technology. Problems of Nuclear Physics and Engineering) (Moscow: Energoatomizdat, 1983) Vol. 2, p. 38