Journal of Russian Laser Research, Volume 31, Number 5, 2010

FORMATION OF A PLANE LAYER OF PLASMA UNDER IRRADIATION BY A SOFT X-RAY SOURCE

Galina A. Vergunova,[1*] Sergey Yu. Gus'kov,[1] Vladislav B. Rozanov,[1] and Olga N. Rozmej[2]

[1] *P. N. Lebedev Physical Institute, Russian Academy of Sciences*
Leninskii Prospect 53, Moscow 119991, Russia

[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH*
Planckstraße 1, Darmstadt 64291,Germany

*Corresponding author e-mail: verg @ sci.lebedev.ru

Abstract

We investigate theoretically the formation of a plasma in a plane layer of polymer foam (density $\rho = 0.002$ g/cm^3 and thickness 800 μm) under the action of an external source of soft X-ray radiation under the conditions of PHELIX experiments. The incident flux is assumed to have a Planck's distribution over the spectrum with $T_{\rm rad} = 20$–40 eV. In numerical calculations, the flux of incident X-ray radiation and the spectral constants of the target substance are varied. The action of an external X-ray radiation source on a low-density foam substance with a density of 2 mg/cm^3 causes a plasma to be formed with relatively homogeneous profiles of density and temperature $T = 15$–35 eV. Absorption of external-radiation energy is distributed in the volume. The plasma temperature increases with increase in the external energy, and the energy passed through the plasma also increases. The results prove to be sensitive to the values of optical constants used in numeral simulation. The spectral flux of external radiation passed through the plasma is chosen as a criterion of correctness of the optical constants used in the calculations. In future experiments using the PHELIX facility, we plan to investigate the slowing-down of an ion beam in a plasma formed as a result of indirect heating of low-density polymer triacetate cellulose (TAC) foam with densities $\rho = 0.001$–0.01 g/cm^3 under the action of a pulse of X-ray radiation, into which the laser radiation is preliminarily transformed.

Keywords: heavy ions fusion, laser plasma, stopping power, soft X-ray radiation.

1. Introduction

Studies of the physics of slowing-down of ions accelerated to 10–90% of the velocity of light in ionized media are important for many inertial confinement fusion (ICF) schemes, including the compression and heating of thermonuclear targets by beams of heavy ions (heavy-ion fusion) and fast ignition of targets preliminarily compressed using various drivers (see [1–3] and references therein), as well as for astronomy applications. In future experiments at the PHELIX facility [1], we plan to study the slowing-down of an ion beam in a plasma formed as the result of the so-called indirect heating of low-density polymer foam (triacetate cellulose, TAC) with densities $\rho = 0.001$–0.01 g/cm^3 under the action of a X-ray radiation pulse, into which the laser radiation is preliminarily transformed. The equilibrium X-ray radiation is generated in a gold cylindrical target converter (hohlraum) upon irradiation of the wall

Translated from a manuscript submitted on August 15, 2010.

inner surfaces by laser beams. Soft X-ray radiation with quantum energy in the range of 1–300 eV and frequency distribution close to the Planck's distribution penetrates into the foam and uniformly heats it up to temperatures of the order of 20–30 eV at free electron density up to 10^{21} cm^{-3}. Due to the slow hydrodynamic expansion of foam, the experiments are expected to yield a homogeneous plasma target with the above-mentioned temperature and density and a lifetime of the order of 5–7 ns, exceeding the ion-beam duration, which is 3 ns.

In this paper, we investigate the formation of a plasma in a plane layer of polymer foam (density $\rho = 0.002$ g/cm^3 and thickness 800 μm) under the action of an external source of soft X-ray radiation under the conditions of PHELIX experiments.

2. Experimental Results

In experiments at the PHELIX facility [1], soft X-ray radiation is initially generated on the side walls of the cylindrical gold converter (hohlraum), which are irradiated by laser beams (Fig. 1). A part of the radiation is thermalyzed, passing through a thin gold foil at the butt end of the cylindrical converter, and acts upon a porous substance (foam) attached to the rear side of the foil. Under the action of thermal irradiation, the porous substance heats up in the bulk and an extended plasma is formed, whose temperature and density weakly change within several nanoseconds. Subsequently, we plan to pass an ion beam through such plasma with the view of determining the energy losses (stopping power) of ions that pass through the ionized substance with given temperature, density, and ion composition.

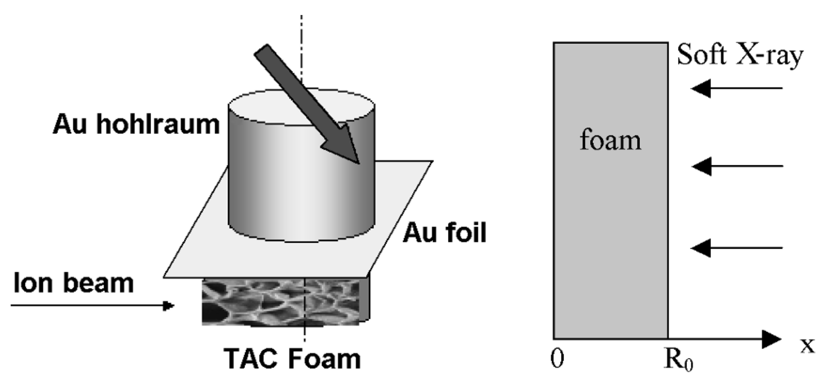

Fig. 1. Scheme of an experiment [1] on the slowing-down of an ion beam (left) and geometry of numerical calculations (right). Cylindrical hohlraum with height 1.7–2 mm, diameter 1.7 mm, and wall thickness 10 μm. TAC foam of density 2–20 mg/cm^3 and areal density $\rho L = 150$–500 μg/cm^2. Au foil has thickness of 0.1 μm.

The PHELIX laser parameters in these experiments were as follows: the first harmonic of Nd laser, pulse duration 1.4 ns, energy in the pulse 200–270 J, focus spot diameter ≈200 μm, laser energy flux >10^{14} W/cm^2, and contrast 10^{-6}. The target was a plane layer of triacetate cellulose (TAC, $C_{12}H_{16}O_8$) polymer foam 800 μm thick of average density 2 mg/cm^3. In such a substance, 99.8% of the volume consists of cavities and 0.2% consists of thin threads and solid-substance films of density ∼1 g/cm^3. The linear size of pores is less than 1 μm, and solid elements are less than 0.02 μm in size.

The experimentally measured temperature of the radiation thermal flux exiting the gold foil and incident on the foam was $T_{\rm rad} = 30$–40 eV at an exposure time $T_{\rm rad} = 5$–8 ns. Under these parameters, the energy of X-ray radiation that passed through a porous target was 10–25% of the radiation energy incident on the target boundary.

3. Statement of the Problem

Under the action of an external source of soft X-ray radiation, the solid elements of the polymer are heated in the bulk at the free path length of heating-radiation photons. The substance of the heated layers is scattered into pores. Due to collisions of fluxes of the substance, a non-equilibrium plasma of the porous target is formed, the formation being accompanied by density oscillations of the plasma and a periodic redistribution of kinetic and thermal energies of the substance. The plasma is homogenized over the time of viscous damping of density oscillations, which is determined by the time of the ion–ion collisions, and thermalyzed over the time of the ion–electron temperature relaxation.

It should be noted that at low temperatures of the plasma under the conditions of the considered problem, the homogenization time of small-pore substance with pore size of about 0.1 μm proves sufficiently large due to the small viscosity of plasma. Indeed, the homogenization time in collisions of plane fluxes of a substance can be assessed in the diffusion approximation by the formula

$$t = \delta_0^2/(2\eta),$$

where the ion viscosity [4] $\eta \approx v^2\tau_{ii}/3$ depends on the time of the ion–ion collisions,

$$\tau_{ii} = \frac{3 \cdot 10^6}{\lambda/10}\left(\frac{m_i}{2m_p}\right)^{1/2}\frac{T_i^{3/2}}{Z^3 n_e}.$$

Here, δ_0 is the mean size of pores, v is the characteristic velocity of ions, m_i is the mass of ion, m_p is the mass of proton, λ is the Coulomb logarithm, T_i is the ion temperature of the plasma in [eV], Z is the plasma ion charge, and n_e is the electron density. Taking into account the mixed fiber–membrane composition of solid elements, we can calculate the homogenization time of the considered porous substance [5]:

$$t_h \approx 10^{-9}\frac{\delta_0^{3/4} b_0^{5/4}}{T^{5/2}}\rho_s \text{ [s]}, \tag{1}$$

where b_0 is the characteristic size of solid structures; δ_0 and b_0 are measured in [μm], T in [keV], and ρ_s in [g/cm^3].

Using the values of $\delta_0 \approx 1$ μm and $b_0 \approx 0.01$ μm for the size of a porous TAC structure, in view of formula (1), we obtain values of several nanoseconds for the homogenization time of the plasma heated up to temperatures of 20–40 eV. Thus, the complete homogenization time is comparable with the duration of the heating radiation source and, therefore, with the lifetime of the plasma. The prolonged homogenization of the plasma, during which a part of the absorbed energy is contained in the form of kinetic energy of substance fluxes inside the pores, can extend the formation of directed hydrodynamic spread of plasma, thus providing more favorable conditions for quasihomogeneous plasma creation. Account for the effect of homogenization in calculations of plasma formation under the action of an external soft X-ray radiation source requires an additional investigation. In this work, we consider the plasma to be homogeneous and equilibrium from the viewpoint of the energy exchange between ion and electron components.

Thus, the calculations assume that a plane layer of a homogeneous substance 800 μm thick and density 2 mg/cm^3 is irradiated from one of the butt ends (in our calculations, the right-hand side, see

Fig. 1, right) by an external source of Planck's radiation with temperature $T_{\rm rad}$ and flux density $W_{\rm rad}$ over time $t_{\rm rad}$.

The penetration depth of the external source depends on the wavelength of the incident radiation. Low-frequency radiation is absorbed more efficiently and with a smaller size of the plasma than higher frequencies, in accordance with the behavior of the optical constants of a plasma at a given temperature.

4. Physical and Mathematical Model

Formation of plasma in a plane layer of foam was simulated by the one-dimensional numerical code RADIAN [6].

The model taken as a basis of this code contains two-temperature hydrodynamic equations, namely, the equation of motion, the continuity equation, the equations of energy change for electron and ion components, and the equations of state for ions and electrons.

The electron–ion energy exchange and the classical Spitzer's thermal conductivity are taken into account. There is a possibility of reducing the thermal conductivity, e.g., with the view of a better correspondence to the experimental data. A possibility is provided for employing various equations of state. In our calculations, we used the equation of state of an ideal gas and the classical coefficient of thermal conductivity.

The spectral radiative transfer is considered in a multi-group approximation. Both the passage of the external radiative emission incident on the plasma and the transfer of intrinsic thermal emission of the plasma are taken into account. Depending on the conditions, we change the splitting of the spectra into spectral groups. To simplify the dependence on the angular variables, in the equation of transfer, the quasidiffusion method was used [7].

The radiative transfer equation includes the spectral coefficients of absorption. We have at our disposal the databases of absorption coefficients calculated using the DESNA (P. N. Lebedev Physical Institute, Moscow) [8] and THERMOS (Keldysh Institute of Applied Mathematics) [9] programs. For light elements, the results of calculating the optical constants using DESNA and THERMOS programs are close. We used the optical constants from the THERMOS database.

Figure 2 shows the absorption coefficients for CH_2 polymer at temperatures $T = 20$ eV and $T = 30$ eV and density $\rho = 0.002$ g/cm^3 calculated by the THERMOS program. It is seen that with temperature increase the absorption coefficient drops down. Within the range of 300–450 eV, jumps of the absorption coefficient are due to transitions in the K shell of carbon, and in the range up to 60 eV, to transitions in the L shell.

Figure 3 presents the absorption coefficients for the target material used in the experiments [8] and calculated by DESNA code. From the comparison of Figs. 2 and 3, one can see that, due to the occurrence of oxygen in TAC, the number of lines in the absorption coefficient in the spectral range of 20–130 eV increases as compared with those for Lavsan. The absorption coefficients differ structurally.

Already a preliminary analysis of the parameters of the incident radiation flux and the dependences of the optical constants show an essentially nonlinear pattern of interaction of the external X-ray radiation flux with the target and the formation of plasma. Indeed, on the one hand, an increase in the radiation temperature of the incident radiation flux leads to increase plasma heating and, as a result, increase in the plasma temperature. On the other hand, an increase in the plasma temperature leads to decrease of the radiation absorption coefficient and increase of the fraction of the radiation that passed through the plasma.

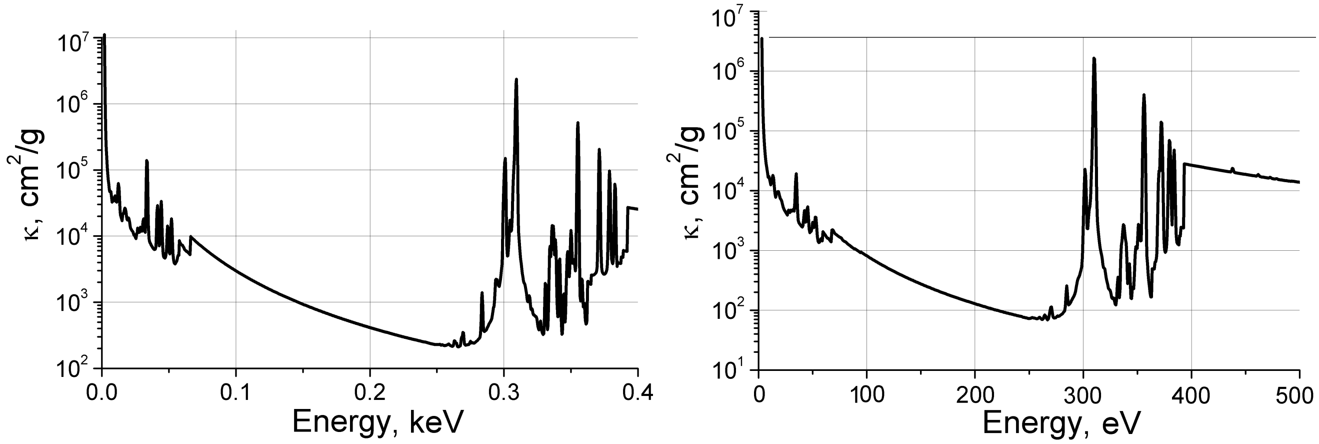

Fig. 2. The spectral coefficient of CH_2 absorption at $T = 20$ eV (left) and $T = 30$ eV (right). Density $\rho = 2$ mg/cm^3.

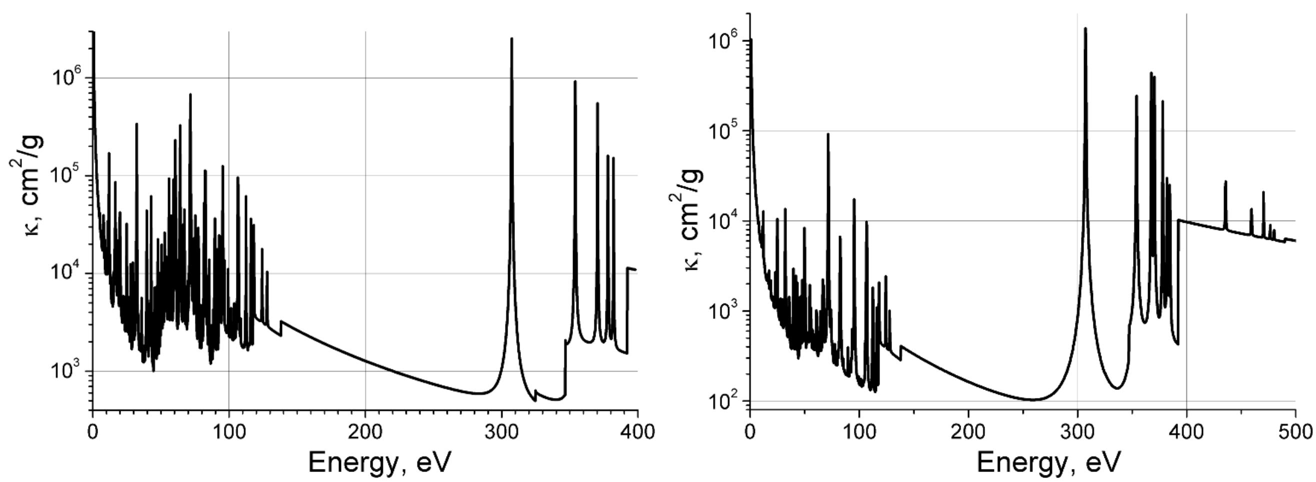

Fig. 3. The spectral coefficient of TAC ($C_{12}H_{16}O_8$) absorption at $T = 20$ eV (left) and $T = 36$ eV (right). Density $\rho = 2$ mg/cm^3.

Thus, the parameters of the plasma and radiation that passed through the target can be controlled by changing two factors — the temperature of the external flux of X-ray radiation and optical transparency of the plasma, e.g., by choosing its composition and/or density.

The range of changing the areal density of target substance (areal density $= \rho L$) in the calculations is 150–300 μg/cm^2. The choice of this range corresponds to the energy of the PHELIX laser required, on the one hand, to heat a sufficiently extended plasma and, on the other hand, to provide penetration of a part of X-ray radiation through the plasma. The latter, as we show below, proves useful for the development of diagnostic methods of studies of optical constants in such a kind of experiments. Note that, as a rule, the dependence of the quantum free path lengths on the plasma density is stronger than the inversely proportional law, which conforms to the dependence of density on the path length of high-energy ions of the beam. For this reason, at a given value of the target's areal density, the choice of a porous substance density can serve as a control factor of the slowing-down of the ion beam, the interaction of which with plasma can be investigated in the experiment.

5. Results of Numerical Simulations

The numerical calculations were performed in order to investigate the formation of a plane layer of a low-density polymer plasma under the action of an external source of soft X-ray radiation. The incident flux was assumed to have a Planck's distribution over the spectrum with $T_{\rm rad} = 20$–40 eV. In the calculations we varied the density of the radiation flux incident on the plasma, as well as the spectral optical constants of the target substance (TAC), to determine the dependence of the plasma parameters. Some results of this simulation are presented in Table 1.

The fifth column indicates the source for optical coefficients used in the calculations. In calculations 169, 176, 171, and 170, the radiation energy passed through the target increases with increase in the incident flux. In calculation 172, we used the absorption coefficients determined only by bremsstrahlung absorption coefficients (simulation of a mostly transparent plasma). In this case, the plasma is optically transparent to the radiation of the external source; 95% of the incident flux leaves the plasma from the rear side (with respect to the external source). Calculations 174 and 175 were performed under changed optical coefficients. In these calculations, all optical coefficients used were multiplied by the corresponding values (column 6 in Table 1).

From a comparison of calculations 169 and 175, one can see that a fivefold increase in the absorption coefficients increases the passed energy from 4 to 15%. A twofold increase of the optical constants decreases the flux that passes through the layer from 32 to 10% (calculations 171 and 174).

Thus, by adjusting the optical coefficients, the re-radiated flux can be made to agree with the experimental data.

In the experiments, the part of the energy that passed through the layer of substance was 10–25% of the incident radiation energy. The results of calculation 171, where the incident radiation flux was $W_{\rm rad} = 8.3 \cdot 10^{10}$ W/cm^2 ($T_{\rm rad} = 30$ eV), agree satisfactorily with the experimental data.

Table 1. Simulation Results.

N	$T_{\rm rad}$, eV	$\tau_{\rm rad}$, ns	$W_{\rm rad}$, 10^{11} W/cm^2	Source for Optical Coefficients	Multiplier	$E_{\rm out}/E_{\rm rad}$
169	20	5	0.17	THERMOS	1	0.04
172	20	5	0.17	Inverse Bremsstrahlung	1	0.95
175	20	5	0.17	THERMOS	0.2	0.15
176	25	5	0.39	THERMOS	1	0.15
171	30	5	0.83	THERMOS	1	0.32
174	30	5	0.83	THERMOS	2	0.10
170	40	5	2.6	THERMOS	1	0.64

5.1. Heating of a Plane Layer by an Equilibrium Source of Thermal Radiation

A flux of X-ray radiation with a Planck's spectrum corresponding to temperature $T_{\rm rad} = 20$ eV, $W_{\rm rad} = \sigma T^4 = 1.7 \cdot 10^{10}$ W/cm^2 for 5 ns acts on the right-hand side of the plane layer (see Fig. 1, right). Figure 5 presents the results of this simulation for calculation 169. It is seen that the plasma is heated by a flux of the external source for 5 ns. Approximately 500 μm of the foam is heated. Upon termination of external irradiation, heat transfer is via the flux of electronic thermal conductivity, and the plasma

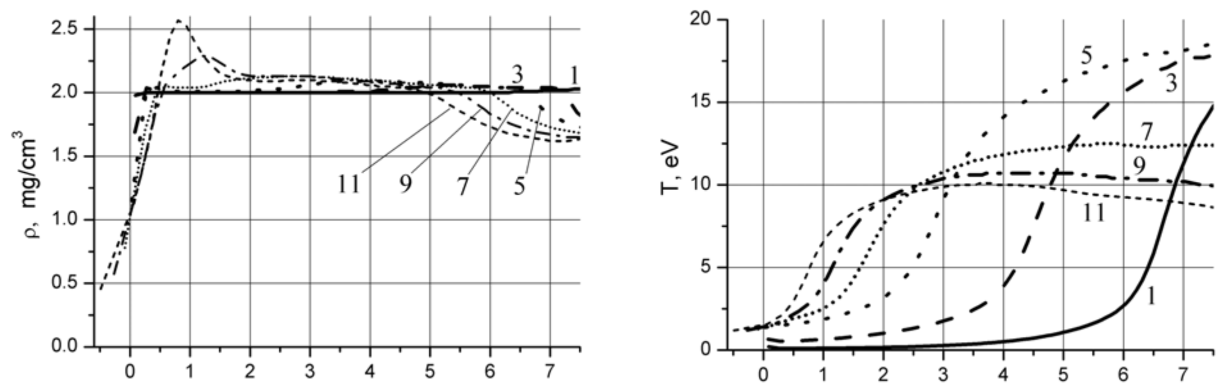

Fig. 4. Density (left) and temperature (right) profiles formed in a plane layer of plasma in times shown by figures near the curves, in [ns]. The initially homogeneous plasma layer 800 μm thick of density 2 mg/cm^3 was irradiated by a thermal source with radiation temperature of 20 eV for 5 ns from the right-hand side boundary R_0.

temperature drops from 17 to 10 eV. During 10 ns, the heat wave heats the substance by 200 μm more.

Figure 5 shows the radiation spectra on the right-hand side (the external flux is incident on this side) and on the left-hand side (rear side with respect to the source) of the plane layer for times of 1 and 4 ns. The radiation propagating inside the target is represented by curves 1 and 2, and the radiation that passed from the plasma on the left-hand (rear) side is represented by curve 4.

The heated-up plasma is by itself a source of intrinsic thermal radiation. The intrinsic-radiation spectrum at the right-hand side boundary (at $r = R_0$) coming forward to the incident flux is shown by line 3. The plasma intrinsic-radiation flux coming out from the rear side (at $r = 0$) is shown by curve 5 at time $t = 1$ ns (the values of the flux density are multiplied by 1000) and curve 6 at $t = 4$ ns (the values of the flux density are multiplied by 100). Since the plasma temperature is lower than that of the external source, the intrinsic radiation is generated at lower spectral frequencies than the spectrum of the incident external radiation.

Figure 5, right presents the spectral energy radiated by times 1, 4, 5 ns from the left-hand side of the plasma layer (from the rear side with respect to the external flux of radiation). Upon a delay of the pulse (5 ns), the losses of plasma for intrinsic radiation decrease. The energy is redistributed along the target thickness. In this calculation, the energy flux of the radiation exiting from the left-hand side boundary was 4% of the incident flux.

An increase in the flux of external X-ray radiation leads, as expected, to an increase in the energy input to the plasma, increase in the plasma temperature, and increase in external-source radiation that passed through the plasma (Table 1, calculation 171, $T_{\rm rad} = 30$ eV). In this calculation, the fraction of energy passed is 32% of the incident radiation energy. The experiment registers 25% of the energy passed. From what was said above, the discrepancy can be explained in different ways. From Table 1, it is seen that one can look for the explanation by correcting the incident radiation temperature and/or changing the absorption coefficients.

5.2. Heating of the Plane Layer by an External-Radiation Source within a Narrow Wavelength Range

In the case where the radiation source is not equilibrium and does not radiate as a black body, but radiates in a narrow spectral range, the energy of the external source is absorbed in a limited spatial

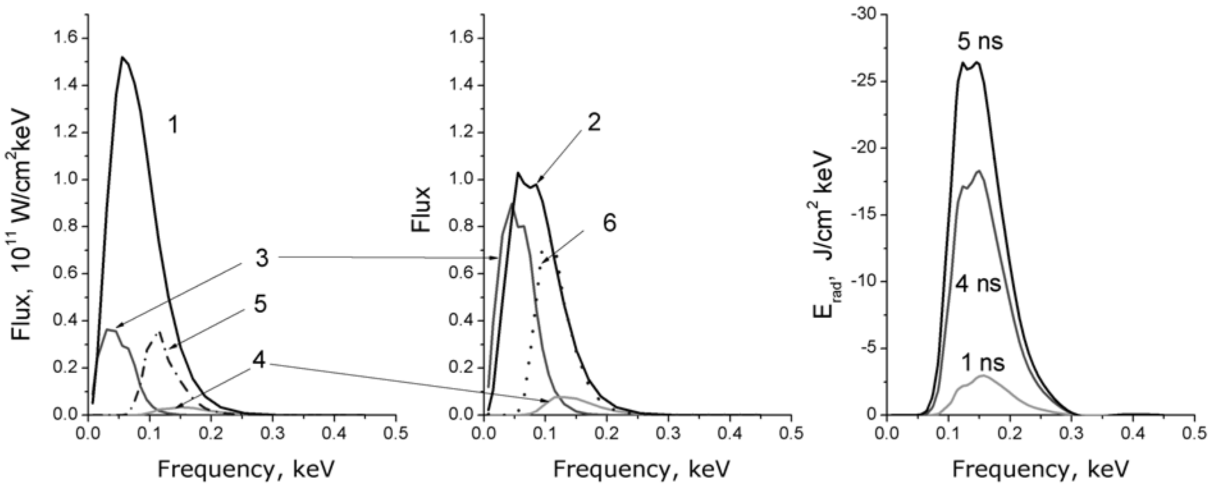

Fig. 5. Radiation spectra at the boundaries of a plane layer of a porous substance at time $t = 1$ ns (left) and $t = 4$ ns (middle) with external-radiation flux incident on the plasma (1), external-radiation flux at $t = 4$ ns absorbed by the plasma (2), intrinsic-radiation flux coming forward to the incident flux (3), and external-radiation flux re-radiated by the plasma and exiting from the rear side of the plasma layer (4). The intrinsic-radiation flux exiting from the left-hand side of the plasma layer (rear side with respect to the incident external flux of radiation) multiplied by 1000 at time $t = 1$ ns (5) and multiplied by 100 at time $t = 4$ ns (6). Spectral energy at the left-hand side of substance re-radiated by the plasma by a given time (right). Time-integrated fluxes 5 and 6 in Fig. 5, left and middle (rear side).

domain of the plasma at a distance corresponding to the absorption path length of these quanta. In our calculations, we simulated this case of external-radiation absorption in one spectral group. Radiation is absorbed in a relatively narrow spatial domain of the plasma. In that domain, a shock wave is formed, which outruns the thermal wave coming from the same region of the external-radiation absorption and heats the plasma. As a result, an essentially inhomogeneous plasma is formed, with the density changed fourfold over the space.

5.3. Heating of the Layer by a Thermal Wave from the Hot Wall

To analyze the processes forming the hydrodynamic profiles of the plasma, we solve the problem of heating of a low-density plane layer of CH_2 polymer ($\rho_0 = 10$ mg/cm^3) 500 μm thick by a single wave of electronic heat conductivity. At the boundary of the layer at $R = R_0$, the condition of constant temperature for 1 ns is set; thereby, the external source energy is transferred along the plane layer by the flux of electronic heat conductivity. The plasma velocity at the boundary $R = R_{\rm right} = 500$ μm is equal to zero, since from this side the plasma is bounded by the gold foil. A series of calculations was performed.

For the sake of an example, Fig. 6 presents the results of calculations where the boundary temperature is 50 eV. A shock wave is seen to be formed in the plasma which, in fractions of a nanosecond, outruns the thermal wave and heats and compresses the substance. As a result, an essentially inhomogeneous plasma is formed.

The solution of the automodeling plane problem on the propagation of heat at a constant temperature at the boundary [10] under our conditions yields the value $x_\Phi = \left(aT^{5/2}t\right)^{1/2} = 0.001$ cm, which coincides with the results of the calculations.

After 1 ns, when the temperature at the boundary ceases to be maintained at a level of 50 eV, the solution to the problem of heat propagation from an instantaneously plane source [10] in an unbounded initially cold medium yields values close in order of magnitude to those obtained in the calculations. Thus, the homogeneous heating of the layer in the regime of electronic heat conductivity appears to be difficult.

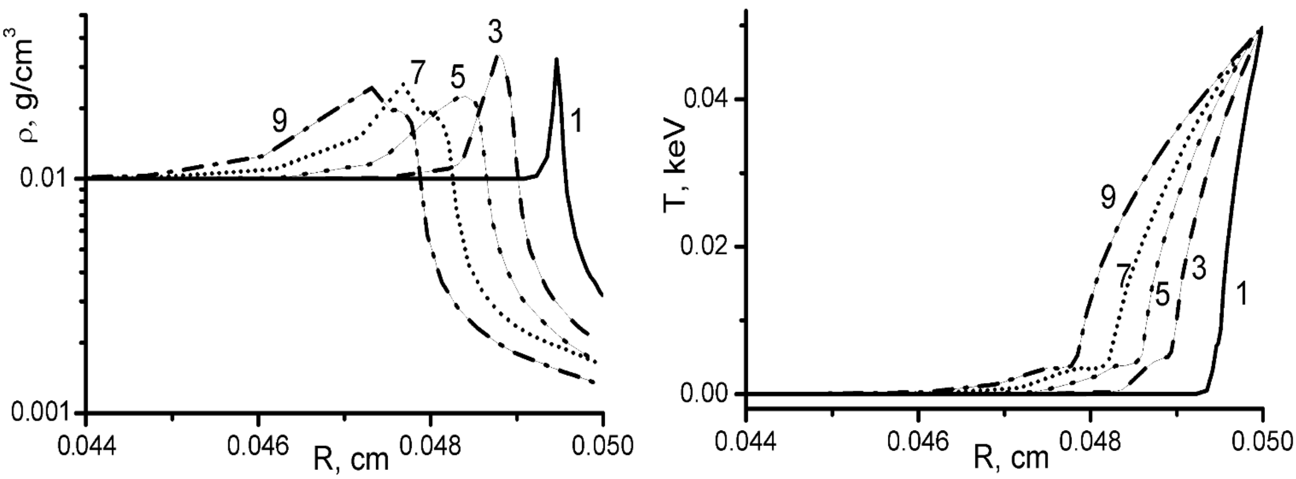

Fig. 6. Density (left) and temperature (right) profiles formed in a plane layer of plasma in times shown in the figures. The initially homogeneous plasma layer (density 10 mg/cm^3 and thickness 500 μm) was heated by a flux of the electronic heat conductivity from the right-hand-side boundary. For this, a temperature of 50 eV was maintained at the right-hand-side boundary for 1 ns.

6. Conclusions

The action of an external source of X-ray radiation with the Planck's spectrum with $T = 20$–40 eV on a low-density porous substance ($\rho = 0.002$ g/cm^3) causes the formation of a plasma with relatively space-homogeneous density and temperature profiles $T = 15$–35 eV. Absorption of external-radiation energy is distributed in the whole volume.

The incident radiation used for heating the substance contains a range of frequencies, and the absorption of external-source energy depends on frequency — as a rule, the higher the frequency, the deeper the radiation flux corresponding to that energy penetrates into the substance. The plasma temperature increases with increase in the external-source energy but, in this case, the fraction of energy that penetrates through the plasma also increases.

When an external radiation flux within a narrow spectral range is acting on a plasma, an essentially inhomogeneous plasma is formed; its spatial size is determined by the wavelength of the incident flux of external radiation and by the heating of the substance in the regime of electronic heat conductivity.

The results prove to be sensitive to the values of optical constants used in numerical simulation. A criterion of testing the optical constants used in the calculations is the spectral flux of external radiation that passed through plasma. Thus, the study of the optical constants of substances based on a comparison of experimental and calculated results for the radiation penetrating through a plasma is an important and topical issue.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research under Project No. 10-02-92104-YaF-a.

References

1. D. H. H. Hoffmann, A. Blazevic, P. Ni, et al., *Laser Part. Beams*, **23**, 47 (2005).
2. M. M. Basko, *Plasma Phys. Control. Fusion*, **45**, A125 (2003).
3. S. Yu. Gus'kov, *Quantum Electron.*, **31**, 885 (2001).
4. S. I. Braginsky, in: M. A. Leontovich (ed.), *Reviews of Plasma Physics* [in Russian], Gosatomizdat, Moscow (1963), No. 1.
5. S. Yu. Gus'kov, A. I. Gromov, Yu. A. Merkul'ev, et al., *Laser Part. Beams*, **17**, 415 (1999).
6. T. K. Govorun, G. A. Evseev, T. V. Mishchenko, "RADIAN code for solving 1D spherical-symmetric problems of radiative gas dynamics" [in Russian], Preprint No. 176 of Keldysh Institute of Applied Mathematics, Moscow (1986).
7. V. Ya. Goldin, *Zh. Vyssh. Mat. Mat. Fiz.*, **4**, 1078 (1964).
8. E. M. Ivanov, V. B. Rozanov, and G. A. Vergunova, *SPIE Proc.*, **4424**, 308 (2001).
9. A. F. Nikiforov, V. G. Novikov, and V. B. Uvarov, *Quantum-Statistical Models of Hot Dense Matter and Methods for Computation Opacity and Equation of State*, Birkhauser Verlag, Boston-Basel (2005).
10. Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, Dover Publications, Mineola, NY (2002).