Spontaneous magnetization of the thermal conductivity in an expanding laser plasma

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We investigated the effect of plasma motion on the generation of spontaneous magnetic fields under the influence of laser radiation. We show that the main features, previously deduced with a simplified model, of the magnetothermal phenomena produced when a flat target is heated, remain unchanged. The physical causes of saturation of the magnetic field in a hydrodynamic time scale are determined. Principal among them is the attuning of the plasma-density profile to the electron-temperature profile. Magnetization of the plasma by spontaneous magnetic fields overheats the electrons and limits the heat transport in a direction perpendicular to the laser beam.

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1. The magnetic fields appearing spontaneously in a plasma heated by intense laser radiation have been investigated in a number of experimental and theoretical studies.[1–13] They are of interest in connection with their possible substantial effect on absorption processes,[6] and primarily on heat transfer from the absorption region to the region where the target material is compressed.[3–5]

One of the most important mechanism of magnetic-field generation in internal plasma layers in which the electron density exceeds the critical value n_{ec} is the thermoelectric effect in the presence of noncollinear electron density and temperature gradients.[2] Magnetic field of intensity ~ 1 MG and of characteristic scales on the order of the plasma-inhomogeneity dimensions were recorded in experiments.[1,2,7,8] Special research is necessary, however, to identify the conditions under which the magnetic fields can reach high intensities in the plasma, to find the physical causes that limit their growth, to determine how strong their influence is on the heat transfer, etc.

In many foreign papers reporting numerical simulation of laser compression,[9–11] magnetic-field generation was taken into account in addition to many other processes. The magnetic fields determined in these calculations agree in order of magntitude with the experimental results (as well, incidentally with the simplest estimates). To answer the questions raised above, however, it is desirable to single out the most essential physical effects that accompany the generation of the magnetic fields, and also the main dependences on the experimental conditions.

It was shown in earlier papers[4,12,13] that the characteristic time of magnetization of the thermal conductivity of a plasma as a result of the increase of the magnetic field B is of the same order as the time of equalization of the electron temperature over the main scale of the inhomogeneity, and is shorter than the characteristic plasma expansion time. It was possible for this reason to separate the magnetothermal part of the total picture of laser heating and to consider the joint evolution of the magnetic field and of the electron temperature in an inhomogeneous plasma at rest. This is permissible if the inequality $l/a \gg (m/M)^{1/2}$ is satisfied, where l is the mean free path, a is the scale of the inhomogeneity of the temperature and of the plasma density, and m and M are respectively the electron and ion masses.

Numerical simulation of laser heating of a flat target[12,13] has shown that the growth of substantial magnetic fields that magnetize the thermal conductivity of the plasma has a threshold. If the heating radiation is focused smoothly enough (i.e., if the distribution of the electron-heat sources is sufficiently uniform) the magnetic-field growth can be limited at a low level, at which its effect on the thermal conductivity is insignficant. Conversely, if the focusing is sharp enough the magnetic field increases with time practically linearly and reaches values ~ 5 MG within a time ~ 0.5 nsec, in which case the thermal conductivity in the magnetized regions is decreased manyfold.

Magnetization of the thermal conductivity takes place at $\omega_e \tau_e \sim (\omega_e \tau_e)^*$ ($\omega_e = eB/mc$ is the cyclotron frequency, τ_e is the time between electron collisions, $(\omega_e\tau_e)^*$ depends on the ion charge and, e.g., in the case of an aluminum plasma $(\omega_e \tau_e)^* \approx 0.1$). Since the most important mechanism that stabilizes the growth of the magnetic fields, namely the drift of the magnetic field together with the heat flow,[4] is turned off simultaneously with the magnetization of the electronic thermal conductivity of the plasma, it is clear that within the framework of the magnetothermal picture the magnetic field increases without limit in the latter case. The strength of the magnetic fields, their distribution, and their influence on the plasma dynamics evolve, as indicated in Ref. 12, over the slow hydrodynamic time scale and must be determined by simultaneously solving the magnetothermal and hydrodynamic equations. The present paper is devoted to a numerical analysis of this problem.

2. The system of the magnetohydrodynamic equations is of the form[14]

$$\partial n_i/\partial t + \operatorname{div} n_i \mathbf{v} = 0, \tag{1}$$

$$\partial n_e/\partial t + \operatorname{div} n_e \mathbf{v} = \Gamma, \tag{2}$$

$$M n_i \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\nabla)\mathbf{v} \right] = -\nabla (p_e + p_i + B^2/8\pi), \tag{3}$$

$$^3/_2 n_e \left[\frac{\partial T_e}{\partial t} + \mathbf{v}\nabla T_e \right] + p_e \operatorname{div} \mathbf{v} = -\operatorname{div} \mathbf{q}_{eT} + \operatorname{div} \mathbf{q}_{eu} + Q_e + S, \tag{4}$$

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$$^3/_2 n_i \left[\frac{\partial T_i}{\partial t} + \mathbf{v}\nabla T_i\right] + p_i \operatorname{div} \mathbf{v} = Q_i, \quad (5)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{c}{e}[\nabla T_e, \times \nabla \ln n_e] - \frac{c}{e}\operatorname{rot}\frac{\mathbf{R}_T}{n_e} + \operatorname{rot}[\mathbf{v}\times\mathbf{B}]$$
$$-\operatorname{rot}\left[\frac{\mathbf{j}}{n_e e}\times\mathbf{B}\right] - \frac{c}{e}\operatorname{rot}\frac{\mathbf{R}_u}{n_e}, \quad (6)$$

where

$$Q_i = Q_\Delta = \frac{3m}{M}\frac{n_e}{\tau_e}(T_e - T_i), \quad (7)$$

$$Q_e = -Q_\Delta - \mathbf{j}\mathbf{R}_u/n_e e - \mathbf{j}\mathbf{R}_T/n_e e, \quad (8)$$

$$\mathbf{R}_T = -\beta_\parallel^{uT}\nabla_\parallel T_e - \beta_\perp^{uT}\nabla_\perp T_e - \beta_\wedge^{uT}[\mathbf{h}\times\nabla T_e], \quad (9)$$

$$\mathbf{R}_u = -\alpha_\parallel \mathbf{u}_\parallel - \alpha_\perp \mathbf{u}_\perp + \alpha_\wedge[\mathbf{h}\times\mathbf{u}], \quad (10)$$

$$\mathbf{q}_{eT} = -\varkappa_\parallel^e \nabla_\parallel T_e - \varkappa_\perp^e \nabla_\perp T_e - \varkappa_\wedge^e[\mathbf{h}\times\nabla T_e], \quad (11)$$

$$\mathbf{q}_{eu} = \beta_\parallel^{Tu}\mathbf{u}_\parallel + \beta_\perp^{Tu}\mathbf{u}_\perp + \beta_\wedge^{Tu}[\mathbf{h}\times\mathbf{u}]. \quad (12)$$

The coefficients in (9)–(12) were taken form Ref. 14, and $\mathbf{h} = \mathbf{B}/B$.

The ionization function Γ describes the processes of ionization and recombination in the electron-ion collisions, as well as the photorecombination process in the mean-effective-charge approximation.[15]

Account is taken in Eqs. (1)–(8) of the specifics of the problem, and many small terms were therefore discarded. Thus, at the characteristic scales and times of the magneothermal phenomena the plasma undoubtedly remains quasineutral, $n_e = Zn_i = Zn$, where Z is the average charge determined from Eqs. (1) and (2). The electron flow velocity $\mathbf{u} = -j/n_e$ is small compared with the characteristic average plasma velocity C_s, since

$$u^2/C_s^2 \sim (1/\Pi)B^2/4\pi n_e T_e, \text{ where } \Pi = 4\pi n_e e^2 a^2 Z/Mc^2$$

is the so-called running number of electrons. It is known that in a plasma with a large number of electrons per unit length ($\pi \gg 1$) the electrons are bound to the ions not only by the quasineutral electrostatic field, but also by the self-consistent magnetic field induced by the electric field that confines the electrons. In the situation considered, not only $\pi > 1$, but the magnetic pressure $B^2/8\pi$ turns out to be small compared with the kinetic pressure $n_e T_e$. The electron velocity was therefore assumed in Eqs. (4) and (5) to be equal to the average ion velocity $\mathbf{v}$ [a sufficient condition for this in Eqs. (1) and (2) is quasineutrality]. In the equation of motion (3), the Lorentz force $\mathbf{j}\cdot\mathbf{B}/c$ in the planar geometry considered hereafter reduces to the gradient of the magnetic pressure. The electron viscosity was left out of (3) and (5) because system is hydrodynamic with a sufficiently large margin ($l \ll a$).

The basic terms in Eqs. (4) and (6) describe the magnetothermal part of the complete laser-heating picture. In Eq. (4) these terms are div $\mathbf{q}_{eT}$ and S, where $\mathbf{q}_{eT}$ is the electron heat flux[14] and S is the density of the electron heat source. The first two terms in the right-hand side of (6) are the principal ones and describe respectively the growth of the magnetic field on account of the source (inhomogeneous thermoelectric emf $ce^{-1}[\nabla T_e \times \nabla \ln n_e]$) and its drift on account of the thermopower. This field-emergence mechanism is not connected with the plasma motion. The magnetic field drifts into the cold region together with the heat flux because it is frozen-in better in the hot than in the cold electrons. Among the terms added to Eq. (6) is the drift of the magnetic field at the average hydrodynamic velocity curl$[\mathbf{v}\times\mathbf{B}]$ of the plasma; its relative value compared with the generation term is $\sim(v/C_s)(m/M)^{1/2}(a/l)\omega_e\tau_e$. When the inequality $l/a \gg (m/M)^{1/2}$ is violated and $v \sim C_s$, the term curl$[\mathbf{v}\times\mathbf{B}]$ can compete with the generation term. The contribution of the hydrodynamic drift can be substantial also at $\omega_e\tau_e \gtrsim (\omega_e\tau_e)^*$, when the velocity of the thermal drift is decreased by the magnetization.

The relative contribution of the current drift curl$[\mathbf{j}/n_e e\times\mathbf{B}]$ which is different from zero in an inhomogeneous plasma (in a homogeneous plasma with a straight-line magnetic field the direction of the current drift coincides with the level lines of B), is of the order $B^2/4\pi n_e T_e$ and was small in the variants considered. The diffusion of the magnetic field makes an even smaller contribution in the magnetized region $(\omega_e\tau_e)^{-1}B^2/4\pi n_e T_e$, but in dense cold layers, where $\omega_e\tau_e \ll 1$ and the mean free path $l < \delta = c/\omega_p$, the relative role of the diffusion $\sim\omega_e\tau_e\delta^2/l^2$ can be substantial.

The relative contribution of the electron-ion energy exchange to the balance of the electron heat (6) is determined by the aforementioned ratio $(m/M)^{1/2}l/A$. The fraction of the Joule heating $-\mathbf{R}_u\cdot\mathbf{J}/n_e e$ in the electron-energy balance is $\sim(\omega_e\tau_e\delta^2/l^2)^2$ and can be noticeable only in the case of substantial diffusion of the magnetic field in the cold region. The relative contribution of the work of the thermoforce is

$$\mathbf{R}_T\mathbf{j}/n_e e \sim \omega_e\tau_e\delta^2/l^2.$$

An equal contribution $-$ div $\mathbf{q}_{eu}$ is made by the outflow of the heat with the electron flux.

3. We consider planar two-dimensional flow in which the distribution of all the quantities is assumed uniform along the y axis. In this geometry, the magnetic field has one component directed along the y axis. This setup corresponds to a physical situation in which radiation propagating along the x axis is focused by a cylindrical lens on a flat target in only the x direction, and was used by us in the numerical analysis of the magnetothermal problem.[12,13] In neodymium amplifiers with rectangular active elements, the radiation divergence in the direction of the small transverse direction of the element is as a rule much larger than the divergence in the perpendicular direction. When radiation of this type is focused on a target by spherical optics the focal spot is an elongated ellipsoid, so that the model assumed here is closed to the experimental conditions in the "Mishen'-2" facility.[16,17]

The system (1)–(8) was solved numerically for an Euler grid of unequal sides, in a rectangular region measuring 1.2 mm along the x axis and 10 mm along the z axis. The solution method is described in detail in Ref. 18.

At the initial instant of time the temperature and the degree of ionization of the target were assumed uniform, and the plasma velocity equal to zero, with its density dependent only on the coordinate z, while the laser radiation propagated along the z axis towards decreasing z.

The initial condition was chosen to be that of a triply ionized plasma with temperature $T_{e0} = T_{i0} = 10$ eV. Calculations have shown that the influence of the initial values of the temperature and of the degree of ionization is negligible. In the region from $z = 0$ to $z = 30$–$100\ \mu$m we specified $n_i = 5\times10^{22}$ cm^{-3}, the density of the solid aluminum target. Next, with increasing z, the density decrease exponentially to the background value $n_b = 5\times10^{18}$ cm^{-3}, and $(\nabla \ln n)^{-1}$ was varied in the range 3–12.5 μm.

For a more detailed investigation of the evolution of the magnetic fields in the region where the energy is transferred from the absorption region to into the ablation zone, we considered the motion of a fully ionized plasma with maximum density $n_e = 5\times10^{22}$ cm^{-3} in the target region. The density decreased exponentially to $n_{eb} = 5\times10^{18}$ cm^{-3}.

The heat source S is connected with the absorption of laser radiation on account of the inverse bremsstrahlung. The radiation reaching the critical surface is absorbed near it. The refraction and reflection of the radiation was disregarded. We investigated Gaussian distribution of the radiation intensity along the x axis in the form $q = q_0 e^{-x^2/b^2}$ with $q_0 = 3\cdot10^{13}$–5.10^{14} W/cm^2 and $b = 33$–$200\ \mu$m.

The boundary conditions were chosen such that the boundary exerted no influence on the solution inside the region during the maximum calculation time.

4. The results of the calculations of the system (1)–(8) have shown that the initial stage of the evolution of the magnetic fields in a moving plasma is the same as in the magnetothermal model. During the first 0.1 nsec the maximum magnetic field in calculations with total ionization did not differ from the values in the magnetothermal problem (see Fig. 1).

If the density of the laser radiation is distributed sufficiently homogeneously ($b = 2000\ \mu$m), the maximum magnetic fields differ little in both setups also over long times, but if the heat release is faster ($b = 50\ \mu$m) the magnetic field, with the plasma motion taken into account, becomes stabilized at a level ~ 2 MG within a time ~ 0.3 nsec.

We note that the saturation of the magnetic field in the region $n_e > n_{ec}$ has as before a threshold with respect to the sharpness of the spatial distribution of the energy input. Thus, at $b = 200\ \mu$m the magnetic field in the region $n_e > n_{ec}$ increases to a value corresponding to $\omega_e\tau_e \sim (\omega_e\tau_e)^*$ and saturates because it is carried away with the heat. The produced "magnetic mirrors" with $\omega_e\tau_e \gg (\omega_e\tau_e)^*$ hardly penetrate into the region with $n_e > n_{ec}$ [Fig. 2(a)], although they are formed in the region with $n_e < n_{ec}$ in all the considered variants, and limit substantially the thermal conductivity in the direction of the x axis. In the case of a faster heat release ($b \leqslant 50\ \mu$m), the dense plasma magnetization threshold $\omega_e\tau_e \sim (\omega_e\tau_e)^*$, is surmounted and the magnetic mirrors penetrate deeply into the region with $n_e > n_{ec}$ [Fig. 2(b)].

Thus, when the threshold is exceded the hydrodynamic processes influence strongly the distribution of the magnetic field and its maximum value over the region. At the same time, the effect of plasma motion on the integral characteristics, e.g., on the total field flux through the half-plane $x > 0$, is weaker. The magnetic field fluxes in the magnetothermal

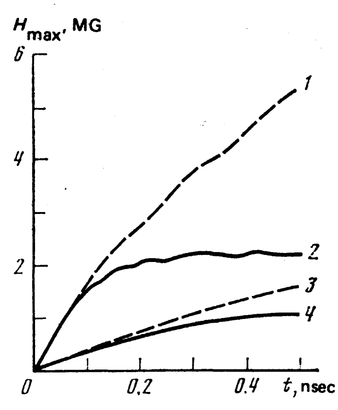

FIG. 1. Time dependence of the maximum value of the magnetic field. The dashed and solid lines correspond respectively to the magnetothermal and complete formulations. Curves 1 and 2 correspond to $b = 33\ \mu$m and $q_0 = 4.5\times10^{14}$ W/cm^2, and curves 3 and 4 to $b = 200\ \mu$m and $q_0 = 0.75\times10^{14}$ W/cm^2.

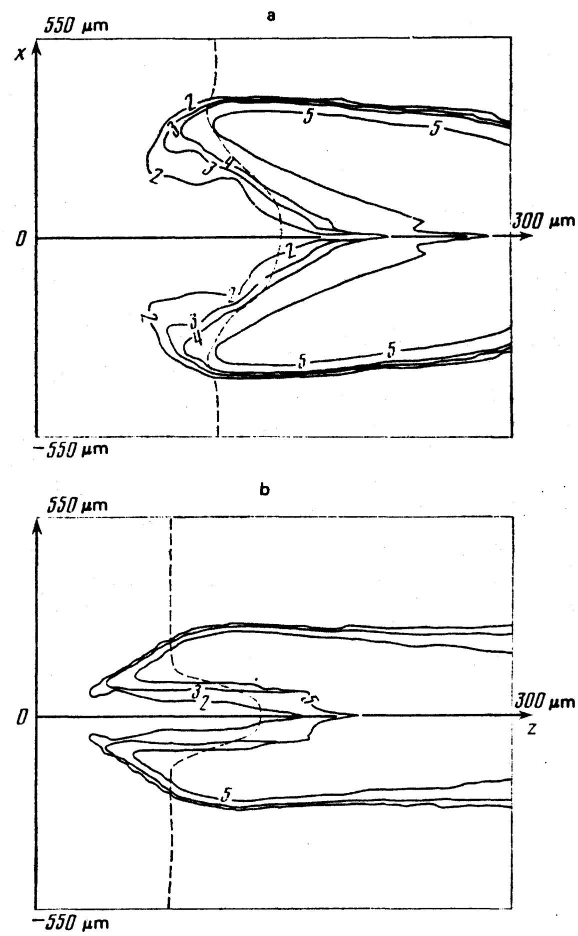

FIG. 2. Level lines of $|\omega_e\tau_e|$ ($t = 0.3$ nsec). Case a and b correspond to $b = 200$ and 33 μm and to $q_0 = 0.75\times10^{14}$ and 4.5×10^{14} W/cm^2, respectively. The line $n_e = n_{ec}$ is shown dashed. Curve 2 corresponds to $\omega_e\tau_e = 0.05$, 3—0.4, 4—0.2, 5—0.5.

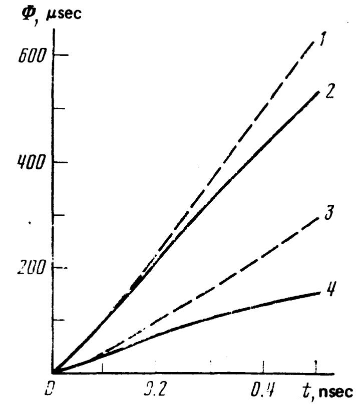

FIG. 3. Magnetic-field flux through the half-plane $x > 0$ (curves 1 and 2) and through the region with $n_e > n_{ec}$ (curves 3 and 4) as function of the time at $b = 33\,\mu$m and $q_0 = 4.5 \times 10^{14}$ W/cm^2. Curves 1 and 3 correspond to the magnetothermal formulation, and 2 and 4 to the complete one.

and complete calculations are close to $t = 0.4$ nsec (Fig. 3).

We note that an appreciable part of the magnetic-field flux is concentrated in the region with $n_e < n_{ec}$, and this part increases with time when allowance is made for hydrodynamics.

To cast light on the main physical mechanisms that limit the growth of the magnetic fields, we varied various processes in the physical model, and compared the contributions of individual mechanisms to the time dependence of the magnetic field. It is certainly clear that saturation of the growth of the magnetic field in the above-threshold regime is due not to the electron-temperature redistribution, which is taken into account also in the magnetothermal setup, but to the plasma motion itself. This motion leads, on the one hand, to departure of the magnetic field from the generation region on account of the freezing, and on the other hand to a density-profile restructuring that alters the very source $[\nabla T_e \times \nabla \ln n_e]$.

A comparison of variants with and without allowance for the hydrodynamic drift in Eq. (6) has shown that the departure of the field is responsible for a partial pushing-out of the magnetic mirrors from the zone with $n_e > n_{ec}$ into the region of the rarefied plasma, and does not change substantially the maximum value of the magnetic field. The region of the most intense magnetic-field generation is located near the front of the thermal wave, and when heated the magnetic mirrors expand into the denser region. It was found that when the plasma motion is taken into account the field sources decreases much more strongly than at a fixed frozen density profile. The heat release increases the pressure and causes expansion of the plasma. Thus, the main cause of the field stabilization is that the density changes to match the electron temperature. Since the acceleration of the new batches of gas is not instantaneous, the profile of the electron density near the thermal wave does not have time to follow the change of the pressure (and hence of the temperature) profile. As a result a source of the magnetic-field generation exists also during hydrodynamic time intervals.

It was shown in the investigation of the magnetothermal problem that the growth rate of the maximum value of the magnetic field depends substantially on the sharpness of the plasma density profile. In a purly hydrodynamic calculation the density profile is established self-consistently under the influence of the heating radiation. Since the heat propagation during the initial stage of the interaction is in advance of the hydrodynamic expansion, the maximum value of the magnetic field also depended on the initial density profile, reaching values 5.2 MG at $(\nabla \ln n)^{-1} = 3\ \mu$m over times ≈ 0.5 nsec. At the same time, the total magnetic-field flux depends little on the initial density profile.

An investigation of the dependence of the magnetic field on the slope of the leading front of the heating pulse has shown that when the front duration changes from 0 to 0.5 nsec the saturation level of the magnetic field does not change. The time of reaching the stationary value correlates well in this case with the pulse growth time.

We have thus shown that the magnetic field strengths are more sensitive to the characteristic of the pre-pulse (which is the one that produces the initial density profile) than to the form of the main heating pulse.

In the calculations presented, the magentic pressure was always much less than the kinetic, i.e., the inequality $B^2/8\pi \ll n_e T_e + n_i T_i$ was satisfied. Owing to the large value $Z = 13$, the internal energy of the ions was much less than the total energy of the plasma. Therefore the redistribution of the ion temperature had little effect on the physical picture of the flow.

We proceed now to discuss the influence of spontaneous magnetic fields the heat transport in an expanding plasma. Figure 4 shows the electron-temperature level lines obtained with and without allowance for magnetic-field generation. The presence of magnetic mirrors (see Fig. 2) leads to a substantial restructuring of the thermal front in the region with $n_e < n_{ec}$. Since the heat-release source is independent of the magnetic field in the approximation considered, the total heat flux in the plasma is fixed. Consequently lowering the thermal conductivity in the magnetic mirrors makes the profile of T_e steeper in both the longitudinal and transverse directions relative to the beam axis. It can be noted in Fig. 4(b) that on the beam axis, where $B = 0$ because of the symmetry of the problem, the channel cross sections with good thermal conductivity do not permit the heat to spread out at the same rate as without the magnetic field [Fig 4(a)]. This overheats the heat-release region. This effect manifests itself particularly strongly when the magnetization threshold of the dense region is broached ($n_e > n_{ec}$). The point is that the bulk of the heat flux is directed towards the dense plasma (towards the target surface). When the magnetic mirrors penetrate into the region with $n_e > n_{ec}$ the overheating of the heat-release region $n_e \approx n_{ec}$ is shown in Fig. 5. The position of the magnetic mirror is illustrated in Fig. 5 by the plot of $|\omega_e \tau_e|$.

The magnetic fields in an expanding plasma were calculated in a number of papers[19–21] in a simplified model, in which no account was taken of the reaction of the magnetic fields on the heat-conduction and plasma motion processes. In the present analysis of the contribution of the various processes to the overall picture of the magnetothermal phenomena we observed a curious circumstance. The magnetic

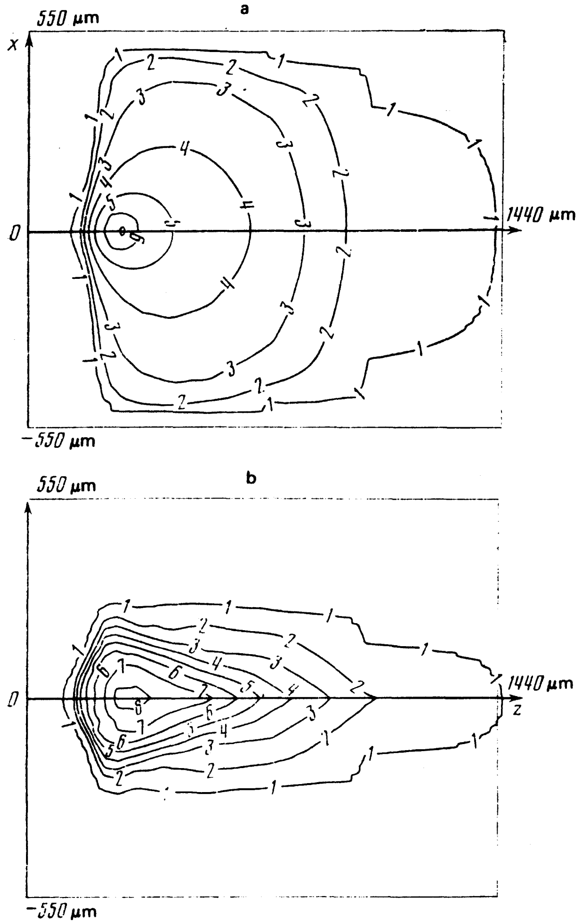

FIG. 4. Level lines of electron temperature at $b = 33\,\mu$m, $q_0 = 4.5\times10^{14}$ W/cm^2, and $t = 0.3$ nsec. The case *a* pertains to the calculation without allowance for the generation and magnetic field, and case *b* to the complete formulation. The curve with index 1 corresponds to $T_e = 0.025$, 2—0.3, 3—0.6, 4—0.9, 5—1.2, 6—1.5, 7—1.8, and 8—2.1 keV.

fields influence not only the heat-conduction processes, but also the rate of generation of the magnetic fields themselves. A calculation was made without allowance for the reaction of the magnetic field to the motion and for the heat conduction of the plasma. In this calculation we retained in the right-hand side of (6) only the generation term $(c/e)[\nabla T_e \times \nabla \ln n_e]$. The magnetic-field flux through the half-

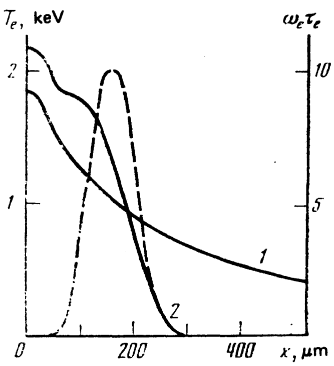

FIG. 5. Transverse profiles of T_e and $|\omega_e\tau_e|$ at $b = 33\,\mu$m, $q_0 = 4.5\times10^{14}$ W/cm^2, and $t = 0.3$ nsec near the critical surface. The dashed line is the profile of $|\omega_e\tau_e|$. Curves 1 and 2 correspond to calculations without and with generation of magnetic fields.

plane $x > 0$ turned out in this case to be much less than in the complete problem. Since the discarded terms of (6) can lead only to a redistribution of the magnetic fields and does not affect the total flux, the decrease of the flux in the simplified model is due only to the decrease of the source $(c/e)[\nabla T_e \times \nabla \ln n_e]$ when the reaction of the fields is turned off. It is interesting that the influence of the magnetization on the generation process itself is found to be much stronger in the hydrodynamic problem than in the magnetothermal formulation. These facts can be explained by recalling that the magnetization of the heat conduction makes the profile of T_e steeper. In addition, the density profile n_e attunes itself in this case to the steeper T_e profile than in the unmagnetized plasma.

Allowance for the ionization processes produced by laser heating has shown that the main characteristics of the magnetic fields differ little from case described above of a fully ionized plasma. The electron temperature in the heated zone is practically the same in both cases. The energy consumed by ionization leads to a somewhat slower motion of the thermal wave.

Although the calculation results pertain directly to heating of the target under conditions of a focal spot that is strongly elongated in one direction, there are grounds for assuming that the deviations from the axisymmetric case are small. In fact, the flow of plasma in the generation region is not accompanied by substantial broadening for which the difference between the two- and three-dimensional pictures can be appreciable.

The main conclusion of the present paper can be taken to be the fact that the main features of the magnetothermal phenomena, previously obtained in a simplified model, are duplicated in the complete formulation of the magnetohydrodynamic problem. The initial stage of the evolution of the magnetic fields, just as in the case of substantial magnetization of the thermal conductivity and in the case of saturation of the growth of the magnetic fields in the dense zone, is the same in the magnetothermal and complete formulations. Saturation of the generation of the magnetic field in the region with $n_e > n_{ec}$ has as before a threshold with respect to the sharpness of the spatial distribution of the heat input. Allowance for the plasma motion limits the maximum value of the magnetic field, but does not change significantly the integral characteristics, e.g., the total magnetic flux. The main cause of the saturation of the magnetic-field growth in hydrodynamic time scale is that the electron-density profile attunes itself to the electron-temperature profile. The magnetization of the plasma by spontaneous fields leads to overheating of the electrons and to limitation of the heat transport in a direction transverse to the laser beam.

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