ment of such instabilities, and obtained quantitative characteristics of this process.

It follows from our analysis that the use of the two-stream instability concepts to interpret the radioemission from pulsars does not contradict the assumption that the near-pulsar plasma is relativistic. Investigations in this direction were performed by a number of workers.[10-15] It must be noted, however, that in these studies the relativism was taken into account by using rather crude and not always consistent simplifying assumptions. This raised objections (see Ref. 3). The approach described above makes it possible to improve the earlier analysis. The development of a consistent theory of collective processes in a relativistic plasma would be useful both for the interpretation of radiation from pulsars and other astrophysical problems, and for laboratory applications.

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1) It is assumed, however, that the distribution function decreases rapidly enough at momenta much larger than the average; for details see below.

2) In the derivation of (2.4) we take into account the one-dimensional character of the particle momentum distribution. For this reason, expressions (2.4) cannot be obtained from the analogous formulas (38) and (39) of Ref. 6, which pertain to an isotropic distribution.

3) The need for introducing a finite p_0 is clear also from the Maxwellian-distribution example considered in Ref. 17.

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Nonlinear effects in the excitation of a magnetic field in a strongly ionized plasma

B. A. Al'terkop

Institute of High Temperatures, USSR Academy of Sciences
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We consider the nonlinear dynamics of the magnetic instability of a one-dimensionally inhomogeneous plasma. It is shown that the principal nonlinear effect that limits the growth of the magnetic perturbations is the dissipation of the temperature inhomogeneity of the plasma. An estimate of the maximum value of the exciting magnetic field is obtained.

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1. It is known that to obtain a high temperature dense plasma with the aid of powerful photon beams or charged particles, the optimal procedure is to produce adiabatically spherically symmetrical heating. Therefore serious misgivings were expressed when spontaneous excitation of a magnetic field, reaching 10^4–10^6 G, was observed in experiments with laser plasma.[1-5] The appearance of strong magnetic fields can lead to asymmetry of the heat flux and affect most adversely the regime of compression and heating of the plasma.

Several assumptions were made concerning the cause of excitation of the magnetic field. It is shown in Refs. 6–8 that the magnetic field can be produced in the re-

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gion of resonance absorption of light. If plane-polarized light is obliquely incident on an inhomogeneous plasma, the electromagnetic wave is transformed into a plasma wave in the reflection region. Under these conditions, the damping of the waves produces a vortical component in the radiation-pressure force, and it is this component which leads to excitation of a quasistationary magnetic field. Usually in experiments the heated target is a plate of organic material. When such a target is irradiated by a focused laser beam, a plasma is produced with a density that varies in the direction of the beam and with a temperature that varies in a plane normal to the laser beam. With this circumstance in mind, it was proposed in Ref. 3 that the mechanism responsible for the excitation of the magnetic field is the action of the thermelectric power in the inhomogeneous plasma.

Indeed, if the plasma pressure gradient is balanced by the electric field:

$$eN\mathbf{E}=-\nabla p,$$

then it follows from Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t}=\frac{c}{e}[\nabla T\times\nabla \ln N]$$

or

$$B(\Gamma c)\approx 0.2 t_p T/L^2,$$

where t_p is the pulse duration in nanoseconds, L is the characteristic dimension of the inhomogeneity in centimeters, and T is the temperature in electron volts. For example, for typical values in experiments with a laser plasma $t_p \sim 1$ nsec, $L \approx 10^{-2}$ cm, $T \approx 10^{-3}$ eV we get $B = 2\times 10^6$ G. In the case of spherically symmetrical heating, the plasma is one-dimensionally inhomogeneous (along the radius), the density and the temperature gradients are collinear, and therefore the considered mechanism turns out to ineffective. The gradients are not parallel possibly as a result of the development of Rayleigh-Taylor instability of the target profile near the front of the thermal wave.[9] In this case the magnetic field is excited in the post-critical region ($N > N_{cr} = m\omega^2/4\pi e^2$, N is the plasma density, ω is the radiation frequency, and e and m are the charge and mass of the electron).

It is shown in Refs. 10–13 that a one-dimensionally inhomogeneous plasma is unstable to the development of magnetothermal perturbations. Physically, the mechanism of this instability consists in the fact that when in a plasma are produced fluctuations of a temperature which is inhomogeneous in a direction other than the direction of the initial inhomogeneity of the pressure, fluctuations are produced in the magnetic field, and this leads to the appearance of a heat flux that strengthens the temperature perturbation. In a strongly ionized plasma[11] the instability of a convective character and the enhancement of the magnetic field occurs in the course of the drift of the magnetic force lines at the rate of thermal diffusion in the electronic component. The necessary condition for instability development is parallelism of the density and temperature gradients, or more accurately $\nabla N\cdot\nabla T > 0$. This situation is realized in the subcritical ($N < N_{cr}$) region of the heated plasma. Thus, an experimental determination of the zone of excitation of the magnetic field could help identify the cause of the instability. However, since the mechanisms considered above can occur simultaneously, an unequivocal separation of one of them is an exceedingly complicated task and has not yet been performed.

The fundamental question in our porblem is the determination of the maximum amplitude of the excited field and of the mechanism of the saturation of this amplitude. In view of the complexity of the problem, no satisfactory answer to these questions has been obtained so far, apart from a numerical simulation with a computer and qualitative estimates.[6,14] A quasilinear theory of the increase of the thermal conductivity of the plasma on small-scale fluctuations of the magnetic field was constructed in Ref. 7, and the amplitude of the fluctuations was again estimated from qualitative considerations.

In the present paper we consider analytically the problem of nonlinear stabilization of the growth of a magnetic field in the course of development of magnetothermal instability of a one-dimensionally inhomogeneous strongly ionized plasma. We discuss the nonlinear effects, their role in the saturation of the unstable perturbations, and their influence on the heat transport, and obtain an upper-bound estimate for the maximum value of the magnetic field.

We note that the mechanism discussed in Ref. 6 for the field saturation due to current of the electrons trapped in a plasma wave is effective only in the region of resonance absorption, and under the condition $l/L > (m/M)^{1/2}$ (l is the electron mean free path and M is the ion mass) the stabilization by convection of the plasma as a whole becomes likewise ineffective for the instability in question.[7,9]

2. The dynamics of the magnetothermal instability of an inhomogeneous plasma is described by the following system of hydrodynamic equations[10,11]:

$$\begin{gathered}\frac{\partial \boldsymbol{\Omega}}{\partial t}=\operatorname{rot}[\mathbf{u}\times\boldsymbol{\Omega}]+\frac{1}{m}[\nabla T\times\nabla \ln N]+\frac{1}{m}[\nabla\beta_\perp\times\nabla T],\\ -\frac{3}{2}N\frac{\partial T}{\partial t}=\operatorname{div}\{N\chi(\gamma_\perp\nabla_\perp T+\gamma_\wedge\tau[\boldsymbol{\Omega}\times\nabla T])\},\\ \frac{\partial N}{\partial t}=0,\quad \mathbf{u}=-\beta_\wedge\frac{\tau}{m}\nabla T.\end{gathered}\tag{1}$$

Here $\boldsymbol{\Omega}=e\delta\mathbf{B}/mc$ is the velocity vector of the cyclotron rotation of the electron, τ is the electron free path time, $\chi = T\tau/m$ is the electron thermal diffusivity, N and T are the density and temperature of the plasma, while the coefficients γ and β as functions of the magnetic field were calculated in Ref. 15.

Equation (1) contained two types of nonlinearity: some are due to the dependence of the transport coefficient on the magnetic field, and others are due to the oblique components of the thermoelectric power and of the heat flux. We choose a coordinate system in which the initial density and temperature are inhomogeneous in the direction of the X axis, the perturbations are inhomogeneous in the XZ plane, and the perturbation of the magnetic field has only y component.

So long as the magnetic field is not too strong, so that $\Omega\tau \ll 1$, under conditions when

$$\frac{dT_0}{dx}=\text{const}, \quad \frac{d\ln N}{dx}, \quad \frac{d\ln T_0}{dx} \ll \frac{1}{L_z},$$

where L_z is the characteristic dimension of the variation of the perturbation in the z direction and T_0 is the unperturbed temperature, the system (1) can be reduced to a single equation with respect to the quantity $\rho \equiv \Omega\tau$:

$$\frac{1}{u_0}\frac{\partial\rho}{\partial t}+(1-3{,}8\rho^2)\frac{\partial\rho}{\partial x}+0{,}14\rho\frac{\partial\rho}{\partial z}=-2{,}25\frac{d\ln N}{dx}(1-0{,}3\rho^2)\rho,$$
$$u_0=-0{,}81\frac{\tau}{m}\frac{dT_0}{dx}. \tag{2}$$

It is easy to establish that the nonlinearities due to the thermoelectric power influence only the trajectory and the drift velocity, and do not affect the field source, which is described by the right-hand side of (2). The decrease of $\beta_\wedge$ with increasing δB leads to a slowing down of the drift in the direction of the X axis, and a decrease of $\beta_\perp$ leads to its acceleration. However, the ratio of the numerical coefficients is such that the summary effect reduces, as is seen from (2), to deceleration. In the Z direction, the situation is just the opposite—the nonlinearity leads to appearance of an increasing z component of the dirft velocity, consequently to a bending of the trajectory of the force lines.

The motion of the perturbation is specified by the characteristics of the equation (2)

$$u_0 dt=\frac{dx}{1-3{,}8\rho^2}=\frac{dz}{0.14\rho}, \tag{3}$$

on which it takes the form

$$\frac{1-3{,}8\rho^2}{1-0.3\rho^2}\frac{d\ln\rho}{dx}=-2.25\frac{d\ln N}{dx}. \tag{4}$$

Integrating (4) we get

$$N^{2,25}\rho(1-0.3\rho^2)^{5,8}=\text{const}. \tag{5}$$

At $\rho^2 \ll 1$ Eq. (5) leads to the result of the linear theory.[11]

It is seen from the solution that the slowing down of the growth of the magnetic field is proportional to the decrease of the temperature gradient along the Z axis:

$$\frac{\partial\delta T}{\partial z}\approx\rho\frac{\gamma_\wedge}{\gamma_\perp}\frac{dT_0}{dx}\approx 1.82(1-0.3\rho^2)\frac{dT_0}{dx}.$$

The nonlinearities determined by the thermoelectric power contribute only to the exponent of the factor that characterizes the decrease of $\partial\delta T/\partial z$. Since the thermal-conductivity coefficients are positive-definite functions of the magnetic field, only the decrease of the thermal conductivity in the increasing magnetic field prevents the quantity $\partial\delta T/\partial z$ from vanishing or reversing sign, and consequently these effects only decrease the growth rate δB, but cannot lead to saturation of the magnetic-field level. Thus, growth of the magnetic field does not stop at the level $\Omega\tau \ll 1$. When the magnetic field is increased to values $\Omega\tau \sim 1$, the nonlinear effects connected with the heat fluxes become substantial.

3. The appearance of a temperature perturbation that is inhomogeneous in z leads to the onset of a magnetic field, and both factors perturb the main heat flux

$$q_{0x}=-N\chi\frac{dT_0}{dx}.$$

This gives rise to fluxes

$$\delta q_z=-N\chi\gamma_\perp\frac{\partial\delta T}{\partial z}+N\chi\gamma_\wedge\rho\frac{dT_0}{dx},$$
$$\delta q_x=-N\chi\gamma_\perp\frac{\partial\delta T}{\partial x}-N\chi\gamma_\wedge\rho\frac{\partial\delta T}{\partial z}. \tag{6}$$

The maximum enhancement of the perturbations corresponds to $\delta q_z=0$. Then

$$\frac{\partial\delta T}{\partial z}=\rho\frac{\gamma_\wedge}{\gamma_\perp}\frac{dT_0}{dx} \tag{7}$$

and

$$\delta q_x=-N\chi\gamma_\perp\frac{\partial\delta T}{\partial x}-\rho^2\frac{\gamma_\wedge^2}{\gamma_\perp}N\chi\frac{dT_0}{dx}. \tag{8}$$

The nonlinear (second) term in (8) describes the additional convective heat transport due to excitation of the magnetic field in the plasma. In the case of stationary heating source (over the time interval characteristic of the instability), this flux leads to a dependence of the initial temperature T_0 on the time. To separate this effect, we substitute in the heat balance equation perturbations of the type $\psi_k(x,t)e^{ikz}$ and average the equation over z. When (8) is taken into account we get

$$\frac{3}{2}N\frac{\partial T_0}{\partial t}=-\frac{\partial}{\partial x}N\chi_{NL}\frac{\partial T_0}{\partial x}, \quad \chi_{NL}=\left\langle \rho^2\frac{\gamma_\wedge^2}{\gamma_\perp}\chi\right\rangle. \tag{9}$$

Relations (9) describe the reaction of the perturbations on the initial state of the plasma. It is seen that it consists of a decrease of the initial inhomogeneity of the temperature, which is one of the causes of the instability. Comparing the time of the decrease of the temperature T_0

$$\tau_T\sim a^2/\chi_{NL} \quad (a^{-1}=\partial\ln T_0/\partial x)$$

with the instability-development time $\tau_i \sim a/u \sim a^2/\beta_\wedge\chi$, we find that $\tau_T < \tau_i$ at

$$\rho^2>\beta_\wedge\gamma_\perp/\gamma_\wedge^2\leqslant 0.2, \tag{10}$$

where the last inequality follows from the definition of the coefficients β and γ.

Let us estimate δB_{max} for a plasma with parameters $N=5\times10^{20}$ cm^{-3} and $T=1$ keV. In this case $\tau\approx 2\times10^{-12}$ sec and $\delta B_{max}\approx 10^4$ G. Thus, a relatively high level of the exciting magnetic field is still insufficient for a substantial distortion of the heat transport in a one-dimensionally inhomogeneous plasma. When the condition $\Omega\tau \approx 0.5$ is satisfied the initial temperature gradient becomes smeared out by the nonlinear heat flux, and the growth of the magnetic field stops.

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Fast waves in a laser plasma

N. E. Andreev, Yu. A. Zakharenkov, N. N. Zorev, V. T. Tikhonchuk, and A. S. Shikanov

P. N. Lebedev Physics Institute, USSR Academy of Sciences
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Heating of spherical targets by intense laser radiation in the Kal'mar installation produced, besides spherically symmetric emission of thermal plasma ions, as various methods have shown, also jet-like emission of groups of fast ions of energy ~ 0.5 MeV. It is shown by analysis of the possible acceleration mechanisms that the observed effect is due to ponderomotive acceleration of the ions in the region of the critical density by the resonantly amplified electric field of the laser radiation. A theory of resonant ion acceleration, in which account is taken of the nonlinear interaction of the plasma waves in the critical-density region, is proposed. Estimates of the energy and of the number of the fast ions agree with the experimental data.

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1. INTRODUCTION

An important problem in laser-mediated thermonuclear fusion is the determination of the redistribution of the absorbed energy in the plasma and the generation of the accelerated particles. The appearance of fast ions that carry away an appreciable fraction of the absorbed energy has been repeatedly reported in recent years.[1-3]

In experiments with the nine-channel "Kal'mar" laser installation in which solid and hollow shell targets were heated, a new effect was observed against the background of the spherically symmetrical expansion of the plasma corona, namely jetlike acceleration of particles to high energy (on the order of 0.5 MeV). The purpose of the present paper is to explain the physical nature of the observed effect and to calculate the main characteristics (number and energy) of the fast particles. It is shown on the basis of an analysis of the possible ion-acceleration mechanism in a nonstationary and inhomogeneous plasma that the formation of a jet of fast ions is due to electrostatic acceleration of the particles in the region of plasma resonance. The presently prevailing theory of ion acceleration in plasma resonance[4] can explain acceleration of the ions to an energy on the order of several dozen kiloelectron volt. To describe ion acceleration to higher energies it is necessary to take into account the nonlinear deformation of the structure of the electric field in the region of the plasma resonance, since the field pressure turns out in this case to exceed the gas kinetic pressure. Such a nonlinear theory of resonant acceleration of ions is developed in the present paper. The derived formulas explain the experimentally observed number and energy of the fast ions.

From the point of view of laser-mediated thermonuclear fusion, an important question is the influence of the ion jets on the symmetry of the compression of shell-like targets. In the case of resonant ion acceleration, this influence turns out to be small because the average momentum transferred to the shell during the time of the collapse is small compared with the gas-kinetic pressure of the plasma. This is due to the short duration of the ion-acceleration process.

2. INVESTIGATION OF THE DYNAMICS OF EXPANSION OF THE PLASMA CORONA

The experiments were performed on the nine-channel "Kal'mar" laser installation, the diagram and diagnostic assembly of which are described in detail in Refs. 5–7. The laser radiation was focused from nine directions on spherical targets of glass (SiO_2) of diameter from 80 to 200 μm, placed in the center of a vacuum chamber. With each light beam having in the region of the target a diameter ~150 μm and an optical

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