Self-focusing of electromagnetic radiation in an opaque layer of plasma

V. A. Isaev, V. N. Kruglov, and B. K. Poluyakhtov

Scientific-Research Radiophysics Institute

(Submitted February 10, 1976)
Zh. Eksp. Teor. Fiz. **71**, 1017–1020 (September 1976)

Experimental data are reported on the dynamics of nonlinear penetration of electromagnetic waves in plasma with $\omega_p > \omega$. It is shown that the nonlinear increase in the transparency of the layer may be accompanied both by self-focusing of the wave field reflected from the plasma and the self-focusing of the radiation penetrating the opaque region.

PACS numbers: 52.40.Db

Thermal self-focusing of electromagnetic radiation propagating in plasma with $\omega_p < \omega$ has frequently been reported.[1–3] In this paper, we report observations of self-focusing on the reflection of waves from plasma with $\omega_p > \omega$, and the nonlinear penetration into an opaque region.

The experimental arrangement was analogous to that described in[1] and consisted of the following. The sharp boundary of decaying plasma, produced by stopping a plasma bunch traveling with ultrasonic velocity with a plane Teflon wall, was illuminated by a beam of electromagnetic waves with wavelength in the millimeter band. The maximum plasma concentration was $N_e = 1.5\times10^{14}$ cm$^{-3} \approx 3N_{\text{crit}}$, the half-life was about 100 μsec, $T_{e0} = T_{i0} = T_m = 0.3$ eV, and the degree of ionization was about 1%. The radiation reflected from the plasma at the specular angle to the boundary ($\theta \sim 45°$) was received by antennas with effective area much smaller than the cross section ($s_{\text{eff}} \ll a^2$, where $a \sim 5\lambda$ is the beam half-width and λ is the wavelength) and was amplitude- and phase-analyzed. The amplitude measurements were normalized to reflection from a metal sheet located parallel to the concentration discontinuity. The variation in the phase of the reflected radiation with time was determined by recording beats produced when the incident and reflected waves were simultaneously received by a mixing diode.

Figure 1 shows the measured energy density in the reflected radiation for two values of the incident wave field, namely, $E_0 = 5\times10^{-3}E_p$ and $E_0 = 3E_p$, 50 μsec after the beginning of irradiation $\{E_0$ is the field strength on the beam axis and $E_p = 4.2\times10^{-10}[\delta T_e(\omega^2+\nu_{\text{eff}}^2)]^{1/2}$ is[4] the characteristic plasma field associated with thermal nonlinearity$\}$. The measurements were performed in the cross section located at 20 cm from the plasma boundary. Comparison of the normalized profiles of the wave beams revealed the presence of self-focusing in the strong radiation reflected from the plasma, which appeared as a reduction in the transverse size of the reflected beam and the substantial (by factors of up to two) increase in the energy density near the axis as compared with the case of linear reflection.

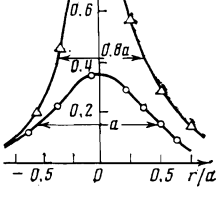

FIG. 1. Energy density distribution in electromagnetic wave beams reflected from a layer of post-critical plasma at $t = 50$ μsec for $N \sim 3N_{\text{crit}}$. $t = 0$—onset of illumination, E_0—maximum field strength in the incident beam, a—beam half-width, ○—$E_0 = 5\times10^{-3}E_p$, △—$E_0 = 3E_p$.

To establish the mechanism responsible for the self-focusing of reflected radiation, we used the phase location method to determine the profiles of the reflection boundary in the nonuniform plasma layer ($N_e = N_{\text{crit}}\cos\theta$). The situation was essentially time-dependent $[N_e(z,t)]$, so that we were able to perform these measurements by conventional interferometry, since the spontaneous decay of the plasma resulted in a continuous reduction in the size of the opaque region, and its boundary traveled inward, into the layer, with the speed $v_0 \sim 7000$ cm/sec. The radial variation in the phase of the reflected radiation was determined with the aid of four antennas separated by distances equal to the half-width of the beam.

The results of phase measurements are shown in Figs. 2 and 3 and indicate directly that, when the plasma was illuminated by the beam with the maximum field strength $E_0 \sim 3E_p$, the motion of the point of reflection in the axial region of the beam was much faster because the period of the beats between incident and reflected waves was appreciably reduced. Analysis of the phase measurements showed that the nonlinear acceleration of the re-

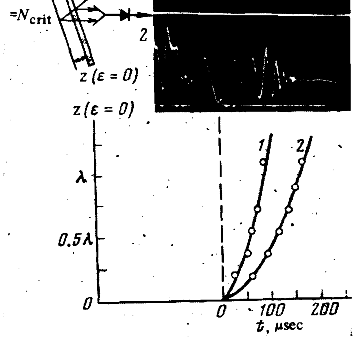

FIG. 2. Oscillograms showing the beats between the reflected and reference waves (receiving antenna located in the axial region of the reflected beam). 1—$E_0 = 3E_p$, 2—$E_0 = 5\times10^{-3}E_p$; lower part of the figure shows the coordinates of the points of reflection ($N_e = N_{\text{crit}}\cos\theta$) in the decaying plasma.

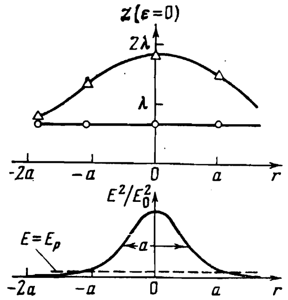

FIG. 3. Instantaneous profiles of the surface of reflection, obtained by the phase location method for plasma exposed to beams with Δ—$E_0=3E_p$ and $\circ$—$E_0=5\times10^{-3}E_p$ for $t=75$ μsec. $t=0$ is the time corresponding to the onset of illumination; the lower graph shows the profile of the electromagnetic wave beam illuminating the plasma.

flecting boundary amounted to $v=v_1-v_0=6000$ cm/sec, so that the strong wave field "pressing" on the plasma gradually penetrated the layer.

Similar measurements at the edge of the beam show that the rate of displacement of the reflecting boundary is an almost local function of the strength of the spatially nonuniform field. This nonuniformity of the nonlinear displacement eventually leads to a substantial curvature of the reflection surface which takes the form of a concave mirror (Fig. 3) and therefore focuses the reflected radiation.

In addition to measurements on the reflected radiation, we have examined the density distribution in the wave field behind a plasma layer of thickness $L_p=10\lambda$. In this case, the beam was incident normally ($\theta=0°$) on the layer, and the low-intensity radiation was in the form of a series of high-frequency pulses, each 125 μsec long.

Oscillograms showing the field energy density behind the plasma layer in the axial region (Fig. 4) clearly indicate the presence of two features in the behavior of the intensity as compared with the linear case. Thus, firstly, there is a substantial reduction in the microwave cutoff time, and secondly, there is an appreciable increase in the axial beam energy density when the plasma begins to transmit. By averaging the measurement results, it was possible to show that, for field strengths $E_0\sim3E_p$ the cutoff time was reduced by a factor of two as compared with the linear case and amounted to 112 ± 6 μsec instead of the 230 ± 11 μsec for $E_0=5\times10^{-3}E_p$. Such a large reduction in the cutoff time clearly shows that the plasma transmits under the action of the incident radiation, since the undisturbed electron concentration for $t=120$ μsec after the onset of cutoff is $1.5N_{\rm crit}$. Measurements of the energy density at the edges of the beam, at a distance of 1.5 cm from the axis, show that the axial region becomes transparent more rapidly than the peripheral region ($\Delta t\sim20$ μsec) and the radiation leaving the layer is focused because the increase in the axial density of radiation is due to the reduction in the transverse size of the beam. The dependence of the axial density on concentration (Fig. 4) shows that the self-focusing is much more clearly defined than in the case of transparent plasma ($N_e<N_{\rm crit}$).

The nonlinear increase in the transparency of plasma which we have observed in our experiment and which is accompanied by the self-focusing of the reflected and transmitted radiation is probably connected with the heating of electrons by collisions in the nonuniform field of the wave beam and the subsequent radial redistribution of its density. In fact, under the conditions of our experiment, the electron thermal conduction length is $L_T=1.45(T_e/m\delta\nu_{ei}\nu_{em})^{1/2}=4$ cm (ν_{ei} and ν_{em} are, respectively, the collision frequencies between electrons and ions and molecules, δ is the fraction of energy transferred from an electron to other particles on collision, and m is the electron mass) and this is comparable with the field nonuniformity ($L_T\sim a$), so that the thermal perturbation of electrons along the radial direction can be regarded as local. The characteristic plasma field associated with thermal nonlinearity is, in this case, much smaller than the incident field ($E_0\sim3E_p$). Hence, it follows that the plasma is strongly heated ($T_e/T_{e0}\leq1+E_0^2/E_p^2$) in a time $\tau_T=1/\nu_{\rm eff}=10^{-6}$ sec, and a region of enhanced pressure with $p=N_e(T_e+T_i)$ appears in the plasma. The relaxation of this region leads to a redistribution of the concentration[4] and to the curvature of the reflecting surface ($N_e=N_{\rm crit}$).

The conditions $E_0^2/E_p^2\geq N_e/N_{\rm crit}$ and $L_T\gg\delta_{\rm sk}=10^{-1}$ cm are also characteristic for our experiments ($\delta_{\rm sk}$ is the skin layer depth). These conditions ensure that the heating of electrons, which occurs under the action of radiation penetrating the plasma to a small depth, occurs throughout the thickness L_p of the layer simultaneously, and the relaxation of the nonuniform pressure results in transmission. The observed transmission time shows that the plasma redistribution is diffusive ($\tau_{\rm obs}=10^{-4}$ sec, whereas the time of ambipolar diffusion is $\tau_N=2a^2M\nu_{\rm im}/T_e=10^{-4}$ sec, where M is the ion mass and $\nu_{\rm im}$ is the ion-molecule collision frequency) and substantially exceeds the time for a thermal perturbation of electrons $\tau_T\sim10^{-6}$ sec. Thus, the temporal dynamics of the nonlinear propagation of the beam is evidently fully determined by the inertia of the redistribution process in the nonuniform plasma. At the instant of nonlinear transmission, the "plasma mirror" is transformed into a "plasma lens," and self-focusing appears

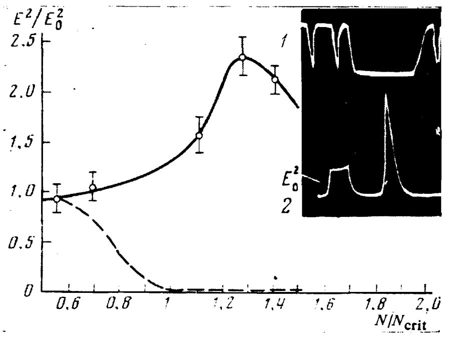

FIG. 4. Radiation density on the axis of the electromagnetic wave beam transmitted by a plasma layer for different concentrations. The oscillograms clearly show the microwave cutoff for signals corresponding to high and low field strengths in the incident radiation in the axial part of the beam. Solid curve—$E_0=5\times10^{-3}E_p$, broken curve—$E_0=3E_p$.

behind the plasma layer.

The increased self-focusing in the case of induced transparency, as compared with the case of transparent plasma ($N_e < N_{\rm crit}$), is probably connected with the appearance in the post-critical plasma illuminated by the incident radiation of a transparency channel of width $d < a$ which, in effect, compresses the beam propagating through it.

The authors are indebted to B. G. Eremin, A. G. Litvak, and M. A. Miller for very useful discussions.

[1] B. G. Eremin and A. G. Litvak, Pis'ma Zh. Eksp. Teor. Fiz. **13**, 603 (1971) [JETP Lett. **13**, 430 (1971)].

[2] V. G. Eremin, A. G. Litvak, and V. K. Poluaktov, Phenomena in Ionized Gases, Contributed Papers, Oxford, 1971, p. 351; Izv. Vyssh. Uchebn. Zaved. Radiofiz. **15**, 1132 (1972).

[3] V. A. Isaev, V. N. Kruglov, A. G. Litvak, and B. K. Poluaktov, Controlled Fusion and Plasma Physics, Contributed Papers, Vol. 1, Moscow, 1973, p. 473.

[4] A. V. Gurevich and A. V. Shvartsburg, Nelineĭnaya teoriya rasprostraneniya radiovoln v ionosfere (Nonlinear Theory of Propagation of Radio Waves in the Ionosphere), Nauka, M., 1973.

Translated by S. Chomet

Stabilization of tearing instability and heating of plasma ions by a modulated particle beam

S. M. Faĭnshteĭn

Gorkiĭ Polytechnic Institute

(Submitted February 20, 1976)
Zh. Eksp. Teor. Fiz. **71**, 1021–1024 (September 1976)

The tearing instability is considered for nonisothermal plasma penetrated by a low-velocity charged-particle beam. Possible stabilization of this instability due to the transformation of the high-frequency wave energy into the energy of a nonlinear ion-acoustic wave is discussed. This phenomenon is equivalent to the nonlinear absorption of the high-frequency waves. The efficiency of heating of heavy particles (ions) by a charged-particle beam is estimated.

PACS numbers: 52.40.Mj, 52.50.Gj, 52.35.En, 52.35.Gq

Tearing (explosive) instability, characterized by a sharp increase in the amplitudes of interacting waves, is known to be possible in nonequilibrium media (see, for example,[1–3]). This instability has been investigated for plasma systems in the case of longitudinal[1,4] and transverse[5,6] waves; efficient generation of microwave radiation in laboratory plasma, previously found under experimental conditions for plasmas[7] and transmission lines,[8] was demonstrated. The main mechanism proposed for limiting the "explosion" was the nonlinear departure from synchronism due to cubic nonlinearity.[9,10,5] In the present paper, we investigate a fundamentally new mechanism for limiting tearing instability. This is connected with the multiwave interaction between hf and lf waves in which the lf waves have positive energy and are attenuated in a linear fashion so that, owing to the presence of a large number of lf branches (or one branch with weak dispersion), nonlinear lf oscillations are generated. The latter situation is equivalent to the nonlinear attenuation of lf waves and leads to the stabilization of the "explosion" in a medium with quadratic nonlinearity. We shall illustrate the analysis by the example of the interaction between a frequency-modulated multivelocity electron beam and the ion-acoustic waves in the main plasma when the modulation frequency is much greater than the Langmuir frequency of the plasma electrons. The higher frequency of the beam wave will then be associated with negative energy, whereas the other beam and ion waves will have positive energies. Linear viscosity-type absorption will be taken into account for the ion sound. It is found that a nonlinear ion-acoustic wave is generated in this system, and this may lead to effective heating of plasma ions as a result of dissipation. The growth of the hf waves is not observed under these conditions, i.e., the tearing instability becomes stabilized by the nonlinear generation of a large number of lf waves, which is equivalent to the nonlinear attenuation of hf waves. The stabilization mechanism for tearing instability is physically interesting in itself, but it can also be used for the effective heating of plasma ions.

1. The basis set of quasihydrodynamic equations is[1)]

$$
\begin{gathered}
\frac{\partial E}{\partial x}=4\pi e(\rho_e-\rho_i+\rho_s),\\
\frac{\partial v_{e,i}}{\partial t}+v_{e,i}\frac{\partial v_{e,i}}{\partial x}=\frac{e}{m_{e,i}}E-\frac{\varkappa T_{e,i}\partial\rho_{e,i}/\partial x}{m_{e,i}(N_{e,i}+\rho_{e,i})},\\
\frac{\partial \rho_{e,i}}{\partial t}+N_{e,i}\frac{\partial v_{e,i}}{\partial x}+v_{e,i}\frac{\partial \rho_{e,i}}{\partial x}=0,\\
\frac{\partial v_s}{\partial t}+V_0\frac{\partial v_s}{\partial x}-\frac{e}{m_e}E=-\nu_s\frac{\partial v_s}{\partial x},\\
\frac{\partial \rho_s}{\partial t}+N_s\frac{\partial v_s}{\partial x}+V_0\frac{\partial \rho_s}{\partial x}=0,
\end{gathered}
\tag{1}
$$

where $\rho_{e,i,s}$ and $v_{e,i,s}$ are the deviations of the concen-