Parametric absorption of laser radiation in a nonisothermal plasma

V. Yu. Bychenkov, V. P. Silin, and V. T. Tikhonchuk

P. N. Lebedev Physics Institute, USSR Academy of Sciences
(Submitted June 24, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 4, 309–312 (20 August 1977)

The roles that the dimension of the parametric-instability region and the finite width of the longitudinal plasma oscillations play in the anomalous absorption of radiation by a plasma is explained.

PACS numbers: 52.25.Ps, 52.35.Py, 52.35.Dm

The study of the anomalous parametric absorption of high-power radiation by a plasma has been attracting much attention. In experiments on laser-driven thermonuclear fusion the plasma is as a rule non-isothermal and the instability saturation is due to secondary parametric decays ($l \rightarrow l' + s$) of the excited Langmuir waves (l) into Langmuir (l') and ion-sound (s) waves,[2] leading to cascaded transfer of the energy of the Langmuir oscillation from the buildup region into the lower-frequency (longer-wavelength region). This model of nonlinear stabilization of ion-sound parametric instability was considered in[3,4] and is a generalization, to the case of a non-isothermal plasma, of the idea of Valeo and Kruer of cascaded transfer of the plasma-wave energy over the spectrum.

It will be shown below that the finite spectral width of the Langmuir-satellite lines leads to a substantial increase of the thresholds of the secondary decay instabilities ($l \rightarrow l' + s$) and contributes to an increase of the rate of parametric absorption of the energy of the pump field.

In an isothermal plasma, when the low-frequency ion oscillations are strongly damped, the spectral width of the core of the nonlinear interaction is of the order of the energy-transfer interval and exceeds the widths of the parametric-buildup region. The spectral widths of the Langmuir-oscillation lines is then determined by the level of the spontaneous noise[5] and turns out to be much less than the dimension of the buildup region. To the contrary, in a non-isotropic plasma the situation is reversed. Because the frequency ω_s of the ion-sound wave greatly exceeds its damping decrement γ_s, the spectral width of the core of the nonlinear interaction $\delta\omega_{NL} \sim \gamma_s + \tilde{\gamma}$ ($\tilde{\gamma} = \nu_{ei}/2$ is the decrement of the Langmuir-oscillation damping) turns out as a rule to be smaller than the spectral width $\Delta\omega$ of the parametric-buildup region. Suppression of the instability is possible in this case only if the widths of the buildup region and of the plasma-oscillation lines are equal. The spectrum of the Langmuir turbulence consists of N satellites. The last (Nth) satellite should have an intensity corresponding to the threshold of the decay ($l \rightarrow l' + s$) instability:

$$E^2_{l,N}/8\pi \approx E^2_{\text{thr}}/8\pi \approx 16\, n_e T_e \frac{\Delta\omega \min(\tilde{\gamma}, \gamma_s)}{\omega_{Le}\omega_s}.$$

This formula takes into account the rise of the threshold of the decay instability for a wave with a large spectral width $\Delta\omega > \max(\tilde{\gamma}, \gamma_s)$ (see[6,7]); n_e and T_e are the density and temperature of the electrons, ω_{Le} is the Langmuir frequency. The satellites with numbers $1 \leq n < N$ have an intensity $E_{l,n}^2 \approx (N+1-n)E_{\text{thr}}^2$.

Besides the Langmuir oscillations, N ion-sound satellites with intensities $E_{s,n}^2 \approx (N+1-n)E_{l,n}^2(\tilde{\gamma}\omega_s/\gamma_s\omega_{Le})$ are excited in a non-isothermal plasma. The ion-sound waves, however make a small contribution in the calculation of the pump-field dissipation, since $\gamma_s E_s^2 \ll \tilde{\gamma}E_l^2$.

To calculate the number of satellites we use the stationarity condition. The power delivered to the plasma by the pump field, which is equal to the product of the characteristic growth rate γ of the primary instability by the intensity $E_{l,1}^2$ of the first peak, is transferred to other satellites, where it is dissipated by collision damping. In the stationary state we therefore have $\gamma E_{l,1}^2 \approx \Sigma_{n\geq 2}\tilde{\gamma}E_{l,n}^2$. This yields $N \approx \gamma/\tilde{\gamma}$. Thus, the level of the parametric plasma turbulence, determined by the combined intensities of all N Langmuir peaks, is given by

$$E_l^2 \approx (\gamma/\tilde{\gamma})^2 E_{\text{thr}}^2 \ . \tag{1}$$

The most important limitation on the region of applicability of formula (1) is the requirement that the Langmuir satellites be stable to aperiodic perturbations. Since the intensity of any satellite does not exceed the intensity of the first one, the stability condition is of the form[7]

$$E_{l,1}^2 < 64\pi n_e T_e (\tilde{\gamma}\Delta\omega)^{1/2}/\omega_{Le} \ . \tag{2}$$

In the case of parametric instabilities, formula (1) enables us to determine the rate of dissipation of the pump-field energy in terms of the effective collision frequency $\nu_{\text{eff}} \approx \nu_{ei}E_l^2/E_0^2$. Let us illustrate the derived general expressions with actual examples of parametric ion-sound, aperiodic, and two-plasmon instabilities under the conditions $\tilde{\gamma} < \gamma_s$ (these conditions correspond to the plasma parameters in controlled thermonuclear fusion). For all these instabilities we have $\Delta\omega = \gamma$ and formulas (1) and (2) can be rewritten in the form

$$E_l^2/8\pi n_e T_e \approx 16\gamma^3/\omega_{Le}\omega_s\tilde{\gamma}; \quad \gamma < \omega_s^{2/3}\tilde{\gamma}^{1/3} \ .$$

We note that these relations hold at a sufficiently high pump intensity, when $\gamma > \gamma_s > \tilde{\gamma}$.[1)]

The growth rate $\gamma \approx (1/4)(v_E/v_{Te})(\omega_{Le}\omega_s)^{1/2}$ of the ion-sound instability increases linearly with the field amplitude at $\omega_s > \gamma > \gamma_s$. (Here $v_E = eE_0/m\omega_0$ is the electron-oscillation pump amplitude in the pump field, and v_{Te} is the thermal velocity of the electrons.) From (1) we get

$$\nu_{\text{eff}} \approx 2\gamma \approx (1/2)(v_E/v_{Te})(\omega_{Le}\omega_s)^{1/2}. \tag{3}$$

At the upper limit $v_E/v_{Te} \sim 4\omega_s^{1/6}\tilde{\gamma}^{1/3}\omega_{Le}^{-1/2}$ of the region of applicability of (4) the value of ν_{eff} exceeds the frequency ν_{e0} of the electron-ion collisions by a factor $(\omega_s/\tilde{\gamma})^{2/3}$. Under conditions of a laser plasma with $T_e \gtrsim 1$ keV this value is of the order of ten.

For an aperiodic instability we have $\gamma = (1/8)\omega_{Le}(v_E/v_{Te})^2$ and the corresponding expression for the effective collision frequency takes the form

$$\nu_{\text{eff}} \approx 2\gamma(\gamma+\gamma_s)/\omega_s\,;\quad (v_E/v_{Te})^2 < 8\omega_s^{2/3}\tilde{\gamma}^{1/3}/\omega_{Le}\,.$$

Attention is called to the fact that the dependence of ν_{eff} on E_0 is much stronger than in (3).

We discuss finally the question of the effectiveness of pump-field absorption in the vicinity of one-quarter of the critical density, where two-plasmon parametric instability takes place. For this instability $\gamma \approx (\sqrt{3}/2)\omega_0 v_E/c$ (c is the speed of light). Therefore ν_{eff} takes the form

$$\nu_{\text{eff}} \approx \omega_0 (v_{Te}/c)^2(\gamma+\gamma_s)/\omega_s\,;\quad v_E/c < \omega_s^{2/3}\tilde{\gamma}^{1/3}/\omega_0\,.$$

Since the region $\Delta x \approx L\,\ln^{-1}(\omega_{Le}\nu_{ei})$[8] of excitation of the two-plasmon instability is appreciable in comparison with the dimension L of the laser-plasma corona, we can find the conditions under which practically all the heating radiation energy is released near one-quarter of the critical density ($\nu_{\text{eff}}\Delta x \gtrsim c$). At the upper limit (in E_0) of the applicability of our theory, this condition takes the form (T_e is in keV and λ_0 and L are in microns)

$$T_e^{1/2} L > 10^3 z^{-1/3}\lambda_0^{4/3}\,.$$

For a plasma produced by a neodymium laser ($\lambda_0 = 1$ μm) with a characteristic inhomogeneity dimension $L = 0.1$ cm, practically total absorption takes place in the region of one-quarter critical density at $T_e > 1$ keV, which is in accord with the conditions necessary to realize a thermonuclear reaction.

[1)]In the opposite case $\gamma < \gamma_s$ we have the result of the known theory of cascade transfer of noise energy,[3] in which no account is taken of the finite spectral line widths of the Langmuir satellites, $E_l^2/8\pi n_e T_e \approx 16\gamma^2\gamma_s/\omega_{Le}\omega_s\tilde{\gamma}$.

[1]V. P. Silin, Parametricheskoe vozdeĭstvie uzlycheniya bol'shoĭ moshchnosti na plazmu (Parametric Action of High-Power Radiation on a Plasma), Nauka, 1973.

[2]V. N. Oraevskiĭ and R. Z. Sagdeev, Zh. Tekh. Fiz. **32**, 1291 (1962) [Sov. Phys. Tech. Phys. **7**, 955 (1963)].

[3]A. A. Galeev, D. G. Lominadze, and G. Z. Machabeli, Zh. Tekh. Fiz. **45**, 1358 (1975) [Sov. Phys. Tech. Phys. **20**, 862 (1975)].

[4]S. Y. Yuen, Phys. Fluids **18**, 1308 (1975).

[5]W. L. Kruer and E. J. Valeo, Phys. Fluids **16**, 675 (1973).

[6]G. M. Zaslavskiĭ and V. E. Zakharov, Zh. Tekh. Fiz. **37**, 10 (1967) [Sov. Phys. Tech. Phys. **12**, 7 (1967)].

[7]V. V. Pustovalov, V. P. Silin, and A. A. Chernikov, Kvantovaya Elektron. (Moscow) (1977) [Sov. J. Quantum Electron.] in press.

[8]V. P. Silin and A. N. Starodub, Preprint No. 44, Phys. Inst., USSR Acad. Sci. 1977; Zh. Eksp. Teor. Fiz. **73**, 884 (1977) [Sov. Phys. JETP **46**, No. 9 (1977)].