Dissipation of strong electromagnetic waves at the point of plasma resonance

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In the linear theory, the absorption of an electromagnetic wave is usually connected with the transformation of the electromagnetic wave into plasma oscillations in the vicinity of the plasma resonance $n = n_c = m\omega^2/4\pi e^2$ (ω is the frequency of the wave incident on the plasma).[1] The smallness of the group velocity of the plasmons leads to their accumulation in the region of the resonance $\Delta z_L \sim (L\lambda_D^2)^{1/3}$ (λ_D is the Debye length and L^{-1} is the characteristic gradient of the density $n = n_0(1 + z/L)$), so that at resonance the longitudinal electric field increases to the large value

$$E_z(0) \sim H(0)\sin\theta\,(L/\lambda_D)^{2/3}$$

Here H is the magnetic field of the wave, θ is the angle between the direction of its propagation in the inhomogeneity direction, and in the case of propagation in the direction of increasing density the wave penetrates beyond the reflection point $n = n_c\cos^2\theta$ only at sufficiently small angles $\theta \sim (c/\omega L)^{1/3}$.

The growth of the field greatly lowers the threshold for the onset of nonlinear effects in the vicinity of the plasma resonance. The deformation of the plasma-density profile, due to the action of the high-frequency pressure force, $\delta n = -|E_z|^2/16\pi nT$, becomes significant under the following condition:

$$\mathcal{E} = \frac{H^2(0)}{16\pi n_0 T}\sin^2\theta\frac{L^2}{\lambda_D^2} > 1. \qquad (1)$$

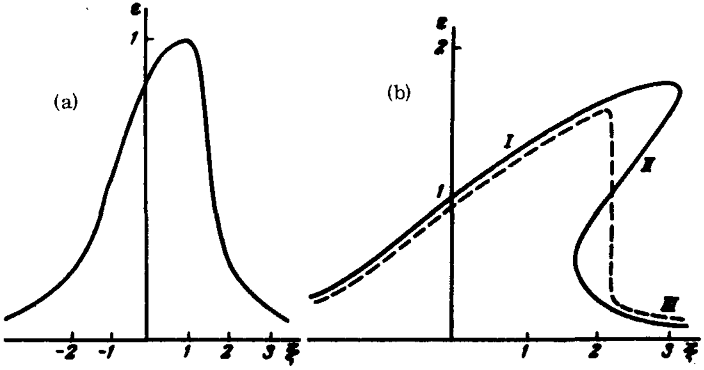
The same inequality is also the condition for the onset of modulation instability—instability to the formation of caverns against the background of a sufficiently uniform distribution of the oscillation energy. The process of the collapse of the caverns and the growth of the field in them has the character of an "explosion" and is bounded only when small scales are reached, for which resonant absorption of the plasmons by the plasma electrons becomes significant because of the increase of the plasmon wave vectors.[4,5]

The development of the modulation instability thus produces a sufficiently effective nonlinear electromagnetic-dissipation mechanism.

Caverns are produced from a pump wave with characteristic dimensions $l \sim \lambda_D\sqrt{16\pi n_0 T/\langle E_z^2\rangle}$ (the angle brackets denote averaging over distances that are large in comparison with the cavern dimension). Under the condition $\mathcal{E} \gg 1$, the initial dimensions of the caverns are much smaller than the width $\Delta z \sim L(\langle E_z^2\rangle/16\pi n_0 T)$ of the region of the plasma resonance, and the energy dissipation of the caverns occurs also in the case of the homogeneous pump wave considered in[5]. The rate of energy dissipation by plasma turbulence is determined by the effective plasma-scattering frequency

$$\nu_{eff} \approx s\,\omega_p\frac{|\langle E_z^2\rangle|}{16\pi n_0 T}. \qquad (2)$$

where s is a numerical coefficient. In computer experiments (see, e.g.[6]), $s \approx 1/4$. In the stationary state, the energy absorbed from the pump wave should be offset by the energy flux into the short-wave part of the spectrum when the caverns collapse:



$$\nu_{eff}|\langle E_z\rangle|^2 \approx \gamma|\langle E_z^2\rangle| \quad (3)$$

$\gamma=\omega_p=\sqrt{(m/M)(\langle E_z^2\rangle/16\pi n_0 T)}$ is the characteristic increment of the modulation stability, which determines the collapse rate.

From (3) we have

$$|\langle E_z^2\rangle| \approx |\langle E_z\rangle|^2 \frac{Ms^2}{m}\frac{|\langle E_z\rangle|^2}{16\pi n_0 T} \quad (4)$$

$\langle E_z\rangle$ is the average field, which varies over distances comparable with the resonance width Δz, and which plays the role of a pump for caverns with plasmons. This field can be obtained by solving Maxwell's equations with nonlinear dielectric constants, with account taken of both the crowding out of the plasma from the resonance region by the high-frequency pressure force, and by the onset of dissipation of electromagnetic energy due to the modulation instability

$$\epsilon_N = -\frac{z}{L} + \frac{|\langle E_z^2\rangle|}{16\pi n_0 T}(1+is). \quad (5)$$

We present the results of the solution for not too large amplitudes in the incident electromagnetic wave, $H_e^2/16\pi n_0 T \ll \sqrt{m/Ms^2}\sin^2\theta$ (under this condition we have $\langle E_z^2\rangle/16\pi n_0 T \ll \sin^2\theta$, and the resonance region does not include the reflection point). The increase of the longitudinal electric field in the resonance region is then determined by the following simple formula:

$$E_z = \frac{H(0)\sin\theta}{\epsilon_N}. \quad (6)$$

The phase of this field changes by π after passing through resonance, and the dependence of the modulus of the field on the coordinate is shown in Figs. a and b. The characteristic values of the field amplitude E_0 at resonance and of the resonance width Δz are obtained from the relations

$$\frac{E_0^2}{16\pi n_0 T} \approx \left(\frac{m}{Ms^2}\right)^{2/5}\left(\frac{H^2(0)\sin^2\theta}{16\pi n_0 T}\right)^{1/5}, \quad (7)$$

$$\Delta z \approx L\left(\frac{Ms^2}{m}\right)^{1/5}\left(\frac{H^2(0)\sin^2\theta}{16\pi n_0 T}\right)^{2/5}. \quad (8)$$

The connection between the magnetic field at resonance $H(0)$ and the amplitude H_e of the incident wave is in this case the same as in the linear theory (see, e.g.,[11]). The wave absorption coefficient R (the ratio of the energy dissipated per unit time in the region of plasma resonance to the energy flux of the incident wave) does not depend on s, and its maximum value [at $(\omega L/c)^{1/3}\theta \approx 0.8$] is $R_{max}=0.4$.

Nonlinear effects in the plasma-resonance region were investigated experimentally,[7] and the results agree quantitatively with the theory developed above. The measured threshold for the onset of nonlinear effects coincides with condition (1). Below the threshold, transformation into plasma oscillations that flow out of the resonance region was observed. When the threshold is exceeded, a region of field localization with crowded-out plasma is produced in the vicinity of the resonance. The initial growth of the field in this region is exponential with an increment that coincides with the theoretical growth rate γ of the modulation instability. During a time $\sim 10/\gamma$ there is established a quasistationary distribution of electric fields, which agrees with the theoretical value (see the table).1) The absence of plasma waves that flow out of the resonance region in the nonlinear regime ("trapped" plasmons) was confirmed experimentally.

	Threshold	Mean-squared field	Average field	Resonance width	Growth rate
	$H^2(0)/16\pi n_0 T$	$\langle E_z^2\rangle/16\pi n_0 T$	$\langle E_z\rangle^2/16\pi n_0 T$	Δz	γ
Theory	$\sim \frac{X_0^2}{L^2}\sim 10^{-6}$	10^{-1}	$5\cdot 10^{-3}$	2 cm	$2\cdot 10^6$ $\gamma\sim\sqrt{\langle E_z^2\rangle}\sim\langle E_z\rangle^2$
Experiment	$\sim 10^{-6}$	0.25 – 0.02	$3\cdot 10^{-2}-3\cdot 10^{-3}$	1-2 cm	10^6 $\gamma\sim H_e^2$

The singularities of the spatial distribution of the longitudinal field, which occur at $s^2 < 0.8$, are shown in Fig. b.[3] In this case, the dependence of the field on the coordinate becomes multiply-valued. Root I corresponds to the stationary state obtained in[2], in which the wave pressure increases in the interior of the plasma z (the wave is an electromagnetic piston).

When dissipation is taken into account, the penetration depth is finite ($\sim \Delta z/s^{2/5}$). At large z, the root III, the width of the transition is realized. Deep pentration of the wave into the plasma is possible only under conditions of sufficiently small dissipation. These conditions are produced in experiment after pulsed application of a high-power electromagnetic wave (see[8]), when the modulation instability does not have time to develop during the time of the pulse. The observed distribution of the longitudinal electric field is close in this case to that shown dashed in Fig. b.

[1)] Columns 2—5 of the table pertain to the case $H^2(0)/16\pi n_0 T \sim 5\times 10^{-5}$, and in the experiment $L = 20$ cm, $T_e = 1$ eV, and $n = 10^9$. The experimental relation $\gamma \sim H_e^2$ is due to the fact that $\langle E_z \rangle \sim H_e$ during the initial stage of the instability.

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