Total resonant absorption of electromagnetic radiation in an inhomogeneous plasma

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Total absorption of an electromagnetic wave under conditions of resonance is revealed, with emission of natural oscillations of an inhomogeneous plasma.

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The development of the most effective method of transferring energy from an electromagnetic field to charged particles is one of the most important problems of plasma physics. In this paper we propose for the input of radiation into a medium a new mechanism that ensures total absorption of the electromagnetic-wave energy incident on the plasma. The physical nature of this absorption mechanism is connected with resonance at the frequencies of the emitted

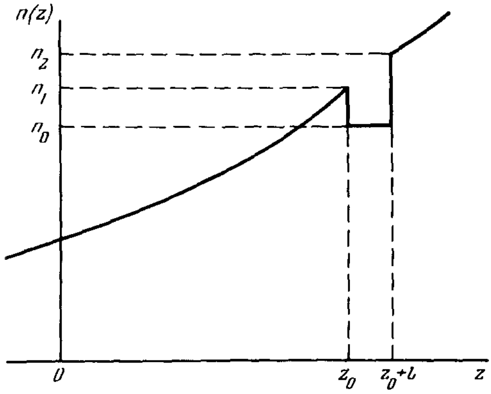

FIG. 1. Plasma particle density vs the coordinate z, where $z=0$ is the point of reflection of the transverse wave.

surface and "trapped" volume waves. These waves exist in a weakly inhomogeneous plasma that contains regions with relatively abrupt variation of the density. These waves attenuate both via the ordinary dissipative mechanisms and as a result of their radiation into the vacuum. Since this radiation is a reversible process, an ideal (without reflection) input of the energy of an electromagnetic field into an absorbing dense medium is possible under conditions when the losses connected with the irreversible dissipative processes are fully cancelled by the energy of the incident radiation.

Consider a plasma with a density distribution $n(z)$ that is inhomogeneous in the z direction (see Fig. 1). We assume that the width l of the square "well" on the density profile is much smaller than the characteristic dimension $L=[d\ln n(z)/dz]^{-1}$ of the plasma inhomogeneity in the regions $z<z_0$ and $z>z_0+l$. We investigate the case when a plane-polarized electromagnetic wave of frequency ω is incident on a plasma having such a density profile, and make the origin $z=0$ coincide with the point where the wave is reflected from the plasma. Assuming the wavelength c/ω to be much smaller than the characteristic inhomogeneity direction L, we can use for the fields, in the regions $z<z_0$ and $z<z_0+l$, the expressions corresponding to the geometrical-optic approximation. Matching these solutions to the expressions for the electromagnetic field intensities in the "well" $z_0<z<z_0+l$, we obtain the following formula for the reflection coefficient

$$R=\left|\frac{G_+-ibG_-}{G_++ibG_-}\right|^2, \tag{1}$$

$$b=\frac{1}{2}\exp\left[-2\int_0^{z_0}\kappa(z)dz\right],\qquad \kappa(z)=\frac{\omega}{c}\left[\sin^2\theta-\epsilon(\omega,z)\right]^{1/2}.$$

Here θ is the angle of incidence of the external electromagnetic wave, $\epsilon(\omega,z)=1-[\omega_{Le}^2(z)/\omega^2]\{1-i[\nu(z)/\omega]\}$ is the longitudinal dielectric constant of the plasma, and $\nu(z)$ is the electron collision frequency.

In the case of s polarization of the electromagnetic wave incident on the plasma, the following expressions hold for $G_\pm$:

$$G_{\pm} = G'_{\pm} + iG''_{\pm} = \left(1 \mp \frac{k_1 k_2}{\kappa_o^2}\right) \mathrm{tg}\, \kappa_o l - \frac{k_1 \pm k_2}{\kappa_o}, \tag{2}$$

$$k_1 = \kappa(z_o), \quad k_2 = \kappa(z_o + l), \qquad \kappa_o^2 = -\kappa^2(z_o < z < z_o + l).$$

It follows from (1) that the reflection coefficient vanishes if the following conditions are simultaneously satisfied:

$$G'_+ = -bG''_- , \tag{3}$$

$$G''_+ = -b\,G'_- . \tag{4}$$

Relation (3) is the condition that the incident wave be at resonance with the transverse oscillations trapped in the "well". These oscillations are radiated from the plasma, additional contribution to their damping decrement. Expression (4) is the condition for complete cancellation of the collision damping of the electromagnetic field on account of the "irradiation" with the flux of the incident external radiation. As can be seen from (3), accurate to exponentially small terms and neglecting the contribution of the collision frequency, the expression for the natural frequencies of the trapped oscillations is

$$\omega_n^2 = \omega_{L0}^2 + k_{\parallel}^2 c^2 + k_n^2 c^2, \qquad \omega_{L0} \equiv \omega_{Le}(z_o < z < z_o + l). \tag{5}$$

Here k_n $(n = 1, 2, 3, \cdots)$ is determined from the equation

$$\mathrm{tg}\, k_n l = \frac{q_n(\sqrt{\Delta_1 - q_n^2} + \sqrt{\Delta^2 - q_n^2})}{q_n^2 - \sqrt{(\Delta_1 - q_n^2)(\Delta_2 - q_n^2)}},$$

$$\Delta_{1,2} = \frac{n_{1,2} - n_o}{n_o}, \qquad q_n = \frac{k_n c}{\omega}, \tag{6}$$

and $\mathbf{k}_{\parallel}$ is the component, perpendicular to the density gradient, of the wave vector of the "trapped" oscillations. Under conditions of space-time synchronism, when $\omega = \omega_n$ and $k_{\parallel} = (\omega/c)\sin\theta$, we obtain from (5) the following expression for the angles θ_n of the wave incidence, at which the reflection coefficient R of (1) vanishes:

$$\sin^2\theta_n = 1 - \frac{\omega_{L0}^2}{\omega^2} - \frac{k_n^2 c^2}{\omega^2}. \tag{7}$$

In the particular case of linear variation of the plasma density in the region $z < z_0[n(z) = n_0(z + L)/L]$, Eq. (4) determines in the following manner the optimal ratio of the densities n_1 and n_0:

$$\frac{n_1 - n_o}{n_o} = q_n^2 + \sigma \ln^{2/3}\left[\frac{c}{\nu l}\,\frac{q_n^3(q_n^2 + \sigma)}{(q_n^2 + \sigma)\,\Delta_2 + (4cq_n^3/\omega_{L0} l)}\right] \tag{8}$$

$$\sigma = (3c\omega^2 \cos^2\theta_n / 4L\omega_{L0}^3)^{2/3}.$$

Here ν is the value of the electron-collision frequency in the "well" $z_0 < z < z_0 + l$.

In the case of p polarization of the electromagnetic wave incident on the plasma it is necessary to use in the reflection coefficient (1) the following expressions for the function $G_\pm$:

$$G_\pm = \left(\frac{\kappa_0}{\epsilon_0} \mp \frac{k_2 k_1}{\epsilon_2 \kappa_0}\right) \operatorname{tg} \kappa_0 l - \frac{k_2}{\epsilon_2} \mp \frac{k_1}{\epsilon_1}, \tag{9}$$

$$\epsilon_0 = \epsilon(\omega, z_0 < z < z_0 + l), \quad \epsilon_1 = \epsilon(\omega, z_0), \quad \epsilon_2 = \epsilon(\omega, z_0 + l).$$

In this case the reflection coefficient can vanish at resonance not only at the frequencies of the "trapped" transverse oscillations ($\omega > \omega_{L0}$), but also under conditions when the frequency of the incident wave coincides with the frequencies of the emitted surface wave ($\omega < \omega_{L0}$).

Thus, as well as in p polarization, the electromagnetic wave in s polarization can be fully absorbed in an inhomogeneous plasma. Calculations show that an analogous effect takes place for all density distributions of a plasma with a "well" in the opacity region, at which "trapped" transverse or surface radiating waves are produced.

We note that under conditions of resonance with the frequency of the radiating waves, the electric field of the wave increases exponentially in the vicinity of the "well" in comparison with the nonresonant case. This can lead to a crowding out of the plasma from the "well" and to the formation of nonlinear plasma configurations of the caviton type.

The distribution of the plasma with a "well" on the density profile was observed experimentally in laser experiments[1] and in numerical calculations. We point out, finally, a study,[3] in which the observed increase of the microwave-power absorption coefficient can also be explained with the aid of the mechanism proposed in this article for the introduction of radiation of radiation energy into a plasma.

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[1] Yu. A. Zakharenkov, N. N. Zorev, O. N. Krokhin, Yu. A. Mikhaĭlov, A. A. Rupasov, G. V. Sklizkov, and A. S. Shikanov, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 557 (1975) [JETP Lett. **21**, 259 (1975)]; Zh. Eksp. Teor. Fiz. **70**, 547 (1976) [Sov. Phys. **43**, 283 (1976)].
[2] K. Estabrook, Phys. Fluids **19**, 1733 (1976).
[3] Yu. Ya. Brodskiĭ, V. L. Gol'tsman, and S. I. Nechuev, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 547 (1976) [JETP Lett. **24**, 504 (1976)].