INFLUENCE OF KINETIC EFFECTS IN AN INHOMOGENEOUS PLASMA ON THE PENETRATION AND REFLECTION OF ELECTROMAGNETIC WAVES

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There is a well-known assertion that electromagnetic waves can penetrate into a plasma by far not at all frequencies ω. Yet the "depth of penetration" of the plasma particles interacting with the wave can greatly exceed the depth of penetration of the field. If furthermore the phase of the velocity distribution function of these particles varies in a regular fashion and has at a certain point in space an extremum with respect to the particle energies, then macroscopic currents appear in the vicinity of this point. Thus, it becomes possible to transmit information concerning the wave motion in a region of space inaccessible to the initial wave, owing to the unique "memory" of this system. In a homogeneous plasma, the "memory" effects become manifest in the form of nonlinear echo signals [1 - 3].

In an inhomogeneous plasma, the "memory" of the system can appear already in the linear approximation, as was demonstrated in [4], where the effect of nonlocal wave reflection was investigated.

We shall study qualitatively, using characteristic examples, the new types of echo that result of inhomogeneity of the plasma and lead, in particular, to the possibility of anomalous penetration of the proper electromagnetic oscillations in the interior of the plasma.

1. Let us consider the propagation of the extraordinary wave in a plasma situated in a magnetic field $\vec{H}_0$ that varies sufficiently slowly in a certain interval of values. Assume that in the vicinity of the points $z_{1,2}(v)$ $(z_1 < z_2)$ there is satisfied for a certain group of particles the cyclotron-resonance condition

$$a(z_n, v) \equiv k(z_n, \omega) - \frac{\omega - \omega_H(z_n)}{v} = 0 \qquad (n = 1, 2), \tag{1}$$

where v is the particle velocity along the force line of $\vec{H}_0$, $k(z, \omega)$ is the wave vector $(k \parallel H_0)$, and the incident wave is absorbed as a result of cyclotron damping in the region $z < z_2(v)$. If the change of the phase of the linear increment of the unperturbed distribution function $F_0(v)$ between the resonance points satisfies the coherence condition

$$\frac{d\theta(v_0)}{dv_0} = 0, \qquad \theta(v) = \int_{z_1(v)}^{z_2(v)} a(z', v)\,dz', \tag{2}$$

which singles out a group of particles near v_0, then the particles of interest to us will emit in the vicinity of the point $z_2(v_0)$ an extraordinary wave that propagates in the region $z > z_2(v_0)$. We shall call this new wave the regenerated wave. For the extraordinary wave, the dispersion equation takes the form

$$\Lambda(\omega, k) \equiv 1 - \frac{c^2k^2}{\omega^2} + \frac{\omega_p^2}{\omega}\int_{-\infty}^{+\infty}\frac{F_0(v)dv}{v\,a(z, v)} = 0.$$

It is easy to show that the conditions (1) and (2) are satisfied if

$$\omega_H = \frac{eH_0}{mc} < \omega, \qquad 3\sqrt{3}\,\omega_p^2 < 2\omega^2.$$

If the solution of the equations for the field, which are not given here, are sought in the WKB approximation (see [4]) in the form of a sum of an incident and regenerated wave with amplitudes $A_\omega(z)$ and $R_\omega(z)$, respectively, then we obtain for the transmission coefficient the expression $[k_{1,2} \equiv k(z_{1,2})]$

$$d(z) = \left| \frac{R_\omega(z)}{A_\omega(z_1)} \exp\left(i \int_{z_2}^{z} k\,dz\right) \right|^2 = \frac{8\pi^3 \omega_p^4 F_0^2(v_0)}{\omega^2 k_1 k_2} \left| \frac{\dfrac{dz_1}{dv_0}\dfrac{dz_2}{dv_0}}{\dfrac{\partial \Lambda}{\partial k_1}\dfrac{\partial \Lambda}{\partial k_2}\dfrac{d^2\theta}{dv_0^2}} \right| \times$$

$$\times \exp\left[-2 \int_{z_2(v_0)}^{z} k_I(z')\,dz'\right].$$

Thus, transport of the electromagnetic field by the plasma particles over a distance on the order of the inhomogeneity length takes place already in the linear approximation.

2. Let us consider the longitudinal echo from two transverse sources in an inhomogeneous isotropic plasma. To simplify the arguments, the bulk of the plasma is assumed to be almost cold with a monotonically decreasing density $N(z)$, to which is added a hot component with a Maxwellian velocity distribution and a uniform density n_0 ($n_0 \ll N$). The external sources

$$j_{ext} = \sum_{n=1}^{2} j_n \delta(z - a_n) \cos \omega_n t \qquad (\omega_1 < \omega_2,\ a_2 - a_1 = d > 0)$$

lie in the region of non-transparency. In second order in the external-signal amplitude, a longitudinal echo current of the hot component is produced at the difference frequency $\omega_3 = \omega_2 - \omega_1$; this echo excites natural oscillations of the bulk of the plasma in the transparency region $\omega_3 > [4\pi e^2 N(z)/m]^{1/2}$ at the point $z_c = a_2 + d(\omega_1/\omega_3)$. In the case when the echo point z_c is far from the reflection point z_0 $[\omega_3^2 = 4\pi e^2 N(z_0)/m]$, the field of the plasma wave is determined by the expression

$$E_l^{(2)} = i\frac{8\pi^3 e d \omega_3 n_0 j_1 j_2 Y}{mc^4 \omega_2 N(z_c) \epsilon_3(z_c)} \times$$

$$\times \exp\left(-\frac{Y^2}{2}\right)\delta(\omega - \omega_3) \left[\frac{N^2(z)\epsilon_3(z_c)}{N^2(z_c)\epsilon_3(z)}\right]^{1/4} \exp\left[i \int_{z_c}^{z} k_3(z')\,dz'\right] \quad (z > z_c), \tag{3}$$

where $Y = (v_T/V_T)/\sqrt{\varepsilon_3(z_c)}$; v_T and V_T are the thermal velocities of the plasma components ($v_T \gg V_T$),

$$\epsilon_3 = 1 - \frac{4\pi e^2}{m} N(z), \quad k_3(z) = \frac{\omega_3}{V_T}\sqrt{\epsilon_3(z)}.$$

It is easy to see from (3) that the echo effect is maximal if the phase velocity $\omega_3/k_3(z_c)$ is of the order of the thermal velocity of the hot component.

3. In an inhomogeneous plasma in the presence of phase coherence of the particles and resonant radiation conditions, there can appear qualitatively new types of nonlinear regeneration of the waves, for example echo at the summary frequency in an isotropic plasma. Let us consider an inhomogeneous isotropic one-dimensional plasma contained by a monotonically-varying effective potential $\Phi(x)$. The external source is given by

$$I_{ext} = \sum_{n=1}^{2} I_n \delta(x - a_n)\cos\omega_n t.$$

After reflection of the particles from the potential $\Phi(x)$, the phase of the second-approximation distribution function takes the form $[v(x, \mathcal{E}) = \sqrt{2(\mathcal{E} - \Phi)}]$

$$\theta(\mathcal{E}, x) = \omega_1\left(\int_{a_1}^{x_\mathcal{E}} \frac{dx'}{v} + \int_{x}^{x_\mathcal{E}} \frac{dx'}{v}\right) + \omega_2\left(\int_{a_2}^{x_\mathcal{E}} \frac{dx'}{v} + \int_{x}^{x_\mathcal{E}} \frac{dx'}{v}\right) \quad (\Phi(x_\mathcal{E}) = \mathcal{E}).$$

Under phase-coherence conditions we have $\partial\theta(\mathcal{E}, x_c)/\partial\mathcal{E} = 0$ in the vicinity of x_c, and a macroscopic current of plasma particles is produced and excites natural oscillations if the resonance point $x_s[k(\omega_1 + \omega_2, x_s) = (\omega_1 + \omega_2)/v(x_s, \mathcal{E})]$ is located near the point x_c.

By way of an example we present a calculation of the echo at the frequency 2ω from one external source, with $\omega < \omega_p(x) < 2\omega$. The field of the echo itself is given by

$$|E_2| = (2\pi)^{5/2} \frac{e\omega_p^2 I^2}{m\omega k_2^3(x_c)} \left| \Pi(x)\,\Pi(x_c) \frac{d^2F_0(\mathcal{E})}{d\mathcal{E}^2} \right|.$$

Here $\Pi(x) = [\partial\varepsilon_2/\partial k_2(x)]^{-1/2}$ and ε_2 is the dielectric constant at the frequency 2ω. The effect under consideration is one of the methods of generating harmonics in an inhomogeneous plasma.

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POSSIBILITY OF DIRECT AMPLIFICATION AND GENERATION OF ELECTRIC WAVES IN SEMICONDUCTORS

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It is well known that in semiconducting crystals acoustic waves can experience Cerenkov amplification under conditions when the carrier drift