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Bleaching of the region of electron cyclotron absorption in a plasma in an inhomogeneous magnetic field

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The results are given of an investigation of the increase in the transparency (bleaching) in the region of electron cyclotron absorption of an electromagnetic wave traveling in a plasma along an inhomogeneous magnetic field. It is shown that measurements of the absorption of electromagnetic waves in a plasma subjected to a magnetic field of known geometry can be used to determine the electron density.

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1. INTRODUCTION

An inhomogeneous magnetized plasma is characterized by the existence of zones (barriers) of total absorption or strong collisionless attenuation of waves traveling in it. It is interesting to create conditions in a plasma that facilitate the penetration of a wave field in the form of undamped oscillations (bleaching). The need for such a bleaching is frequently encountered when hf and microwave methods are used to heat a plasma in thermonuclear experiments.

There are various ways of bleaching which can be divided arbitrarily into local and nonlocal. The local effects are realized under the conditions of validity of the hydrodynamic approximation. One should mention here particularly the penetration of a large-amplitude field into an opaque medium and wave transformation.[1,2] Plasma bleaching occurs as a result of transformation of oscillations because the region of a plasma under discussion becomes transparent to the secondary wave formed as a result of such transformation.

The nonlocal effects are the echo-type kinetic phenomena in which plasma memory elements in one of the microscopic oscillations of the distribution function becomes manifest. In contrast to the homogeneous case, an inhomogeneous plasma may exhibit linear echo effects, such as nonlocal reflection of waves and their regeneration behind the wave barrier. We shall consider the bleaching effect in a region of electron cyclotron absorption as a result of interference of waves reflected from the cyclotron resonance points in a plasma subjected in an nonmonotonically varying magnetic field.

2. THEORY

We shall consider the profile of a plasma-confining magnetic field (Fig. 1) used in the experiments described below. An electromagnetic wave travels from the left to right and its frequency is ω varying from ω_{e0} to ω_{e1}, where ω_{e0} and ω_{e1} are the minimum and maximum electron cyclotron frequencies, respectively. Under these conditions there are two points of electron cyclotron resonance in the plasma, $\omega=\omega_e(z)$, separated by a distance l. The resonance at the first point can be treated in the same way as in the case of a linearly decreasing magnetic field when a wave travels in the direction of reduction in the field. It has been shown[3,4] that under these conditions there is partial absorption of a wave without reflection. At the second point the resonance occurs when a wave travels in the plasma in the direction of increase in the magnetic field. Under these conditions there is partial reflection of an incident electromagnetic wave. If the electron density in the plasma is sufficiently high, the wave is practically totally reflected. The phase of the wave changes by the angle $\Delta\varphi$ as a result of such reflection.

If there are two resonance points separated in space, a wave reflected from the point 2 reaches the point 1 and the latter is the reflection point for the wave because it now travels in the direction of increasing magnetic field. A characteristic capture of oscillations in-

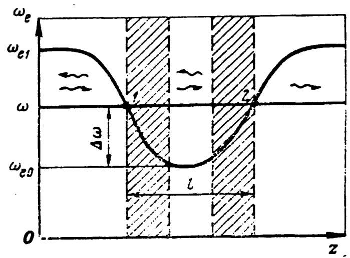

FIG. 1. Variation of the electron cyclotron frequency ω_e along the z axis of the system. The total absorption region is shown shaded.

side a trap then takes place. Clearly, if the phase shift of the oscillations is $kl + \Delta\varphi = \pi n$, where k is the wave vector and n is an integer, natural cyclotron oscillations are established in the trap. This is accompanied by an increase in the wave transmission coefficient, i.e., by bleaching.

Using the random phase approximation (the electron revolution phase is destroyed by each passage through the resonance region) and assuming that $\nu < c/L$, where ν is the electron collision frequency, and $L = B^{-1}(dB/dz)$ at $z = z_{res}$, where L is the characteristic size of the inhomogeneity of the magnetic field, we find that general expressions obtained by Timofeev[5] allow us to deduce the following values for the transmission τ, reflection ξ, and absorption η coefficients of an electromagnetic wave:

$$\tau = \frac{e^{-2\beta}}{1 + (1-e^{-\beta})^4 - 2(1-e^{-\beta})^2 \cos 2\Phi}, \qquad \xi = \tau(1-e^{-\beta})^2, \quad \eta = 1 - \tau - \xi. \tag{1}$$

Here, ω_{pe} is the electron plasma frequency, the parameter used above is

$$\beta = \pi\omega_{pe}^2 L/\omega c, \tag{2}$$

and

$$\Phi = kl - \frac{2\beta}{\pi} kl + i\ln\left(\frac{\Gamma(1-i\beta/2\pi)}{\Gamma(1+i\beta/2\pi)}\right) \tag{3}$$

is the phase shift (advance) of oscillations in a magnetic trap; Γ denotes the gamma function. The last two terms on the right-hand side of Eq. (3) describe the change in the oscillation phase on reflection of a wave from a resonance point.

It is clear from the system (1) that for $\Phi = \pi n$ the transmission and reflection coefficients are maximal and the absorption coefficient of an electromagnetic wave is minimal. For $\beta \gg 1$ (i.e., when the plasma density is sufficiently high), we find that these coefficients are $\tau = \xi = 0.25$ and $\eta = 0.5$. Under these conditions the wave amplitude rises strongly inside the trap and becomes $e^{\beta/2}$ times greater than the amplitude of the incident wave. In the case when $\Phi = \pi(n + 1/2)$, the coefficients τ and ξ are minimal and the coefficient η is maximal. Then, if $\beta \gg 1$, the coefficients τ and ξ tend to zero and the oscillations are absorbed completely.

In the case of a plasma inside a waveguide the system (1) still applies except that the parameter β is now replaced with β_1 (see Ref. 6) and the quantity k is replaced with $k_w = (k^2 - k_{cr}^2)^{1/2}$, where k_{cr} is the critical wave vector in the waveguide.

3. APPARATUS AND EXPERIMENTAL CONDITIONS

We used apparatus described by us in detail earlier.[7] The experiments were carried out in a glass cylindrical tube filled with helium, argon, or krypton. The plasma was formed by an hf oscillator with an output power of 100 W at 40 MHz. The maximum magnetic field created in a solenoid was less than 2 kG and the mirror ratios $R = \omega_{e1}/\omega_{e0}$ were selected to be 1.15, 1.3, and 1.7. An electromagnetic wave of fixed frequency 2.92 GHz was excited using a low-power oscillator (up to 0.5 mW), which avoided any nonlinear effects. This was indicated also by the fact that the values of τ, ξ, and η were independent of the wave amplitude. The gas pressure was at least 1×10^{-3} Torr and the electron density was $n \leq 1 \times 10^{10}$ cm^{-3}.

Under the experimental conditions the frequency of the plasma-probing oscillations was much higher than the frequency ν of collisions of electrons with neutral atoms and the absorption of the wave due to collisions was negligible outside the resonance points. Since, moreover, the condition $\nu \ll c/L$ was satisfied, the collisions did not affect either the coefficient of reflection of the electromagnetic wave from the resonance point 2 (Fig. 1). The mean free path of electrons was of the order of the trap length and, therefore, the experimental results could be interpreted using the random phase approximation.[5] When the electron density in an inhomogeneous (in respect of the density) plasma was high, the upper hybrid and cyclotron resonance points were spatially separated. However, the condition $\omega_{pe}^2 \ll \omega^2 \approx \omega_e^2$ was satisfied in our experiments and, therefore, in spite of the plasma inhomogeneity across the magnetic field, it could still be described by a one-dimensional model and the results could be analyzed by means of Eq. (1).

4. RESULTS OF MEASUREMENTS

We studied the dependences of the transmission coefficient τ, reflection coefficient ξ, and absorption coefficient η of an electromagnetic wave on the ratio $\Delta\omega/\omega_{e0}$. The value of $\Delta\omega$ was varied (Fig. 1) by altering the current passing through the solenoid. Since measurements indicated that the probe ratio remained constant and the electron density, as well as the value of L, changed only slightly, we assumed that the parameter β was hardly affected when $\Delta\omega$ was varied. This variation of $\Delta\omega$ made it possible to alter the distance l between the resonance points and, consequently, the phase Φ, in accordance with Eq. (3). Figure 2 shows the results obtained for an argon plasma at a pressure of 3×10^{-3} Torr for the mirror ratio $R = 1.15$ and the parameter $\beta = 0.5$. It is clear from Fig. 2 that the dependences of the coefficients τ, ξ, and η on $\Delta\omega/\omega_{e0}$ are characterized by maxima and minima, in agreement with Eq. (3).

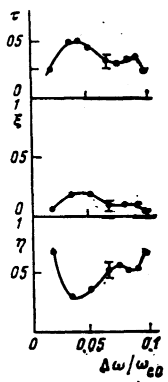

FIG. 2. Dependences of the transmission τ, reflection ξ, and absorption η coefficients on the ratio $\Delta\omega/\omega_{e0}$.

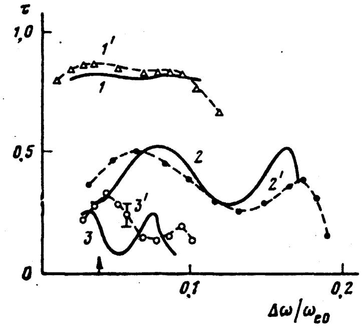

FIG. 3. Dependences of the transmission coefficient τ on $\Delta\omega/\omega_{e0}$. The continuous curves are calculated. 1), 1′) $R=1.15$, $\beta=0.1$; 2), 2′) $R=1.3$, $\beta=0.5$; 3), 3′) $R=1.15$, $\beta=1$.

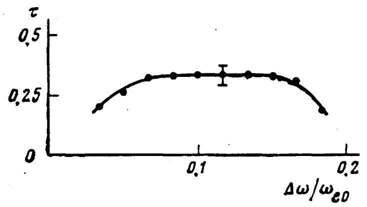

FIG. 4. Dependence of the transmission coefficient τ on $\Delta\omega/\omega_{e0}$.

The transmission τ and reflection ξ coefficients vary in phase but the absorption coefficient η is in antiphase with both τ and ξ. The interval between the maxima in Fig. 2 is in agreement with that calculated from Eq. (3), namely $\Delta l=\lambda_w/2$, where λ_w is the wavelength in the waveguide.

Figure 3 shows the dependences of the coefficients τ on $\Delta\omega/\omega_{e0}$ measured at a pressure of 4×10^{-3} Torr for different electron densities (parameters β) in a helium plasma and for different mirror ratios R. The continuous curves in Fig. 3 are the calculated dependences obtained by means of Eq. (1). A comparison of the experimental and calculated curves in Fig. 3 shows that they are in good agreement. The curves are calculated on the assumption that $\beta=\text{const}$ and $\Phi\approx kl$. However, the first of these conditions is violated when ω approaches ω_{e1} and ω_{e0}: in this case the value of L and, consequently, the parameter β increases (Fig. 1). Allowance for the dependence of β on $\Delta\omega/\omega_{e0}$ produces a better agreement between the calculated and experimental dependences. The second condition applies when $\beta<1$ and it is obeyed for curves 1 and 2 shown in Fig. 3. For high values of β (for example, in the case represented by curve 3), we have to include all the terms in Eq. (3). This shifts the calculated dependence $\tau(\Delta\omega/\omega_{e0})$ to the right and improves the agreement between calculations and experiment. The new position of the maximum of the theoretical curve 3 in Fig. 3 is denoted by an arrow.

The above experiments were carried out under conditions such that the quantity $\nu L/c<1$ and plasma collisions played no significant role. However, it is interesting to generalize Eq. (1) to the case when $\nu L/c>1$, which can easily be achieved under gas-discharge conditions.[4] Then, the formulas in Eq. (1) transform to

$$\tau=\frac{e^{-2\beta}}{1+\xi_0^2-2\xi_0\cos2\Phi},\quad \xi=\tau\xi_0,\quad \eta=1-\xi-\tau,\quad \xi_0=(1-e^{-\beta})^2e^{-4\nu L/c}. \tag{4}$$

It is clear from the formulas (4) that an increase in the ratio $\nu L/c$ reduces the bleaching of a magnetic mirror. This is due to the fact that as $\nu L/c$ increases, there is a reduction in the electromagnetic wave power reflected from the resonance point 2 (Fig. 1) and transmitted by the plasma. An increase in the gas pressure in a weakly ionized plasma then increases the frequency of collisions of electrons with neutral atoms. If $\nu L/c \gg 1$, the resonance points can be considered independently of one another and a symmetric magnetic mirror is then characterized by

$$\tau=e^{-2\beta},\quad \xi=0,\quad \eta=1-e^{-2\beta}. \tag{5}$$

Figure 4 shows the dependence of the transmission coefficient τ on the ratio $\Delta\omega/\omega_{e0}$, obtained for a krypton plasma at a pressure of 5×10^{-2} Torr, mirror ratio $R=1.3$, and parameter $\beta=0.5$. The value of $\nu L/c$ then exceeds unity. It is clear from Fig. 4 that the periodicity of the dependence of τ on $\Delta\omega/\omega_{e0}$ is no longer observed. The reduction in the transmission coefficient of an electromagnetic wave at low and high values of $\Delta\omega/\omega_{e0}$ is due to an increase in the parameter β when the frequency ω approaches ω_{e0} and ω_{e1}, respectively.

We shall conclude that the experimentally determined absorption coefficients of an electromagnetic wave in a plasma are related by a single-valued simple expression to the plasma concentration and, if the magnetic field geometry is known, they can be used to determine the plasma concentration in adiabatic traps.

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