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Absorption of electron plasma waves in a magnetized inhomogeneous plasma

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Results are presented of an experimental study of electron plasma wave absorption in an inhomogeneous magnetized plasma. Comparison of the experimentally-found reflection coefficients with the theoretically computed values reveals they are in fairly good agreement.

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1. INTRODUCTION

The object of the present paper is to study the absorption of magnetized electron plasma oscillations in a plasma of non-uniform density. Propagating along a plasma with a decreasing density, a wave packet formed by electron plasma oscillations reduces its phase (group) velocity $\omega/k_{\parallel}(z)=\omega_{pe}(z)/k_{\perp}$, where ω and ω_{pe} are the oscillation and electron-plasma frequencies, while $k_{\parallel}$ and $k_{\perp}$ are the longitudinal and transverse components of the wave vector. As follows from the quasi-classical analysis,[1] absorption of the electron plasma wave should occur in the resonance region, where the phase velocity of the wave is comparable with the thermal velocity of the electrons. The absorption of such waves is of fundamental importance in the analysis of the stability of one of the prototypes of thermonuclear reactors—open magnetic traps. The opinion has been expressed in a number of theoretical papers (see, for example, the review article[2]) that the potential oscillations spontaneously excited in the central part of the trap should be absorbed at the trap ends. If this conclusion turns out to be correct, then we can, by creating for a plasma a special density-distribution profile, substantially improve the confinement of the plasma in an open trap. The experimental investigation of the absorption of potential oscillations in thermonuclear devices has so far not been carried out.

The results obtained in the experimental investigations[3,4] cannot be used to verify the correctness of the theoretical results.[5,6] Indeed, in[3] the authors studied the reflection of a magnetized electron-plasma wave from a plasma layer near the electrode, when the geometrical-optics approximation, on which the calculations in[5,6] are based, is not applicable. On the other hand, in[4], where the geometrical-optics approximation is applicable, the wave vector of the detected potential oscillations was such that its longitudinal component was of the same order of magnitude as, or even somewhat exceeded, its azimuthal component.

In the present investigation conditions similar to the conditions that obtain at the ends of a magnetic trap are created in a tenuous, weakly-ionized plasma produced with the aid of a gas discharge. Magnetized electron plasma oscillations (the electron cyclotron frequency, ω_{ce}, exceeds the electron plasma frequency, ω_{pe}) are excited by an external generator. The coefficients of reflection of the oscillations from a densitywise inhomogeneous plasma are measured in the cases of longitudinally uniform and nonuniform magnetic fields. The experimental data obtained in the investigation for waves with $k_{\parallel}<k_{\perp}$ are compared with the theoretical results.

2. EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

A schematic diagram of the experimental setup for the study of the reflection of waves is shown in Fig. 1. For the production of the plasma we used a discharge with oscillating electrons, I, and a stabilized current. The inside diameters of the anode A and the reflectors K and the length of the anode cylinder are each equal to 5 cm. One of the reflectors has a hole of diameter 1.5 cm at its center. In some cases the discharge was produced with the aid of a filamentary cathode. The discharge current reached 100 mA. The plasma produced in the region I filled a cylindrical glass tube, 3, of diameter 2.8 cm. The tube is located inside a multisectional solenoid, 4, of total length 150 cm. The series-parallel connection of the individual sections of the solenoid allows the production of both a uniform magnetic field[7] (the inhomogeneity along the axis does not

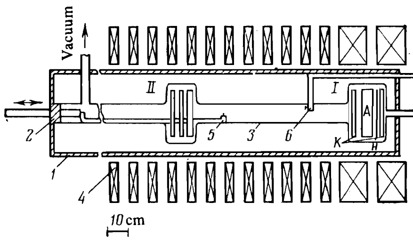

FIG. 1. Schematic diagram of the experimental setup. I) discharge with oscillating electrons: A) cylindrical anode, K) cold-cathode plates, H) filamentary cathode; II) cylindrical electrodes for the creation of a charged-particle concentration gradient in the plasma: 1) copper sheath, 2) vacuum seal, 3) cylindrical glass tube, 4) solenoid coil, 5) movable high-frequency probe, 6) exciting probe.

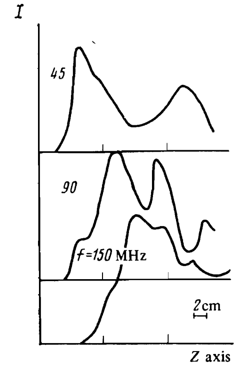

FIG. 3. Distribution of the amplitude, I, of the high-frequency signal along the tube axis, Z.

exceed 5%; over the cross section of the tube, 2%) and a field that varies linearly along the axis. In the latter case the deviation from linearity does not exceed 10%. The variation of the magnetic field leads to the creation of a spatially varying plasma concentration (see Fig. 2, curve 3).[8] For the variation of the electron concentration along the axis of the plasma column located in the uniform magnetic field, we used hollow cylindrical molybdenum bushings located inside the glass bulb II. The diameters of the cylinders were each 5 cm, their lengths were 2 and 4 cm, and the distance between them was 1 cm. By applying different potentials to the cylinders, we can, as shown in[4], establish a concentration distribution profile for the plasma and vary it. The measurement of the plasma concentration was performed with the aid of a movable—along the tube axis—cylindrical probe oriented perpendicularly to the lines of force of the magnetic field. In the measurements we used the ionic part of the probe's current-voltage characteristic. The maximum electron concentration did not exceed 4×10^9 cm^{-3}. The plasma was in this case weakly ionized. The electron temperature in the experiments varied within the limits from 3 to 5 eV.

In Fig. 2 we show typical plasma concentration distribution profiles obtained by the above-described procedure.

The waves were excited in the plasma with the aid of the probe 6, to which was applied a high-frequency voltage potential of amplitude up to 0.5 V in the frequency range from 25 to 200 MHz. The probe 6 has been displaced along a radius through a distance of 0.7 cm from the tube axis.

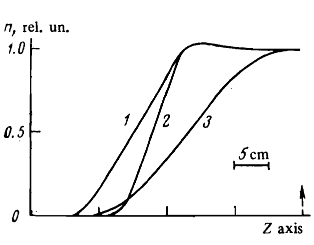

FIG. 2. Typical electron-concentration distributions along the axis, Z, of the plasma column in relative units. The arrow indicates the position in the plasma of the point separated from the exciting probe by a distance of 30 cm. 1) and 2) profiles corresponding to different voltage potentials on the cylindrical electrodes II, 3) profile obtained in an inhomogeneous magnetic field.

For the reception of the signals we used a movable, insulated, high-frequency probe, 5, carefully matched with the receiver. To eliminate external inductions, including the direct influence on the receiving probe of the signals propagating from the probe 6, the system was placed inside a metallic cylindrical tube of diameter 8 cm. The tube was closed at the ends with metallic caps. In the measurement of the oscillation-amplitude distribution in the plasma, the signal from a probe movable along the tube axis was fed into a broadband U3-32 amplifier and then through a narrow-band Kh4-4 amplifier into an automatic X-Y recorder. The variation in space of the phase of the signal was determined either with the aid of an S7-8 stroboscopic oscillograph, or from an interferometer pattern at the output end of the Kh4-4 amplifier.

The reflection coefficient was determined from the measured standing-wave ratios.[9]

The investigations were carried out in an argon plasma at pressures in the range from 1×10^{-4} to 5×10^{-3} Torr in the case of a continuous flow of gas through the system.

3. RESULTS OF THE MEASUREMENTS

In Fig. 3 we show typical amplitude distributions along the tube axis Z (the Z axis is directed along the magnetic field) for the oscillations excited in the plasma. In this case, as shown by the phase measurements, performed by the reference-signal method, a standing wave is detected which is formed upon the reflection of the excited wave from the densitywise inhomogeneous plasma. The frequencies, f, of the external excitation are equal to 45, 90, and 150 MHz. The profile of the electron-concentration distribution in the plasma corresponds to the case 1 in Fig. 2. The electron concentration in the region of the homogeneous part of the plasma $n_0 = 1.2 \times 10^9$ cm^{-3}; the frequency of the electron plasma oscillations $\omega_{pe} > \omega = 2\pi f$. The data presented in Fig. 3 were obtained in a magnetic field $B = 600$ G. In such a field, the condition, $\omega_{ce} > \omega_{pe}$, necessary for the existence of a magnetized Langmuir wave is fulfilled.

The experiments show that, for a given electron-concentration profile, a decrease in the frequency, f, of the external influence is accompanied by a decrease in the longitudinal component of the wave vector. Thus, for the concentration profile 1 (see Fig. 2) and for $n_0 = 1.2\times10^9$ cm^{-3}, the quantity $k_\parallel$ varies from 1.1 to 0.14 cm^{-1} as the frequency f is varied from 200 to 25 MHz.

As the oscillations propagate in the direction of decreasing plasma density, the longitudinal wavelength and, consequently, their phase (group) velocity decrease. In the vicinity of a resonance region, where absorption of the oscillations occurs, the density of their energy increases, which, as can be seen from Fig. 3, is accompanied by a marked increase in the oscillation amplitude.

In Fig. 4 we show the dependence of the ratio ω/ω_{pe} on $k_\parallel/k_\perp$. In this case the magnitude of the component of the wave vector in the azimuthal direction $k_\perp = 1.5$ cm^{-1}. The experimental data presented in Fig. 4 were obtained for different electron concentrations, gas pressures, and magnetic fields. In the experiments, the electron-neutral atom collision rate $\nu_{en} < 0.01\omega$, and the phase velocity of the wave in the homogeneous part of the plasma exceeds the thermal velocity of the electrons. The condition

$$t=\int_0^L \frac{dz}{V}=\int_0^L k_\perp \frac{dz}{\omega_{pe}(z)}<\frac{1}{\nu_{en}}, \quad L=\left(\frac{1}{n}\frac{dn}{dz}\right)^{-1}, \tag{1}$$

where L is the characteristic electron-concentration variation length along the Z axis, is then fulfilled. It follows from the expression (1) that, under the conditions under consideration, we can neglect the collisions of the electrons with the neutral atoms.

In this case it is possible to excite in the plasma magnetized Langmuir waves,[10] the dispersion relation for which has the form

$$\omega=k_\parallel\omega_{pe}(k_\parallel^2+k_\perp^2)^{-1/2}. \tag{2}$$

The dependence $\omega/\omega_{pe} = f(k_\parallel/k_\perp)$ computed from the formula (2) is represented in Fig. 4 by the solid curve, and is in good agreement with the experimental data shown in the same figure.

We carried out measurements of the coefficients of

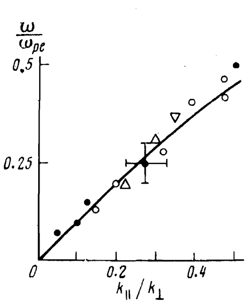

FIG. 4. Dependence of the quantity ω/ω_{pe} on $k_\parallel/k_\perp$. The solid curve was computed from the formula (2). The symbols correspond to the following values of the electron concentration in cm^{-3}, magnetic field in gauss, and gas pressure in Torr: ●) 2×10^9, 400, 5×10^{-4}; ○) 1.2×10^9, 600, 2×10^{-3}; △) 5×10^8, 500, 1×10^{-3}; ▽) 2×10^8, 600, 2×10^{-3}.

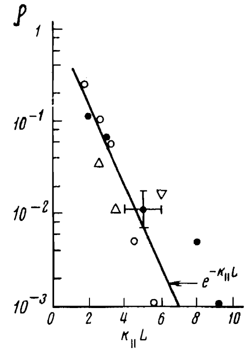

FIG. 5. Dependence of the reflection coefficient ρ on the quantity $k_\parallel L$. The symbols have the same meanings as in Fig. 4.

reflection of electron plasma waves from the plasma boundary. The quasi-classical approximation, which predicts total absorption of the waves in an inhomogeneity of the plasma, turns out to be not quire correct. A more rigorous consideration of the problem leads to the appearance of wave reflection even in the case of a smooth variation of the plasma concentration profile. The expression for the coefficient of reflection of the waves then has the form[5,6]

$$\rho=\exp(-k_\parallel L). \tag{3}$$

The coefficient of absorption of the electron plasma waves $\eta = 1-\rho$.

In Fig. 5 we show the experimentally obtained dependence of the coefficients of wave reflection on the quantity $k_\parallel L$. As the product $k_\parallel L$ is varied from 2 to 9, the reflection coefficient decreases from 0.3 to 0.001. Notice that for $k_\parallel L = 6$ the fraction of the oscillation energy reflected from the inhomogeneous plasma does not exceed 1%. The solid line in Fig. 5 represents the values of the coefficients ρ computed from the formula (3).

It can be seen from Fig. 5 that there is entirely satisfactory agreement between the experimental and theoretical curves for $\rho(k_\parallel L)$. The experimentally obtained reflection-coefficient values do not depend on the amplitude of the alternating voltage potential which was applied to the exciting probe and which was varied from 0.01 to 0.5 V.

Notice that a similar type of dependence of the reflection coefficient on the quantity $k_\parallel L$ was observed earlier in[4], in which, however, the values of the coefficients ρ were obtained for plasma waves under the condition that $k_\parallel > k_\perp$. In this case the expression (2) becomes invalid, since the dispersion properties of the oscillations should depend on the electron temperature.[4] Furthermore, in[4] the excitation of the waves was accomplished with the aid of a metallic ring surrounding the plasma column. In such an excitation procedure, surface waves could, as has been shown in[11], have been generated in the plasma.

4. CONCLUSION

Thus, we have discovered in the investigation considerable absorption of magnetized electron oscillations as they propagate in a densitywise inhomogeneous plasma. The absorption of the oscillations increases with decreasing plasma-density gradient and increasing oscillation frequency. Virtually total absorption is observed in the case when the wavelength of the oscillations turns out to be comparable in magnitude to the characteristic dimension of an inhomogeneity of the plasma.

The found experimental values of the reflection coefficients are in fairly good agreement with the values theoretically computed from the formula (3).

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Direction of transfer of energy and quasi-particle number along the spectrum in stationary power-law solutions of the kinetic equations for waves and particles

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We determine the sign of the flux along the spectrum in exact power-law solutions of the kinetic equations for waves and particles. The direction of the fluxes is uniquely determined by the exponents of the distribution and of the dispersion law, and for the activation spectrum also by the sign of the dispersion term; it depends only on the sign of a simple combination of the exponents. In particular, the direction of the energy flux for waves with a decay spectrum depends on whether the index of the distribution is larger or smaller than -1. We obtain similar criteria also in other cases.

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§1. INTRODUCTION

We know at present many examples of power-law distributions for waves[1–4] and also for particles,[5] obtained as exact solutions of the kinetic equations which describe the interaction of a stochastic ensemble of waves or particle collisions. Stationary non-equilibrium isotropic solutions correspond to a constant, nonvanishing flux of the number of quasi-particles or of energy along the spectrum (see, e.g.,[6,7]). The direction of the flux, which is an important characteristic of the distribution, can sometimes be determined from qualitative considerations using the specific nature of the system (e.g., short-wavelength damping in hydrodynamics, and so on).

We obtain in the present paper general results about the direction of the fluxes for waves with a non-decay (§3) and with a decay (§6) spectrum, and also for particles (§4).[1)] We consider separately the case of an activation spectrum which is of interest in connection with plasmon, exciton, electron, and hole distributions in metals and semiconductors (§5). It turns out that when we determine the direction of the flux we can bypass the calculation of the integral which connects the flux with the distribution functions (§2) if we use symmetry transformations which enable us to find the power-law distributions.[1,2,7,9] These calculations are, however, necessary for finding the dimensionless constants in the distribution function (see the Appendixes).

The direction of the flux is determined by simple inequalities concerning the exponent of the distribution. An analysis of these inequalities shows, in particular, that the transfer of energy and of quasi-particle number proceeds, as a rule, in different directions, as was noted by V. E. Zakharov for hydrodynamic types of systems.

§2. CONNECTION BETWEEN FLUXES AND DISTRIBUTION FUNCTIONS

In a uniform medium when there are no external forces the kinetic equation has the form

