Quasi-electrostatic wave trapping in the thermal channel formed by the near field of an electromagnetic antenna in a magnetized plasma

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The structure of the field of a powerful magnetic source in a dense magnetized plasma is investigated in the lower-hybrid frequency range. Heating-induced transparency of the plasma to quasi-electrostatic waves was recorded. This is due to electron heating in the near field of the antenna and to a lowering of the collisional damping rate for the electrostatic mode. A significant increase of the field amplitude near the boundary of the thermal channel is observed. An analysis of the distribution of the source field together with a detailed study of the dynamics of formation of the profile of plasma density and temperature perturbations lead one to conclude that the field enhancement observed is due to the presence of a sharp boundary of the heated region in the magnetized plasma and to the specific behavior of resonance characteristics near the boundary.

In connection with design of active experiments in the ionosphere there is presently great interest in the problem of formation of artificial plasma structures with regular parameters in the field of an external source as well as the influences of these structures on the radiation of antennas in a plasma.[1-3] Solution of these problems supposes an analysis of the structure and dynamics of the field and plasma in the near zone of the antenna with various source, background plasma, and magnetic field parameters.

To study these questions we carried out research on the dynamics of heating and establishment of quasi-stationary density distributions close to a magnetic radiator in the lower-hybrid (LH) frequency range in a dense magnetized plasma.[4,5] In this study special attention is given to studying the distribution of the field and effectiveness of the source radiation in the process of formation of quasi-stationary plasma structures in the near zone of the antenna.

It is well known that in the lower-hybrid range the field of a source of small dimensions ($a \ll \lambda_{\rm em}$, where a is the size of the antenna and $\lambda_{\rm em}$ is the wavelength of the electromagnetic mode) placed in a plasma has a resonant structure due to the intense perturbation of quasi-electrostatic waves. In a homogeneous medium the field of such a source is localized in the resonance cone.[6] In an inhomogeneous plasma the distribution of the source field can be more complex (see, for example, Refs. 7, 8). In particular, the inhomogeneity can lead to the appearance of singular points[9,10] and resonant surfaces that do not pass through the source. Thus the localization of field on a surface parallel to the boundary of the resonance region was observed in an experiment with a strong magnetic field ($\omega_{\rm pe} \ll \omega_{\rm He}$, where $\omega_{\rm pe}$ and $\omega_{\rm He}$ are the Langmuir and cyclotron frequency of electrons, respectively) and a smoothly varying density profile.[11]

It is shown in the present study that in a magnetized plasma one can have a resonant growth of the field at sharp boundaries of the thermal channel formed in the vicinity of a sufficiently powerful source. It turns out that the angle of inclination of the boundary of the temperature profile to the magnetic field has an important significance in the formation of the field structure of the radiator.

Conditions and basic results of experiments are described in Sec. 1, an analysis of the observed field structure is given in Secs. 2–3, and the influence of local heating on the radiation of an antenna in a plasma is discussed briefly in Sec. 4.

1. The experiments were carried out in a vacuum chamber of length 150 cm and diameter 180 cm. Helium plasma was created at a pressure of 10^{-2} Torr by a high frequency pulse discharge in a homogeneous magnetic field ($H_0 = 200$ G). The antenna consisting of a loop with current (loop radius $a = 0.8$ cm) was placed on the axis of the plasma column of diameter 40 cm. The plane of the loop was oriented across the magnetic field lines. After turning off the high frequency pulse source at the stage of plasma decay ($\tau_N \cong 1$ ms is the characteristic plasma decay time) at a density $N \cong 2\cdot 10^{12}$ cm^{-3} a pulse of high-frequency voltage ($\tau_p = 250$ μs, $\omega = 1.8\cdot 10^8$ s^{-1}, and $U_{\rm inc} = 100$ W) was supplied to the antenna. In the experimental conditions ($T_e \cong T_i \cong 0.4$ eV, where T_e and T_i are the electron and ion temperatures, respectively) the unperturbed frequency of electron-ion collisions $\nu_{ei} \cong 2\cdot 10^8$ s^{-1} was of the same order as the radiation frequency ω and considerably exceeded the frequency of electron-neutral collisions $\nu_{en} \cong 6\cdot 10^6$ s^{-1}. Because the ion-neutral collision frequency $\nu_{in} \gg 2m_e\nu_{ei}/M_i$ (m_e and M_i are the electron and ion masses, respectively), one can consider that the ion temperature was not changed in the heating of electrons.

Moveable double probes and interferometers ($\lambda_0 = 8$ mm and 3 cm) were used for studying the spatial distribution of electron temperature and plasma density, and study of the high-frequency field structure in the plasma was carried out with loop antennas of diameter 4 mm. The emitting and receiving antennas were covered by a layer of dielectric in order to exclude the dependence of entering impedances on processes connected with precipitation of charged particles on the surface of the antenna.

It follows from an analysis of experimental results that due to Ohmic heating of electrons in the quasi-stationary field of the antenna the electron temperature in the vicinity of the radiator increased by a factor of three and reached a value of $T_e \cong 1.2$ eV. In the process of establishing a stationary state a thermal wave with a fairly sharp front between the heated and unperturbed parts of the plasma propagated from the source of heating along the magnetic field.[4] A pro-

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ule of perturbed plasma density was formed as a result of thermal diffusion in the vicinity of the source.[4,5] Quasi-stationary spatial distributions of temperature and density perturbations are presented in Fig. 1.

The appearance of a signal in the high-frequency probe was observed simultaneously with passage of the thermal front which evidenced penetration of the field into the heated region, i.e., transparency of the plasma occurred. Measurements showed that the electromagnetic field in the channel produced by heating was basically localized close to the cone-shaped surface corresponding to the boundary between heated and cold plasma. Spatial distributions of the high-frequency field amplitude at different times are presented in Fig. 2. Specific features of the source field structure are analyzed below.

2. The chosen frequency range was characterized by the inequalities $\Omega_{LH} < \omega \ll \omega_{He} \ll \omega_{pe}$, where Ω_{LH} is the lower-hybrid resonance frequency. In this range propagation is possible only for waves of extraordinary polarization with index of refraction

$$n_e^2=g(|\cos\theta|-\mu)^{-1},$$

where $\mu = (-\varepsilon_1/\varepsilon_3)^{1/2}$, and θ is the angle between the wave vector **k** and the magnetic field; ε_1, ε_3, and g are components of the dielectric permeability tensor. The waves propagating at angles $|\cos\theta| \gg \mu$ are called whistlers and those propagating close to the angles $|\cos\theta| = \mu$ are called electrostatic waves. The dispersion and polarization of whistlers and electrostatic waves differ strongly. We note, in particular, that in electrostatic waves the electric field is much larger than the magnetic field and for whistler waves the opposite relationship is satisfied.

Estimates show that in the conditions of the experiment even in the unperturbed plasma the collisionless damping length of whistler waves

$$L_c=2\omega_{He}c/\nu_e\omega g^{1/2}$$

exceeds the system size. Hence, the effect of field penetration in the heated plasma is connected with excitation of electrostatic waves. In fact, wave numbers of electrostatic waves satisfy $k_e > k_p = \omega_{pe}/c \cong 2.5\ \text{cm}^{-1}$; therefore their damping length satisfies $L_e < \omega_{He}/\nu_e k_p$, i.e., in the unperturbed plasma we have $L_e > 8$ cm. Since $\nu_e \approx T_e^{3/2}$, the inequality $\nu_e \ll \omega$ is satisfied in the heated plasma and the damping scale of electrostatic waves grows sharply, i.e., they can reach the boundaries of the heated region. Measurements show that the field amplitude maximum was observed close to the surface $\mu_e \cong \omega$; a plane cross section of this surface passing through the system axis (at time $t = 140\ \mu$s) is shown in

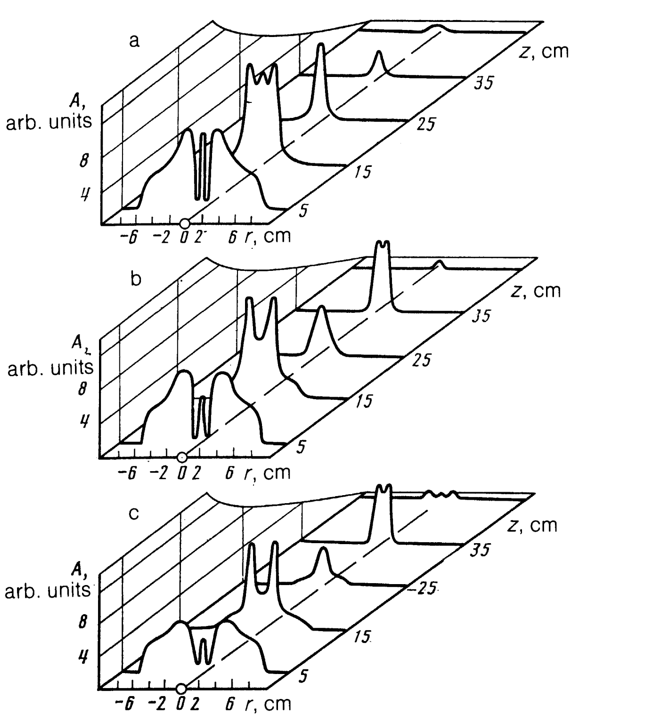

FIG. 2. Spatial distributions of the field in the thermal channel ($P_{inc} = 105$ V) at different times after turning on the source: a—40 μs, b—140 μs, and c—230 μs (the signal amplitude A is proportional to the value $|H_z|^2$).

Fig. 3. The characteristic scale of collision frequency change close to this surface, $l_\nu = \nu_e |\nabla \nu_e|^{-1}$, was approximately 0.5 cm. Thus the heated region was separated from the unperturbed region by a fairly sharp boundary.

Because the loop radius a is small in comparison with the length of a whistler wave $\lambda_c = 2\pi c/\omega g^{1/2} \cong 10.5$ cm, the excitation coefficient of electrostatic waves considerably exceeds the excitation coefficient of whistler waves.[12] As a result the electric field of the thin loop in the transparent plasma has a characteristic resonant structure with a sharp maximum on the conical surface $(r_\perp - a)^2 = \mu^2 z^2$, along which the group velocity vector of electrostatic waves is directed. In the approximation of a cold collisionless plasma the electric field of the thin loop on the indicated surface has a singularity (see Ref. 13), but under the present conditions the amplitude of resonance oscillations is limited due to the collisions. As shown by a simple geometrical construction (Fig. 3), electrostatic waves excited by the antenna reach the boundaries of the heated regions at distances $z_s = 30$–15

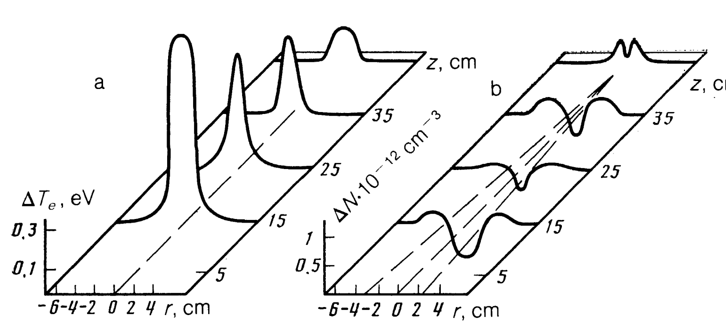

FIG. 1. Spatial distributions of perturbations ΔT_e and ΔN at time $t = 250\ \mu$s ($T_{back} = 0.4$ eV and $\overline{N}_{back} = 2\cdot 10^{12}$ cm^{-3}).

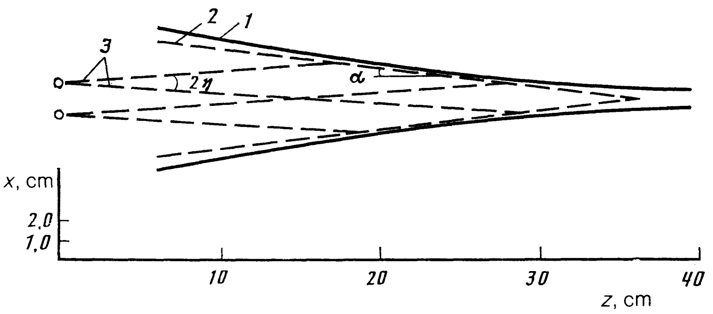

FIG. 3. Cross section of the thermal channel: 1 is the boundary of the thermal channel ($\nu_c = \omega$), and 2 and 3 are characteristics corresponding to reflected and incident waves.

cm from the plane of the loop. A specific feature of the packet of electrostatic waves is its wide spatial spectrum. In fact, all harmonics with wave numbers $k > k_p \cong 2.5$ cm^{-1} which are electrostatic propagate at a fixed angle $\eta \cong \mu$ to the magnetic field independently of the wave vector. It is easy to verify that the primary maximum in the wave spectrum (the spectrum is proportional to $J_1(ka)$, where J_1 is a Bessel function of first order[13]) excited by the current loop corresponds to the point $k_{max} \cong 2/a \cong 3$ cm^{-1}. However, because of the slow fall-off of the spectrum ($\sim k^{-3/2}$), harmonics of much smaller scales are also strongly excited. Waves with $k > 2\pi/l_v \cong 12$ cm^{-1} should apparently be absorbed in the vicinity of the boundary.[1)] At the same time waves whose lengths are larger than l_v with corresponding wave numbers lying in the internal $k_p < k < 2\pi/l_v$ (we shall see that this interval is quite wide and contains the point k_{max}) can be reflected from the boundary of the heated region.

3. In order to clarify the qualitative picture of the generated field structure we consider a model problem supposing that the boundary between transparent plasma ($\nu_c^{(1)} \ll \omega$) and absorbing plasma ($\nu_c^{(2)} \gtrsim \omega$) is sharp. Suppose a plane electrostatic wave propagating in the transparent magnetoactive plasma (specified by the tensor ε_{ij}) falls on a sharp boundary which is inclined at an angle α to the magnetic field $\mathbf{H}_0$ lying along the **z** axis (see Fig. 3). The wave vector and the group velocity vector orthogonal to it of the incident wave as well as the vector of the external magnetic field lie in a plane perpendicular to the boundary. The absorbing plasma is characterized by a dielectric permeability tensor $\varepsilon_{ij}^{(2)}$. We write the electric field of the incident, reflected, and transmitted waves in the form $\mathbf{E}_i \exp(i\mathbf{k}_i\mathbf{r})$, $\mathbf{E}_r \exp(i\mathbf{k}_r\mathbf{r})$, and $\mathbf{E}_t \exp(i\mathbf{k}_t\mathbf{r})$, respectively. The vectors $\mathbf{E}_i$, $\mathbf{E}_r$, and $\mathbf{E}_t$ lie in a single plane and components of the wave vectors are connected by dispersion relations:

$$k_{iz} = -(-\varepsilon_1/\varepsilon_3)^{1/2} k_{ix} = -\mu k_{ix}, \quad k_{rz} = \mu k_{rx},$$

$$k_{tz} = -(-\varepsilon_1^{(2)}/\varepsilon_3^{(2)})^{1/2} k_{tx} = -\mu^{(2)} k_{tx}.$$

From the continuity condition of tangential components of the electric field at the boundary we immediately find

$$k_i \sin(\alpha+\eta) = k_r \sin(\alpha-\eta) = k_t \sin(\alpha+\eta^{(2)}), \tag{1}$$

where $\eta = \arctan \mu$ and $\eta^{(2)} = \arctan \mu^{(2)}$.

Relations (1) show that the wavelength changes in reflection and transmission of electrostatic waves. It is remarkable that when the group velocity of the reflected wave is directed along the boundary (i.e., the wave vector $\mathbf{k}_r$ is orthogonal to the boundary), the length of the reflected waves becomes zero. Using Eqs. (1) and inequalities α, η, $\eta^{(2)} \ll 1$, continuity conditions of the tangential component of the electric field and normal component of the electric induction vector at the boundary can be put into the form

$$(\alpha+\eta)E_i + (\alpha-\eta)E_r = (\alpha+\eta^{(2)})E_t, \tag{2}$$

$$(\varepsilon_3\alpha\eta-\varepsilon_1)E_i - (\varepsilon_3\alpha\eta+\varepsilon_1)E_r = (\varepsilon_3^{(2)}\alpha\eta^{(2)}-\varepsilon_1^{(2)})E_t. \tag{3}$$

The system of Eqs. (2), (3) provides a means of finding the electrostatic-wave reflection coefficient

$$R = \frac{E_r}{E_i} = \frac{(\varepsilon_3\alpha\eta-\varepsilon_1)(\alpha+\eta^{(2)}) - (\varepsilon_3^{(2)}\alpha\eta^{(2)}-\varepsilon_1)(\alpha+\eta)}{(\varepsilon_3\alpha\eta+\varepsilon_1)(\alpha+\eta^{(2)}) - (\varepsilon_3^{(2)}\alpha\eta^{(2)}-\varepsilon_1)(\alpha-\eta)}. \tag{4}$$

Taking into account the definitions of η and $\eta^{(2)}$, we find that

$$R = \frac{\alpha+\eta}{\alpha-\eta}\,\frac{\varepsilon_3\eta - \varepsilon_3^{(2)}\eta^{(2)}}{\varepsilon_3\eta + \varepsilon_3^{(2)}\eta^{(2)}}. \tag{5}$$

In our case of reflection from an absorbing medium the coefficient R can be written in the form

$$R = \frac{[\omega\nu_e^{(2)}]^2}{\omega_{He}^4}\,\frac{\alpha+\omega/\omega_{He}}{\alpha-\omega/\omega_{He}}. \tag{6}$$

Equations (5) and (6) show that in reflection of electrostatic waves the angle of inclination of the boundary plays the most important role: in the case $\alpha \to \eta$ the field the amplitude of the reflected wave grows resonantly and R formally becomes infinite. The sense of this result can be understood by noting that for $\alpha = \eta$ the group velocity of the reflected wave is directed along the boundary and the wave vector is directed orthogonal to it; therefore all wave fronts of the reflected wave lie in the plane of the boundary [which corresponds to the limit $k_r \to \infty$ in Eq. (1)], i.e., the energy of the reflected wave is concentrated in an infinitely thin layer. Thus close to the critical angle $\alpha = \eta$ in the problem of incidence of a plane electrostatic wave on a sharp boundary it is necessary to take into account, for example, the rotational character of the wave or the finite thickness of the boundary. Note that in passing through the critical angle the direction of the group velocity of the reflected wave changes. Hence for $\alpha > \eta$ (see Fig. 4a) the energy flux in the reflected wave is directed along the resonance characteristic to the plane of the source location and for $\alpha < \eta$ it flows in the opposite direction (Fig. 4b).

Because in the experiment the angle α was close to η, the conclusion about the existence of a critical angle and the resonant growth of field amplitude for $\alpha \to \eta$ is important for explaining the observed properties of the field structure. The

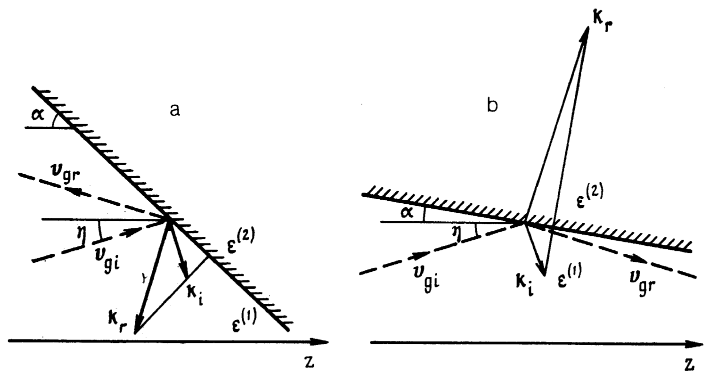

FIG. 4. Reflection of quasi-electrostatic waves from the plane boundary of the heated region in a strongly magnetized plasma: a—$\alpha > \eta$ and b—$\alpha < \eta$. The magnitudes and directions are indicated for wave vectors of the incident ($\mathbf{k}_i$) and reflected ($\mathbf{k}_r$) waves, but only the directions are indicated for the group velocities of incident ($\mathbf{v}_{gi}$) and reflected ($\mathbf{v}_{gr}$) waves.

near-equality of α and η can be understood from the following considerations. The angle α actually corresponds to the angle of inclination of the isothermal surface $\nu_e(T_e) \cong \omega = \nu_e^{(2)}$ to the magnetic field. In magnetized plasma with local electron heating the stationary temperature profile and correspondingly the angle α are determined by the ratio of electron thermal conductivity coefficients perpendicular to and along the magnetic field:

$$\alpha = \left(\frac{\varkappa_{e\perp}}{\varkappa_{e\parallel}}\right)^{1/2} \approx \frac{\nu_e}{\omega_{He}}.$$

The angle of inclination of the resonance characteristics of the field of electrostatic waves in the range of frequencies we studied is $\eta \cong \omega/\omega_{He}$. Therefore during the process of establishing a stationary temperature distribution the angle α approaches η, i.e., it turns out to be close to critical.

It follows from the results of experiments that the characteristic time to establish quasistationary profiles of temperature and plasma density was $\tau_y \cong 60\,\mu$s. Afterwards (for $t > \tau_y$), up to the time of signal turn off on the heating antenna the distributions of density, temperature, and field in the plasma change little.

We turn to a discussion of the properties of the field structure connected with the inhomogeneous distribution of temperature and collision frequency in the plasma volume surrounding the source. These include, first, field growth at large distances from the axis corresponding to the position of the boundary of the heated region. High values of the field and its slow decrease (with the growth of $r_\perp$) in cross sections close to the plane of the antenna at distance $r_\perp \cong 2$–6 cm from the axis should also be noted. Here the largest field values were observed for $t \lesssim \tau_y$, after which the field amplitude decreased (a slow decrease with increasing $r_\perp$ occurred as before), but the relative field amplitude grew close to the system axis at distances $z \cong 35$ cm from the source, i.e., much larger than the focus. For $z = z_s = 15$ cm and $r_\perp \cong 2$ cm an absolute field maximum took place at times $t \gtrsim \tau_y$.

These properties can be explained on the basis of the analysis presented above taking into account the nearness of the angle of inclination of the boundary of the heated region α_s (for $z \cong z_s$) to the critical one. The latter circumstance leads to the growth of fields close to the surface $\omega \cong \nu_e^{(2)}$. At the same time the radius of curvature of the boundary in the experiment has a finite value (see Fig. 3); thus for $\tau \cong \tau_y$ the angle α changes somewhat at the aperture of the incident beam of electromagnetic waves from values less than η to $\alpha > \eta$. It is clear that in these conditions insignificant changes of the temperature distribution can lead to significant changes of the field structure. For $t \lesssim \tau_y$ we have $\alpha > \eta$. Here one should have (together with absorption) reflection of a part of the energy of electrostatic waves incident on the boundary along reflection characteristics in the direction to the emitter. As a result, taking into account the symmetry of the system relative to the antenna plane ($z = 0$) and the possibility of secondary reflections, the energy of plasma oscillations is concentrated in a region quite close to the source for which the field decreases slowly with increasing $r_\perp$. At time $t \cong \tau_y$ the temperature perturbation extends along the magnetic field and the angle α_s decreases, while for $t \gtrsim \tau_y$ we have $\alpha_s \lesssim \eta$. It follows that for sufficiently large times reflection of waves from the boundary in the direction of the source can become important and capable of leading to field growth on the axis at $z = 35$ cm.

As shown by the dependence of field amplitude on the system axis as a function of the power supplied to the source (see Fig. 5) for $z = 35$ cm, this dependence has a threshold character: the field appears at these points only for values $P_{\rm inc} > 80$ V. This effect may be due to the fact that the angle α_s reaches the critical value η beginning with fairly high values of power because the coefficient of thermal conductivity depends significantly on temperature. It should also be noted that for significant field amplitudes in the region where it is localized self-excitation effects can also take place.

4. Simultaneously with study of the radiation field structure we carried out measurements of the power of incident and reflected waves in the antenna feed system. These show that the absorbed power $P = P_{\rm inc} - P_{\rm ref}$ was approximately $\lesssim 0.1\,P_{\rm inc}$, i.e., $P \leqslant 10$ V for $P_{\rm inc} \cong 100$ V. Estimates

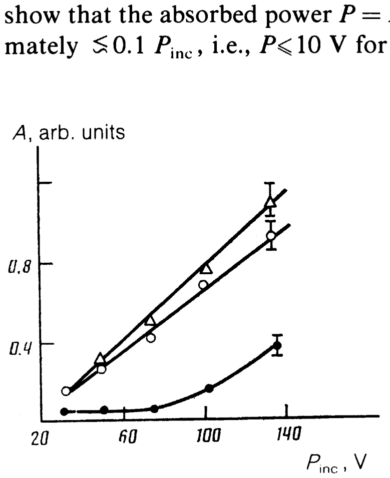

FIG. 5. Dependence of the field amplitude in the thermal channel as a function of the power supplied to the antenna at time $t = 40\,\mu$s at different distances from the radiator: ○—$z = 5$ cm, Δ—$z = 15$ cm, and ●—$z = 35$ cm.

show that the loss of energy (per unit time) in heating the plasma

$$P_\sigma \approx (N_e \Delta T_e + T_e \Delta N_e) V \tau^{-1}$$

was $P_\sigma \cong 5$–7 V (here ΔN_e and ΔT_e are electron density and temperature perturbations in the volume of heated plasma V and the time is $\tau \cong 60\ \mu s \cong \tau_y$). For the radiated power of electrostatic waves we have

$$P_\Sigma = {}^1/_2 R_\Sigma^m I_a^2 \approx 1\ \text{Bт}$$

(where I_a is the current amplitude in the antenna and $R_\Sigma^m = 16\pi a^3 \omega^3 g/3c^4 \cong 0.2\ \Omega$ [Ref. 10]). Thus a large part of the absorbed power is expended in heating.

Because the resistance of the feeder ρ considerably exceeded the value $R_\sigma = 2P_\sigma / I_a^2$ and ωL_a (L_a is the loop inductance), plasma temperature changes surrounding the antenna did not influence the matching of the antenna with the external generator. Thus the emitted power

$$P_\Sigma \approx \frac{U_{\rm inc}^2}{\rho^2} R_\Sigma^m,$$

depending upon the value of the radiation resistance $R_\Sigma^m \sim N_e$, was determined by the plasma density in the vicinity of the radiator. A characteristic oscillogram of the signal from the receiving antenna (Fig. 6) placed close to the radiator ($z = 5$ cm) illustrates the decrease of radiation field amplitude due to the rapid removal of plasma from the heated region as a result of thermal diffusion. Hence plasma heating in the vicinity of the antenna led to a significant change of its radiation efficiency.

5. The experimental studies carried out showed that as a result of plasma heating the structure of the electromagnetic field in the vicinity of the antenna is significantly modified. This is due to the following basic factors.

1) Transparency of the magnetized plasma caused by the sharp drop of electron-ion collision frequency.

2) Decrease of the excitation coefficient of quasi-static waves W_e connected with the rapid removal of plasma from the heated region as a result of thermal diffusion.

3) Growth of the field in the boundary of the heated region due to reflection of quasi-static waves.This effect is connected with the formation of a sharp temperature gradient at the boundary of the heated region of magnetized plasma and depends significantly on the form of this region and spatial spectrum of waves excited by the source.

The decrease of wavelength for reflection at angles close to the critical one provides a means of forming narrow spatial distributions of the radiation field of quasi-electrostatic waves whose scales are comparable with the width of the boundary of the heated region.

4) The resonant growth of the reflection coefficient of quasi-static waves from the sharp boundary inclined to the magnetic field at the critical angle coinciding with the inclination angle of resonance characteristics. For $\nu_e \cong \omega$ in the quasi-stationary state which is formed by the source in the magnetized plasma the reflecting boundary has an inclination angle close to the critical one.

In order to generalize the last conclusion in the study we solved the problem of reflection of a quasi-static wave propagating in a magnetized plasma from a sharply inclined boundary. In spite of its simplicity, this problem was not specifically considered previously.

We note that the problem of reflection from a sharp boundary of electrostatic waves propagating in a magnetized plasma is analogous to the problem of reflection of internal gravity waves propagating in a stratified liquid. Because the dispersion properties of these waves coincide, specific features of the reflection considered above (change of wavelength, and conservation of the angle between the wave vector and direction of anisotropy) occur for internal waves also. In hydrodynamics these specific features were discussed previously in the study of reflection of internal waves from an inclined bottom (see Refs. 14, 15 and the literature cited there) and also observed experimentally (Ref. 16).[2)] In this regard the results obtained in this study together with their practical use in laboratory and space experiments are also of interest for the development of general wave concepts about radiation of sources and dispersive media.

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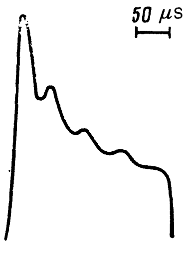

FIG. 6. Oscillogram of the signal from the receiving antenna situated at a distance $z = 5$ cm on the system axis.

[1)] Propagation of such small scale waves can be considered in the BKG approximation.

[2)] In particular, the possibility of accumulation of wave energy in a wedge shaped region was indicated, for example, in the region of the continental shelf as well as the transfer of energy along the spectrum of spatial harmonics connected with reflection.

[1] Active experiments in space. Proceedings of the Intern. Symp., Alpbach (Austria), 1983.

[2] Yu. I. Gal'prin, R. Z. Sagdeev, F. K. Shuiskaya, *et al.*, Kosmicheskie Issled. **19**, 34 (1981).

[3] James H. Gordon, T. R. Darlington, C. H. Henderson, *et al.*, Proc. IEEE **75**, 218 (1987).

[4] G. Yu. Golubyatnikov, S. V. Egorov, A. V. Kostrov, *et al.*, Fiz. Plazmy **14**, 482 (1988) [Sov. J. Plasma Phys. **14**, 285 (1988)].

[5] S. V. Egorov, A. V. Kostrov, and A. V. Tronin, Pis'ma Eksp. Teor. Fiz. **47**, 86 (1988) [JETP Lett. **46**, 102 (1988)].

[6] R. K. Fisher and R.W. Gould, Phys. Fluids **14**, 857 (1971).

[7] N. P. Galushko, N. S. Erokhin, and S. S. Moiseev, Zh. Eksp. Teor. Fiz. **69**, 142 (1975) [Sov. Phys. JETP **42**, 73 (1975)].

[8] A. A. Andronov and Yu. V. Chugunov, Usp. Fiz. Nauk **116**, 79 (1975) [Sov. Phys. Usp. **116**, 343 (1975)].

[9] A. D. Piliya and V. I. Federov, *High Frequency Plasma Heating* [in Russian], IPF, Gorky, 1983.

[10] A. D. Piliya and V. I. Fedorov, Zh. Eksp. Teor. Fiz. **60**, 389 (1971) [Sov. Phys. JETP **33**, 210 (1971)].

[11] R. G. Briggs and R. R. Parker, Phys. Rev. Lett. **29**, 851 (1972).

[12] G. Yu. Golybyatnikov, S. V. Egorov, A. V. Kostrov, *et al.*, Zh. Eksp. Teor. Fiz. **94**, 124 (1988) [Sov. Phys. JETP **67**, 70 (1988)].

[13] E. A. Mareev and Yu. V. Chuganov, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **30**, 961 (1987).

[14] P. H. Le Blond and L. A. Mysek, *Waves in the Ocean*, Elsevier/North Holland, New York (1977).

[15] O. M. Philips, *Dynamics of the Upper Ocean Layer*, Cambridge Univ. Press, New York (1977).

[16] D. Cacchione and C. Winsch, J. Fluid Mech. **66**, 233 (1974).

Translated by D. F. Smith