Investigation of large amplitude oscillations in an inhomogeneous plasma near ion cyclotron resonance

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(Submitted September 6, 1973)
Zh. Eksp. Teor. Fiz. **66**, 598–610 (February 1974)

The excitation of large amplitude oscillations at a frequency $\omega \sim \omega_{Hi}$ in a radially inhomogeneous plasma produced by a high-current linear discharge in hydrogen is investigated experimentally. The plasma density at the axis was of the order of several units of 10^{14} cm^{-3}. The oscillations were generated by a Stix coil, which was the inductor of a surge circuit with stored energy up to 7 J and a frequency of 6.6 MHz. The spectrum of the oscillations excited in the plasma is investigated. Excitation resonance is observed at $\omega \approx \omega_{Hi}$. The radial distribution of the high-frequency field in the plasma is studied, and the type of the excited oscillations is determined. A sharp increase is observed for the high-frequency field strength in the resonant layer, for which $n_{\parallel}^2 \approx \epsilon_1$. At excitation resonance, up to 70% of the energy stored in the circuit was transferred to the plasma. The high-frequency field amplitude in the plasma reached 500 Oe and a rapid increase (within a time $\sim 2\pi/\omega$) of the transverse plasma energy, by an amount 7×10^{15} eV/cm, occurred. This transverse-energy increase may be due to turbulent heating of the plasma in the resonant layer.

INTRODUCTION

In this paper we mean by large-amplitude oscillations those oscillations in the field of which the relative velocity $u_\perp = u_{\perp i} - u_{\perp e}$ of the electrons and ions of the plasma transverse to the constant magnetic field, exceeds some critical value $u_{cr} \sim [(T_i + T_e)/m_i]^{1/2}$. As is well known,[1,2] upon satisfaction of this condition in a plasma, small-scale oscillations are excited, the wavelength of which is much smaller and the frequency much greater than the wavelength and frequency, respectively, of the initial oscillations. Scattering of charged particles by the turbulent electric-field pulsations due to the development of such instabilities should lead to an effective heating of the plasma.

Rapid heating of electrons and ions of a plasma by a strong high-frequency field, upon satisfaction of the criterion given above, has been observed experimentally in the excitation in the plasma of a direct ($\omega_{Hi} < \omega \sim (\omega_{He}\omega_{Hi})^{1/2}$) [3] for an oblique ($\omega_{Hi} < \omega \ll (\omega_{He}\omega_{Hi})^{1/2}$ [1,2,4] magnetosonic wave of large amplitude (ω is the frequency of the wave; ω_{He} and ω_{Hi} are the cyclotron frequencies of electrons and ions). Here the heating time of the electrons was less than one period of the high-frequency oscillations. Effective heating of the plasma also occurred in experiments on the excitation of ion cyclotron waves of high amplitude.[5,6] Under conditions of excitation of a fast magnetosonic wave of high amplitude in a plasma, small-scale high-frequency oscillations were discovered experimentally and were identified with one of the possible types of instabilities described above.[7]

In experiments for obtaining high-frequency fields of large amplitude,[2-6] along with powerful energy sources – shock excited circuits – the phenomenon of resonance excitation or resonance coupling was also used effectively, wherein the high-frequency field in the plasma increases significantly when the wavelength and the frequency of the oscillations generated by the external source are close to the wavelength and frequency of the characteristic oscillations of the plasma column. The energy entering the plasma also increases in corresponding fashion.

In the present research, the possibility of resonance excitation of high-frequency fields of large amplitude is explored experimentally in the region of ion cyclotron resonance in a plasma column that is highly inhomogeneous along its radius. In contrast with the case in which an ion cyclotron wave is excited in a homogeneous or weakly inhomogeneous plasma (the corresponding experiments are described, for example, in [8,9]) the problem of the resonance excitation of oscillations with frequency $\omega \approx \omega_{Hi}$ in a highly inhomogeneous plasma becomes complicated if the so-called resonance layer exists and is characterized by the relation

$$n_{\parallel}^2 \approx \varepsilon_1. \qquad (1)$$

Here $n_{\parallel} - k_{\parallel} c/\omega$ is the longitudinal index of refraction, the value of which is determined by the axial period $\Lambda = 2\pi/k_{\parallel}$ of the excited system, and $\epsilon_1 \approx \omega_{pi}^2/(\omega_{Hi}^2 - \omega^2)$ is the component of the dielectric tensor.

As is well known,[10-12] in the vicinity of this layer, the square of the transverse index of refraction $n_\perp = k_\perp c/\omega$ has a singularity and the component of the electric field of the oscillations in the direction of the density gradient increases rapidly. In particular, it is known[10-12] that conditions are possible for which the ion cyclotron wave, which is excited by the external source on the surface of the plasma column, and which propagates towards the axis (in the direction of increasing density), will be completely absorbed in the resonance layer and then the resonance excitation will generally no longer take place.

In the present research, the high-amplitude oscillation spectrum is studied in detail; these oscillations are excited in the region of ion cyclotron resonance ($\omega \sim \omega_{Hi}$) of a Stix coil in an essentially inhomogeneous plasma, created by a high-current direct discharge. Resonance excitation was observed, the high-frequency field distribution in the plasma was measured, and the type of excited oscillations was determined. Here the phenomenon of a sharp increase in the amplitude of the high-frequency field in the resonance layer, predicted by the theory, has been observed.[1)] When the high-frequency field was turned on, a rapid heating of the plasma was observed (within a time of the order of a single oscillation period).

2. SETUP AND METHODS OF MEASUREMENT

The experiments were carried out on apparatus whose schematic diagram is shown in Fig. 1. The plasma was

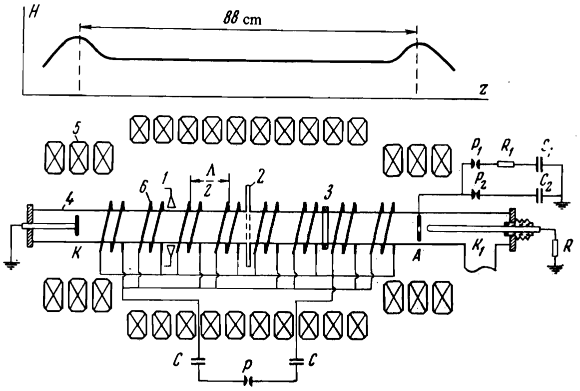

FIG. 1. Schematic diagram: 1—microwave horn; 2—arrangement for introduction of probes; 3—diamagnetic probe; 4—discharge tube; 5—coils for creating magnetic field; 6—coils for creating high-frequency field; A—anode of sources of plasma; K, K_1 cathodes of the principal and auxiliary sources of plasma; C_1, C_2 capacitors in supply circuits of plasma sources; P_1, P_2— spark gaps; R_1, R—ballast resistances; C—capacitors of high-frequency circuit; P—spark gap of high-frequency circuit.

produced by direct high-current discharge in hydrogen (the initial pressure $\sim 10^{-3}$ mm Hg) in a quasi-constant longitudinal magnetic field. The internal diameter of the quartz discharge tube was $a = 6.2$ cm, the distance between the cathode K and anode A was 88 cm. The electric circuit for producing the plasma is quite analogous to the circuit described by Dubovoĭ and Fedyakov.[5] Ignition of the spark gap P_1 starts first a discharge with oscillating electrons in the electrode system consisting of cathode K, ring anode A, and auxiliary cathode K_1. Here the capacitor C_1 (0.4 μf, 18 kV) discharges through the resistance R_1, the discharge gaps AK and AK_1, and the resistor $R \gg R_1 = 30\ \Omega$. The anode current in this case does not exceed ~18A and is determined by the value of the resistance R. Upon the achievement of a sufficiently high degree of ionization in the discharge chamber, breakdown of the gap AK takes place. The anode current reaches a value of the order of several hundred amperes and the density of the plasma on the axis exceeds 7×10^{13} cm^{-3}. About 40 μsec after breakdown of the spark gap P_1, the spark gap P_2 breaks down and discharge of the capacitor C_2 (0.4 μfd, 35 kV) takes place across the gap AK. The discharge current has an oscillatory character (period ~2.5 μsec), a total length ~10 μsec, and a maximum value ~17 kA. At the end of this stage of the discharge, the plasma density at the axis as a rule exceeds 2×10^{14} cm^{-3}. The transverse pressure of the plasma, as recorded by a diamagnetic probe, averaged over the radius of the discharge chamber, amounts to 5×10^{15} eV/cm^{-3} and decreases with a time constant of ~50 μsec.

It should be noted that the presence of the auxiliary direct discharge maintained by the capacitor C_1 is not obligatory, but it does significantly increase the stability of the parameters, from pulse to pulse, of the plasma produced upon discharge of the capacitor C_2. The distribution of the quasiconstant longitudinal field H along the axis (Fig. 1) has a homogeneous region of length ~70 cm in the central part of the system, and small bulges with maximum voltages at the points of location of the cathode K and anode A.

The high-frequency oscillations in the plasma were excited by a Stix coil, which consisted of eight two-turn sections of diameter 8.5 cm with an axial period $\Lambda = 2\pi/k_{\parallel} = 20$ cm. This coil was the inductance of a shock-excited circuit with a characteristic frequency of $\omega/2\pi = 6.6$ MHz and stored an energy of 7 J. The quality factor of the unloaded circuit amounted to 35. The maximum amplitude of the intensity of the longitudinal alternating magnetic field H_z on the axis in vacuum amounted to 180 Oe. The density of the plasma was estimated from the cutoff of microwave oscillations with wavelengths 8.1, 4.0 and 2.3 mm. The character of the radiation distribution of the density was established by simultaneous observation of the incident microwave signal and that reflected from the plasma. To measure the field H_z on the axis of the system, we used a magnetic probe, which consisted of a 10-turn coil of diameter 3.5 mm. This probe was introduced in the plasma through an aperture in the cathode K into the insulating quartz tube with outside diameter 6 mm. The maximum distance from the cathode, to which the probe is introduced, amounted to 40 cm.

The azimuthal and radial components of the alternating magnetic field H_φ and H_r were measured by magnetic probes comprising 20-turn coils of diameter 2 mm. To obtain the radial distribution of H_φ after a single pulse, a probe was used that consisted of 8 such coils. The distance between the axes of the neighboring coils was equal to 4 mm. All these probes were introduced into the plasma from the side, in the region between two neighboring sections of the excitation coil, in a quartz tube with outside diameter 4 mm. At the time of the direct discharge, the plasma is at a potential of the order of the voltage on the anode. To avoid breakdown at the probe and destruction of the quartz tube, all the probes were insulated from ground by broadband isolation transformers. The signal received by the probe was integrated by an RC network with an integration constant of 2 μsec. The absolute calibration of the probes was carried out by the method described by Brown and Shepherd.[14]

The transverse pressure of the plasma was estimated from the change in the diamagnetism, which was recorded by a ten-turn coil in the electrostatic screen which enclosed the discharge chamber and which was placed between two neighboring sections of the Stix coil. The signal induced in the diamagnetic probe was integrated by an RC network with an integration constant of 200 μsec.

The effectiveness of the transfer of high-frequency energy from the circuit to the plasma was characterized by the transfer coefficient α, which is the ratio of the energy absorbed in the circuit in the presence of the plasma, after subtracting ohmic losses in the circuit itself, to the total energy stored in the capacitor circuit before switching it on. The value of α was determined with the help of apparatus for measurement of the logarithmic decrement.[15] A high-frequency magnetic probe served as the pickup for this apparatus; it yielded a signal proportional to the current in the circuit.

In obtaining the experimental results described below, the high-frequency field was turned on ~7 μsec after termination of the current of the direct discharge. The distribution of the plasma density over the radius at this instant of time, for $H = 4.5 \times 10^3$ Oe, is shown in Fig. 8a (see below). From several independent estimates, the plasma density at the axis at this instant was found to be in the range $(2.5-5) \times 10^{14}$ cm^{-3}, while the density averaged over the radius amounted to about 6×10^{13} cm^{-3}. The density distribution shown in Fig. 8a

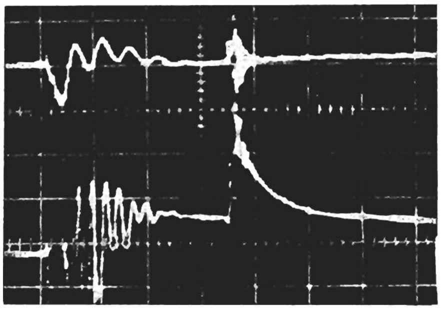

FIG. 2. Upper trace—simultaneous oscillograms of the direct discharge current and the high-frequency current; lower trace—diamagnetic signal; scale—5 μsec/div.

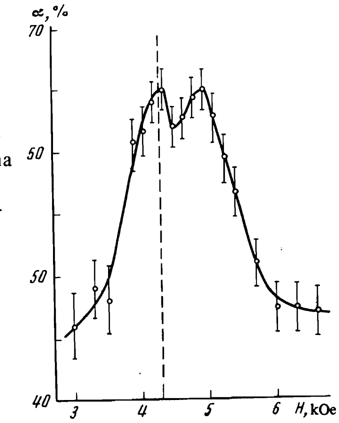

FIG. 3. Dependence of the high-frequency energy entering the plasma on H. The vertical dashed line denotes the magnetic field corresponding to the ion cyclotron resonance at the characteristic frequency of the circuit without plasma.

did not change materially throughout the high-frequency pulse. The sequence of operations and the change in the transverse pressure of the plasma in the region $\omega \sim \omega_{Hi}$ are graphically illustrated in Fig. 2. In particular, it follows from the oscillogram shown that a significant heating of the plasma takes place upon turning on the high-frequency field.

3. RESULTS OF THE MEASUREMENTS

A. Spectrum of Oscillations Excited in the Plasma

The dependence of the high-frequency energy fed into the plasma on the intensity of the constant magnetic field H is represented by a twin-peaked resonance curve (Fig. 3). At the maxima of α, 65% of the energy stored in the circuit flows into the plasma (in individual pulses, this value reached 70%). In what follows we shall for brevity denote the field $H \approx 4.5 \times 10^3$ Oe, which corresponds to the minimum value of α in the valley between the peaks, by H_0, and the fields corresponding to the maximum absorption by H_1 and H_2 ($H_1 < H_0 < H_2$).

To make clear the nature of the observed absorption, the shape and distribution along the axis of the oscillations excited in the plasma were investigated. It should be noted that introduction, along the axis of the plasma, of a quartz tube with a probe to measure H_z did not change materially the regime of the direct discharge and the shape of the resonance absorption curves (Fig. 3). Figures 4a–e are oscillograms of the high-frequency current in the excitation coil (the upper traces) and of the field H_z on the axis (the lower traces). These oscillograms were obtained at a single position of the probe for the four more characteristic values of H in the interval from 3 to 6 kOe (oscillograms in the absence of the plasma are given for comparison). It follows from the oscillograms that everywhere in the considered interval of H the high-frequency field in the plasma is a superposition of two oscillations with different frequencies, and that at the absorption maxima these frequencies approach each other and the amplitude of the oscillations in the plasma grows appreciably (a reverse transfer of high-frequency energy from the plasma to the circuit is even evident in Figs. 4c and 4d). In the region of maximum absorption, the amplitude of the field H_z in the plasma on the axis increased by a factor of about four in comparison with its value in vacuum and reached 700 Oe.

Figure 5 shows examples of the frequency spectra obtained as a result of Fourier analysis of the oscillograms of the high-frequency current and the field H_z on a "Dnepr-1" electronic computer. The dependence of the characteristic frequencies of the oscillations ex-

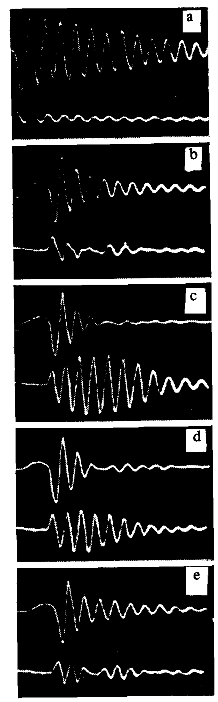

FIG. 4. Oscillograms of the high-frequency current in the coil (upper trace) and the field H_z on the axis: a) without plasma; b) for $H < H_1$; c) for $H = H_1$; d) for $H = H_0$; e) for $H > H_2$.

cited in the plasma was constructed from these data (Fig. 6). Measurements of the distribution of amplitude of the field H_z along the axis have shown, the longitudinal wavelength of the oscillations at frequencies corresponding to branch 1 and to branch 2 are close to the axial period $\Lambda = 20$ cm of the exciting current.

B. Radial Distribution of the High-Frequency Field in the Plasma

To determine the type of oscillations excited in the plasma, we carried out investigations of the radial distribution of the field H_φ and also of the phase shift between H_φ and H_r. Upon introduction of a quartz tube (transverse to the plasma column) along which the probes which measure H_φ and H_r were moved, the plasma perturbation produced by the tube was manifest in the fact that the mean value of α at the absorption maximum decreased to a value of the order of 60%, and the mean scatter of the values of α from pulse to pulse increased appreciably.

As a consequence of the instability of the plasma parameters, the radial distributions of the field H_φ, measured by the 8-turn probe, differed significantly from one another in the different pulses. Nevertheless, they could be divided into two basic groups, correspond-

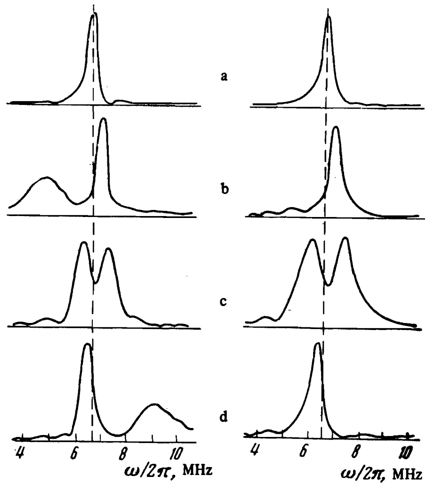

FIG. 5. Frequency spectra of oscillations of the field H_z (at the left) and the high-frequency current (at the right) without plasma a) and in plasma: b) for $H < H_1$, c) for $H_0 = H$ and d) for $H > H_2$. The vertical dashed lines denote the frequency of the characteristic oscillations of the circuit without the plasma.

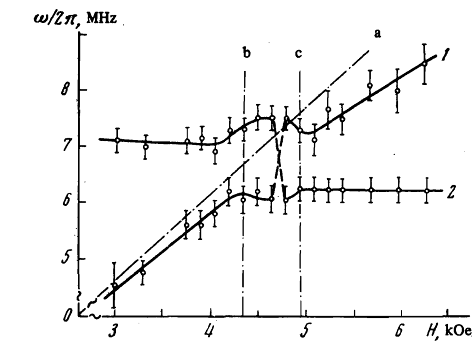

FIG. 6. Dependence of the frequency of oscillations excited in the plasma on the intensity of the constant magnetic field. The straight line a denotes $\omega_{Hi}/2\pi$, b, c—the locations of the absorption maxima.

ing evidently to different initial parameters of the plasma column and corresponding to different conditions of excitation of the oscillations. These distributions, measured at $H = 4.65$ kOe, are shown in Figs. 7a, b. In both groups, the $H_\varphi(r)$ dependence has a well-pronounced maximum for some value of the radius r_0. The difference between the distributions (see Figs. 7a, b) is that in the case of the distribution in Fig. 7a, for the case of a decrease in r, the function $H_\varphi(r)$, passing through a maximum, changes sign. In the case of the distribution in Fig. 7b, the maximum of H_φ is always located at some larger radius.

More detailed measurements of the function $H_\varphi(r)$ were carried out by a single probe in a series of repeated discharges. The probe was moved in steps of 3 mm. To decrease the effect of scatter of the plasma parameters, we used a so-called monitor probe. This probe, which measures H_φ, was introduced into the quartz tube from the opposite side and was placed in the most probable location of the maximum of H_φ for the distribution of Fig. 7a. To plot $H_\varphi(r)$, we picked out only those oscillograms of the signal from the movable probe which corresponded to a sufficiently large amplitude of signal from the control probe (not less than 300 Oe).

The signal from the probe which measures H_r, and which is located in series with the probe which meas-

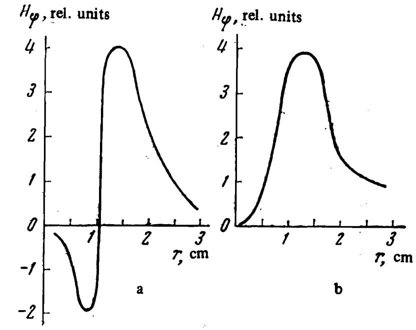

FIG. 7. Distribution of H_ϕ (r) in plasma, obtained with the help of an 8-turn probe.

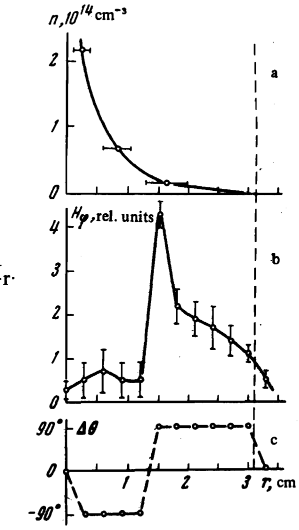

FIG. 8. Radial distributions: a) plasma density; b) the field H_ϕ and c) the phase difference between H_ϕ and H_r. The vertical dashed line denotes the location of the wall of the discharge chamber.

ures H_φ, was recorded simultaneously. The results of the measurements of $H_\varphi(r)$ carried out in this manner at $H = 4.65$ kOe are plotted in Fig. 8b, along with the radial distribution of the plasma density (Fig. 8a) and the radial distribution of the phase difference $\Delta\theta(r)$ between H_φ and H_r (Fig. 8c). It should be noted that the amplitudes H_φ are plotted on Fig. 8b without account of direction. It follows from this figure that there actually exists a plasma layer in the vicinity of some radius $r = r_0 \approx 1.5$ cm in which H_φ increases sharply, and that in this same layer a discontinuous change by 180° takes place in the phase difference between H_φ and H_r. This difference corresponds at $r < r_0$ to the ion cyclotron oscillations (Fig. 9a, the total vector of the transverse alternative magnetic field $H_\perp$ rotates in the direction of the Larmor rotation of the positive ion), and at $r < r_0$ to a fast magnetosonic wave (Fig. 9b, $H_\perp$ rotates in the direction of the Larmor rotation of the electron). Under the distribution conditions shown in Fig. 7b, the quantity $\Delta\theta(r)$ is close to zero at $r < r_0$ (Fig. 9c).

The maximum measured value of the amplitude H_φ at the point $r = r_0$ amounted to 500 Oe. It can be assumed that, in the absence of the quartz tube, when the maximum of the dependence $\alpha(H)$ was more clearly delineated, this quantity was larger.

C. Heating of the Plasma

As has already been pointed out above (see Fig. 2), turning on the high-frequency field leads to the rapid increase in the transverse energy of the plasma. The dependence on H of the increase in the transverse

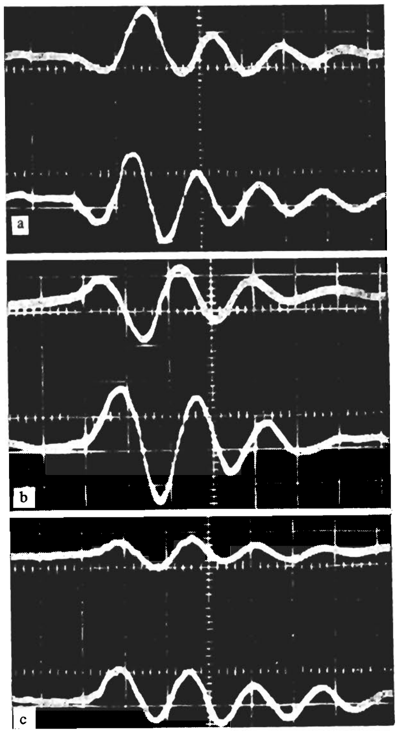

FIG. 9. Oscillograms of the field H_r (upper trace) and H_ϕ (lower trace) in resonance absorption a) for $r > r_0$; b) for $r < r_0$, the distribution a in Fig. 7; c) for $r < r_0$, the distribution b in Fig. 7; scale—0.1 μsec/div.

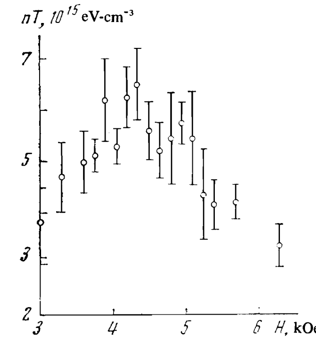

FIG. 10. Dependence of the increase in the transverse plasma pressure, due to the high-frequency heating, on the intensity of the constant magnetic field.

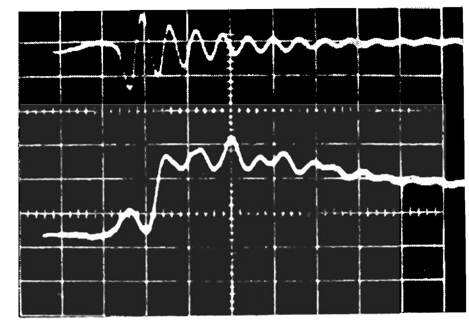

FIG. 11. The high-frequency current in the excitation coil (upper trace) and the diamagnetic signal: scale—0.25 μsec/div.

pressure of the plasma, averaged over the radius, calculated from the diamagnetic signal, after the high-frequency field is turned on, is shown in Fig. 10. As follows from the drawing, this dependence is similar in its general features to the $\alpha(H)$ dependence. The oscillograms of the high-frequency current in the excitation coil and the diamagnetic signal, taken with a short sweep in the region of maximum α, are shown in Fig. 11. It follows from these oscillograms that, first, the plasma begins to heat up not from the moment of turning on the high-frequency field, but after a lapse of some time comparable with the length of the period of the oscillations; second, the duration of the significant heating is also of the order of the period $2\pi/\omega \approx 1.6 \times 10^{-7}$ sec.

The maximum value of the increase in the transverse energy of the plasma, measured by the diamagnetic probe and averaged over the radius, amounted to 7×10^{15} eV/cm^3 in the described experiments (only the dc component of the diamagnetic signal is taken into account). Under the assumption that this energy is distributed uniformly over the length $l = 88$ cm of the plasma column, we obtain the value 3J for the total increase in the transverse energy at the maximum of the diamagnetic signal. This amounts to about 70% of the high-frequency energy input to the plasma at the absorption maximum. In this estimate, we have not taken into account the energy losses due to cooling of the plasma, which are always considerable, since the diamagnetic signal due to the high-frequency field falls off rapidly after cessation of the oscillations.

4. DISCUSSION OF THE RESULTS

The plot given above of the characteristic frequencies excited in the plasma against the intensity of the constant magnetic field (see Fig. 6) is similar to the dependence of the characteristic frequencies of an oscillatory system with two degrees of freedom on the detuning, which is well known from the theory of vibrations (see, for example, [16]). In the given case, the parameter which determines the detuning (or one of the partial frequencies) is the intensity of the constant magnetic field, on the value of which depends the frequency of the characteristic oscillations of the plasma column. The difference of the graph shown in Fig. 6 from that usually considered in the theory of vibrations is that the difference between the frequencies of branches 1 and 2 is increased in the region of maximum absorption, evidently as the consequence of an increase in the coupling between the circuit and the plasma in this interval of magnetic fields.

From a somewhat different viewpoint, branch 2 represents the induced oscillations of the plasma column, excited by the axially periodic high-frequency field flowing along the Stix coil. The frequency of these oscillations differs from the frequency of the characteristic oscillations of the unloaded circuit as a consequence of the reactance inserted in this circuit by the plasma. Branch 1 represents the frequency of the characteristic oscillations of the plasma column, the longitudinal wavelength of which is equal to the axial period Λ of the exciting current. This frequency also undergoes a perturbation as a consequence of the strong coupling of the plasma with the circuit. The natural oscillations of the plasma column, at a frequency different from the frequency of the circuit, are excited because of the finite (different from zero) width of the spectrum of the exciting current.[17,18] The increase of α in Fig. 3 is due to the closeness of branches 1 and 2, i.e., to resonance excitation. The maximum transfer of energy from the circuit to the plasma takes place near those values of H where the difference between the frequencies lying on branches 1 and 2 is minimal.

In agreement with known data,[10,17,18] we might have expected also excitation, in the plasma, of oscillations with the frequency of the exciting current and wavelength corresponding to the wavelengths of the free oscillations of the plasma column. These oscillations would be due to the finite length of the exciting coil. However, in contrast with our experiments [17] on the excitation of a fast magnetosonic wave it was not possible to separate such oscillations in the experiments described for the measurement of the distribution of the field H_z along the axis. Evidently, this is explained by the strong spatial damping of such oscillations, which are in turn due to the smallness of the longitudinal group velocity of the wave near $\omega = \omega_{Hi}$.

Even without analyzing the data on the radial distribution of the high-frequency field in a plasma, it can be established that the oscillations excited in the plasma do not constitute a fast magnetosonic wave. Actually, in the frequency range and plasma densities under consideration (we assume the density averaged over the radius to be 6×10^{13} cm^{-3}) the approximate dispersion relation for the fast magnetoacoustic wave can be represented in the form [13]

$$\omega=\omega_{Hi}c^2k_\parallel(k_\parallel^2+k_\perp^2)^{1/2}/\omega_{pi}^2, \quad (2)$$

where we can set $k_\perp \sim \pi/a \sim 1$ for the fundamental radial mode of the oscillations. As a result we find that resonance excitation of the fast magnetosonic wave in the experiments described should take place at $H\approx 1.6$ kOe, which is much less than $H_0 \approx 4.5$ kOe.

The experimental data given in Sec. 3B indicate the presence in the plasma of a resonance layer characterized by relation (1). The plasma density $n_0 \approx 5.2\times10^4 \times k_\parallel^2(\omega_{Hi}^2/\omega^2-1)$ calculated from (1) depends strongly on the ratio ω_{Hi}/ω. The exact value of this ratio under experimental conditions is not known, in view of the large width of the spectrum of excited oscillations. Also, one should not attach great significance to the agreement between the density $n(r_0)\approx 1.7\times10^{13}$ cm^{-3} at the point of resonance, determined from the graph of Fig. 8, with the value calculated from Eq. (1). The most convincing proof of the existence of the resonance layer are the sharp increase in the field H_φ at $r=r_0$ (Fig. 8b), the jump in the phase difference between H_φ and H_r at $r=r_0$ (Fig. 8c), and the change in the direction of the vector of the transverse magnetic field on going from the region $r>r_0$ to the region $r<r_0$.

From consideration of the approximate expression for the transverse index of refraction of the low frequency ($\omega \ll (\omega_{He}\omega_{Hi})^{1/2}$) oscillations in a plasma (see, for example, [19])

$$n_\perp^2\approx\frac{(\varepsilon_1-n_\parallel^2)^2-\varepsilon_2^2}{\varepsilon_1-n_\parallel^2} \quad (3)$$

it follows that a fast magnetosonic wave will be excited (i.e., $n_\perp^2>0$ at $n_\parallel^2 \ll \epsilon_1$) in the near-axis layer of the inhomogeneous plasma, the density of which increases monotonically in the direction from the periphery to the axis, if the density in this layer exceeds the value (for a hydrogen plasma)

$$n_1\approx5{,}2\cdot10^{14}k_\parallel^2\left(\frac{\omega_{Hi}}{\omega}+1\right)\frac{\omega_{Hi}}{\omega}. \quad (4)$$

It can be assumed that under experimental conditions, when a quartz tube was introduced into the plasma, this density $n_1 \sim 10^{14}$ cm^{-3} was not achieved in all pulses. The distribution in Fig. 7b could also correspond to the case in which the density n was everywhere less than n_1 for $r<r_0$, and therefore the value of $n_\perp^2$ remained negative and the fast magnetosonic wave was not excited.

Thus, in these experiments, the phenomenon of excitation resonance turned out to be possible in spite of the presence of the resonance layer. Even by itself, this fact indicates that the absorption mechanism in the resonance layer and the thickness of the layer are such that the wave is not completely absorbed in the layer, and partially penetrates through it into the region $r<r_0$. The conditions for the existence of characteristic radial modes of the entire plasma column as a whole are guaranteed in the same way.

The maximum measured value of the azimuthal magnetic field in the resonance layer, $H_\varphi = 500$ Oe, corresponds to a radial electric field $E_r\approx H_\varphi/n_\parallel \approx 650$ V/cm. The corresponding transverse current velocity $u_r \approx k_\parallel cH_\varphi(r_0)/4\pi en(r_0)$ amounts to about 5×10^7 cm/sec. The maximum possible thermal velocity of the plasma ions at the instant of turning on the high-frequency field, which can be estimated from the diamagnetic signal, amounts to $\sim10^7$ cm/sec, i.e., much less than the current velocity. Under these conditions, small-scale high-frequency oscillations of the type previously considered [1,2] should be excited in the plasma. It can be assumed that the rapid heating of the plasma that is observed upon turning on the high-frequency field is due to interaction of the electrons and ions with these oscillations. The threshold character of the heating also supports this explanation.

Actually, as has already been pointed out above, the plasma begins to heat up not immediately after the high-frequency field is turned on, but after a lapse of some time of the order of the duration of the period of oscillations, when the amplitude of the oscillations in the plasma (Fig. 4) and consequently, the current velocity reaches a certain large value.

The authors express their deep gratitude to I. Yu. Adamov, V. I. Kononenko, V. T. Pilipenko for help in carrying out the experiments, and to K. N. Stepanov and A. V. Longinov for useful discussions of the research.

[1)]Experiments on the discovery of the resonance layer have been described previously [[13]].

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Translated by R. T. Beyer
61