MAGNETOACOUSTIC RESONANCE IN A PLASMA

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The work is devoted to the experimental study of magnetoacoustic vibrations in a cold plasma. It is shown that under certain conditions a high frequency electromagnetic field strongly penetrates into the plasma with an attendant resonance absorption of energy of the field. Results of the investigation of resonance at frequencies of 12.5 Mc/sec and 50 Mc/sec by various methods are described. These results are compared with the theoretical predictions.

1. For the investigation of the interaction of plasma with a variable electromagnetic field, it is first necessary to investigate the conditions for the appearance of vibrations inside the plasma. It is well known that in the absence of a static magnetic field, an electromagnetic field with a frequency lower than the plasma is reflected from the boundary of the plasma and does not penetrate inside. According to the theory, a static magnetic field should make possible the penetration into the plasma of vibrations with frequencies below the plasma frequency. In the present research, the problem was to investigate the appearance of vibrations perpendicular to the static magnetic field in a plasma. The physical picture of the phenomenon reduces in this case to compression and dilatation of the material together with the field "frozen" in it. The intensity of the field inside the plasma does not change as a consequence of the penetration of the external field but as a result of the compression and dilatation of the field "frozen" in the plasma. In its physical mechanism the process is analogous to ordinary sound vibrations, except that the fundamental role is played by the magnetic pressure $H^2/8\pi$ rather than the gas pressure. Therefore, the plasma oscillations that are investigated are known as magnetoacoustic.

As is known from theory, the velocity of propagation of magnetic "sound" in a cold plasma is close to the Alfvén velocity $H_0/\sqrt{4\pi\rho}$, where H_0 is the intensity of the static magnetic field and ρ is the density of the plasma. Under certain relations between H_0, ρ, the angular frequency of the vibration ω, and the radius of the plasma cylinder R, magnetoacoustic resonances should be observed.[1]

The resonance condition can be put in the form

$$\alpha H_0/\omega R\sqrt{4\pi\rho} = 1, \tag{1}$$

where α is a dimensionless number characterizing the type of vibration. If the frequency ω were less than the collision frequency, then the quantity ρ would represent the total density of the gas. Under our conditions, the frequency ω is large in comparison with the collision frequency, so that only charged particles take part in the vibrations. In this case ρ in Eq. (1) represents only the density of the charged particles of the plasma.

In the idealized case of purely radial vibrations of an infinite plasma cylinder,[2] where the wave vector is perpendicular to the direction of the magnetic field, penetration of the vibrations into the plasma should remain impossible for frequencies higher than the "hybrid" frequency,[3] which is close to the geometric mean of the electronic and ionic cyclotron frequencies. Here, anomalous dispersion should be observed close to the "hybrid" frequency. However, a small component of the wave vector along the magnetic field[1] is sufficient to prevent the anomalous phenomena pointed out above.

The spatial distribution of the amplitudes over the radius of the plasma cylinder should, according to theory,[1,2] be expressed in terms of Bessel functions of first order. If the static magnetic field is directed along the axis of the cylinder while the wave vector is almost perpendicular to it, then the fundamental role will be played by the axial component of the variable magnetic field $\tilde{H}_z \sim J_0(kr)$ and the azimuthal and radial components of the electric field E_φ, $E_r \sim J_1(kr)$.

The boundary condition is that E_φ vanish on the internal surface of the metallic housing. Since the velocity of propagation of the wave is much greater in the vacuum than in the plasma, one can consider the same condition to be satisfied on the lateral surface of the plasma cylinder. Then the radial wave number k is determined from the condition that kR be the root of the Bessel function of first order.

The amplitude of the velocity of the radial motion of the plasma is estimated as

$$v_r \approx \tilde{H} u_{ph} / H_0 \approx \tilde{H} / \sqrt{4\pi\rho},$$

where u_{ph} is the phase velocity of the magnetic "sound." In first approximation, the ions and electrons move in the radial direction together. Moving in the azimuthal direction are essentially the electrons; their motion has a drift character with a velocity amplitude that can be estimated as $v_\varphi \approx \omega_i v_r/\omega$, where ω_i is the ionic cyclotron frequency.

2. In the experiment we investigated the interaction of a high-frequency electromagnetic field with a cold plasma in a cylindrical volume in the presence of an axial quasi-static magnetic field H_0 (see Fig. 1).

It must be noted that the plasma was generated by the same high-frequency field whose interaction with the plasma was being studied. This led to a marked change in the density of charged particles

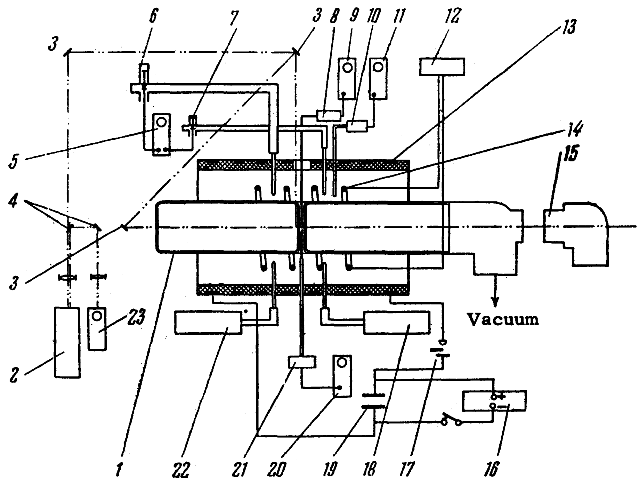

FIG. 1. Block diagram of the experimental setup. 1 – vacuum chamber; 2 – electron-optical light amplifier; 3, 4 – mirror projecting the illumination of the plasma and the time marker from the screen of the oscillograph 23 on the electron-optical light amplifier; 5, 9, 11, 20 and 23 – OK-17M oscillographs; 6, 7 – high-frequency detectors; 8 – magnetic probe; 10 – photomultiplier; 12 – self-excited generator (f = 12.5 Mc/sec); 13 – solenoid of the quasi-static magnetic field (H_{0max} = 12 koe); 14 – tank circuit of the generator 12; 15 – spectrograph; 16 – charging system; 17 – discharger; 18 and 22 – probe-signal generators with wavelengths 3 cm and 8 mm; 19 – capacitor bank; 21 – optical probe.

in the plasma under resonance conditions. Consequently, the experiments were carried out under essentially nonlinear conditions.

The plasma was prepared in a glass tube 7 or 10 cm in diameter and 175 cm long. The field H_0 was generated by an oscillating discharge of a capacitor bank through a solenoid.

The experiments were conducted under two arrangements. The period of vibration of the field H_0 was 6.25×10^{-3} sec in the first arrangement, and 8×10^{-3} sec in the second. The high-frequency magnetic field $\tilde{H}$ was excited parallel to the direction of the field H_0 by means of an induction coil mounted on the discharge tube. In the first arrangement, the coil was 20 cm long, composed of four windings, and formed the inductance of the high-frequency oscillator tank circuit. The generator operated at a frequency of 12.5 Mc/sec and had a power of approximately 20 kw.

In the second arrangement, the coil of the high-frequency magnetic field consisted of a single winding and was a copper tube 60 cm long with an axial cut to which was attached the capacitance of the circuit. This circuit was excited at a frequency of 50 Mc/sec from an independent generator. The power from the generator was of the order of 200 kw and was supplied through a coaxial line of length $(3/4)\lambda$.

Various methods were employed for the investigation of the character of the charge under observation.

With the aid of a FÉU-19 photoelectric multiplier and an OK-17M oscillograph, the time sweep of the glow of the plasma was observed, and the distribution of the brightness over the radius of the discharge column was studied. In the latter case a miniature photoconductor lying along the radius of the discharge tube was used as the optical probe 21.*

The penetration of the high-frequency vibrations into the plasma and the distribution of amplitude of the high-frequency magnetic field along the radius were studied by means of a magnetic probe 8, which moved along the radius of the discharge tube (see footnote).

In the arrangement with frequency f = 12.5 Mc/sec, the load of the high-frequency generator during the discharge process was determined by means of the grid and anode currents.

The discharge glow was swept by means of an electron-optical light amplifier through a small slit diaphragm (see reference 4). The time scan

*A thin glass tube which isolated the probe from the volume of the plasma was employed for this purpose.

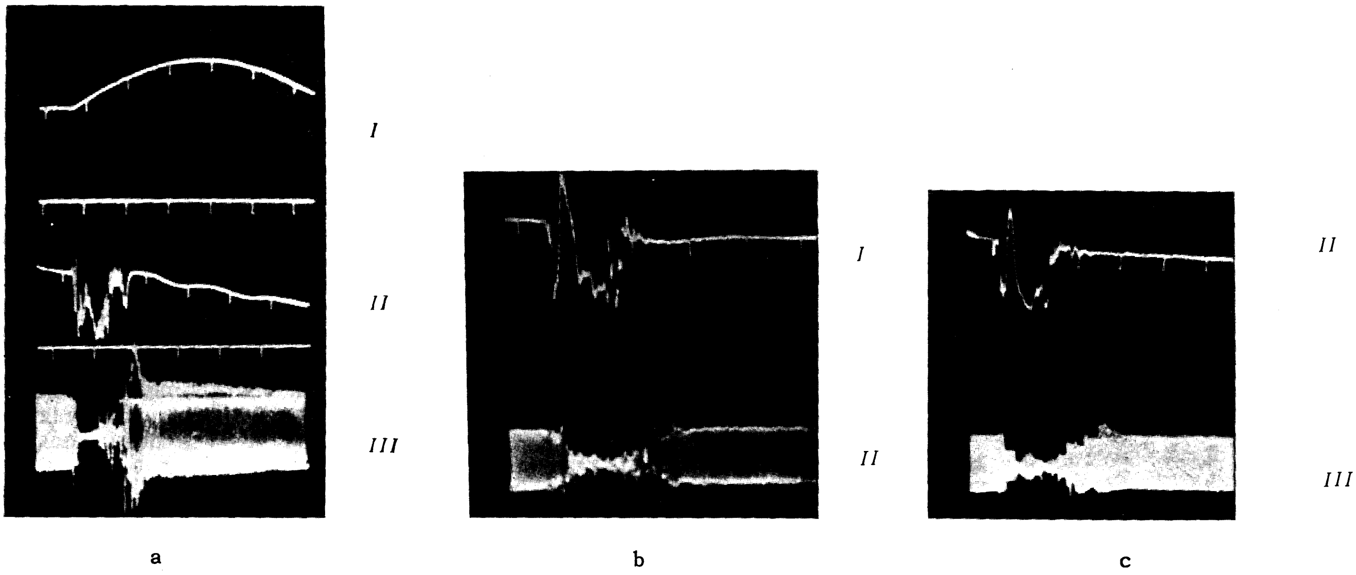

FIG. 2. The results of observation of the discharge in hydrogen (a), air (b), and argon (c) for a frequency of 50 Mc/sec. The pressure was 8×10^{-4} mm of mercury (a, b) and 3×10^{-3} mm of mercury (c). The amplitude of the magnetic field in the oscillator circuit was 27 oe (a), 13.5 oe (b) and 15 oe (c). The amplitude of the quasi-static magnetic field H_0 = 5.3 koe with a period of 8×10^{-3} sec. The time markers on all the oscillograms are 5×10^{-4} sec apart: I – oscillogram of the field H_0; II – oscillogram of the voltage on the magnetic probe placed in the center of the discharge chambers; III – the oscillogram of the high-frequency probing signal with wavelength $\lambda = 8$ mm.

of the discharge spectrum was observed and the Doppler half-width of the line $H\beta$ was measured by the same method.

The plasma was probed with plane polarized microwaves of wavelengths 3 cm and 8 mm to estimate the concentration of the charged particles. In this case the direction of the electric vector was parallel to H_0. The experiments were carried out on hydrogen, helium, argon, and air in the range of initial pressures from 10^{-4} to 6×10^{-3} mm of mercury.

The most interesting result of these experiments was the discovery in the range of magnetic fields from 300 oe to 5 koe of characteristic resonance phenomena, which were accompanied by a sharp increase in the brightness of the plasma radiation, by an increase in the concentration of charged particles, by penetration of the high frequency vibrations into the plasma, and by an increase in the loading of the generator. These peculiarities of the process are clearly seen in the photographs of Figs. 2 and 3. Figure 2 shows an oscillogram of the magnetic probe and an oscillogram of the passage of radio waves of wavelength 8 mm through the plasma. These were obtained in the arrangement with frequency of 50 Mc/sec for a discharge in hydrogen (a), argon (b), and air (c). Figure 3 shows the different experimental results obtained in the other arrangement (f = 12.5 Mc) for discharge in hydrogen.

It is seen in these photographs that for a certain (resonance) value of the quasi-static magnetic field $H_0 = H_p$, the loading of the high-frequency generator increases sharply while the high-frequency oscillations penetrate up to the axis of the discharge. In this case the illumination of the discharge increases rapidly and the microwave probe is cut off. This picture is repeated periodically, twice every half cycle of the magnetic field H_0.

The characteristic resonance interaction of the high-frequency electromagnetic field with the plasma also appears clearly in the brightness of the individual spectral lines, see Fig. 4, where streak photographs are shown of the individual parts of the hydrogen spectrum.

It can be noted in the photographs that, in addition to the lines of the atomic and molecular hydrogen in resonance, there is a number of admixture lines (for example, the lines 4794.5, 4810.1, and 4819.5 A). It is interesting that the time of their light emission constitutes only a part of the time of the passage through resonance from the side of low values of H_0. Since the admixture lines appear because of the interaction of the plasma with the walls of the discharge tube, the latter circum-

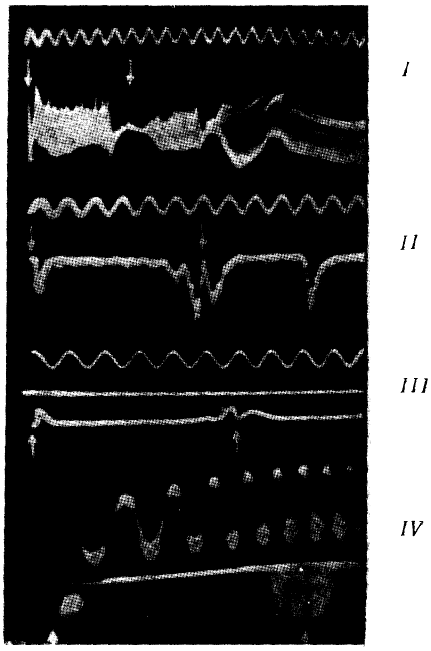

FIG. 3. The results of observation of discharge in hydrogen at a frequency of 12.5 Mc/sec obtained in a single experiment. The pressure was 10^{-4} mm of mercury. The amplitude of the quasi-static magnetic field H_0 and of the high-frequency magnetic field in the oscillator circuit $\tilde{H}$ were equal to 3.43 koe and 30 oe, respectively. The times of passage of H_0 through zero are marked by arrows. The time scale (period of sinusoidal vibrations) on all oscillograms was 0.5 msec. I – oscillogram of the high-frequency testing signal with wavelength $\lambda = 3$ cm; II – oscillogram of the signal from the photoelectric multiplier which recorded the brightness of the plasma in the center of the discharge tube; III – the oscillogram of the anode current of the high-frequency generator; IV – streak photograph of the illumination obtained with the help of the light amplifier. The photography was carried out perpendicular to the direction of H_0 through a narrow slit diaphragm located perpendicular to the axis of the discharge tube.

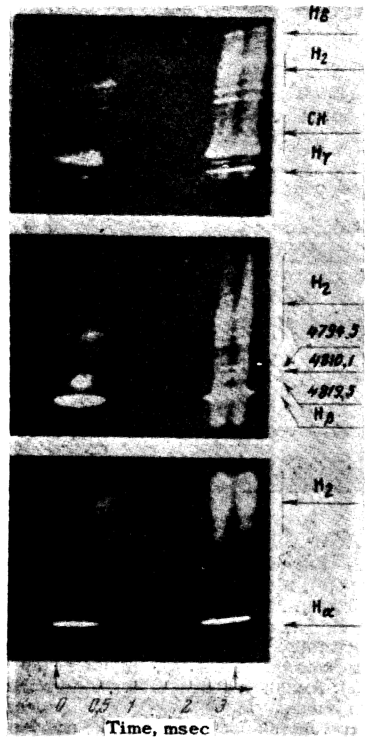

FIG. 4. Streak photographs of the separate parts of the discharge spectrum in hydrogen under conditions of resonance (f = 12.5 Mc/sec) obtained by means of a light amplifier and an ISP-51 spectrograph. The arrows denote the instants of the passage of H_0 through zero.

stance means that in resonance, during the time when the admixture lines are not radiating, the plasma has not reached the walls of the tube.

The dependence of the resonance magnetic field Hp on the amplitude of the high-frequency magnetic field H in the circuit in the absence of plasma was discovered and investigated in these experiments. In the arrangement with frequency 50 Mc/sec, the following experimental results were obtained for discharge in hydrogen:

$\tilde{H}$	13.5	16.5	19.5	22.2	27.3	33.3 oe
H_p	1300	1500	1750	2050	2850	3400 oe

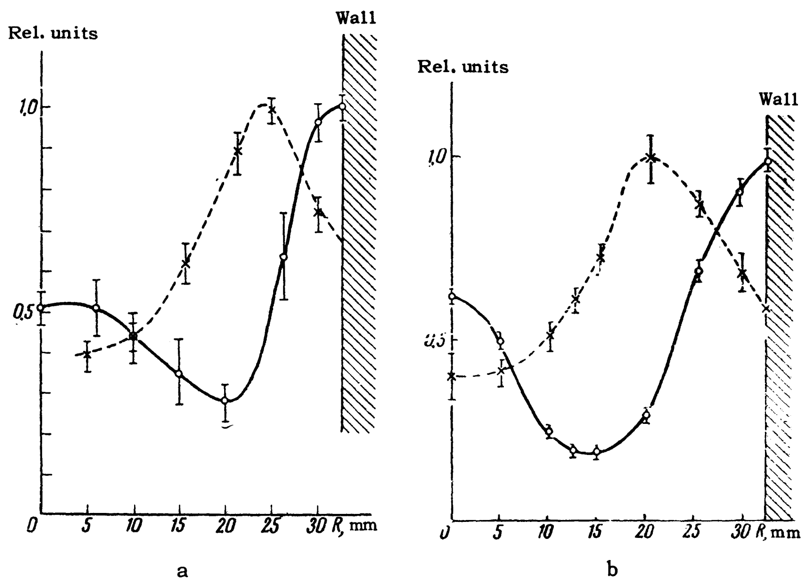

FIG. 5. Amplitude distribution of the high-frequency magnetic field (solid line) and of light (dashed line) along the radius: a – discharge in hydrogen (p = 9 × 10^{-4} mm mercury); $H_p \approx 800$ oe; b – discharge in argon (p = 3 × 10^{-3} mm mercury); $H_p \approx 1000$ oe.

One can see from these data that the field H_p increases with increasing $\tilde{H}$.

The dependence of H_p on the mass M of the ions taking part in resonance was also studied. For investigation of this dependence, experiments were carried out on hydrogen, helium, argon, and air under approximately the same conditions. An increase of H_p with increase in M was established in this case.

In Fig. 5a are shown the radial distributions of amplitude of the high-frequency magnetic field and the light emission of the plasma for resonance in hydrogen, obtained in the arrangement with a frequency of 50 Mc/sec. In Fig. 5b are shown the similar distributions for resonance in argon. It can be seen that the amplitude of the magnetic field has a relative maximum on the axis of the discharge, passes through a minimum approximately in the middle of the radius, and reaches its maximum value at the boundary of the plasma.

Attention should be paid also to a peculiarity of the phenomenon — the fine structure of the resonance. It can be noted in all the photographs shown in Figs. 2 and 3. It is most clearly evident in the streak photographs of the plasma shown in Fig. 6. This resonance in the second quarter of the period of the field H_0 is divided in one case (a) into two, and in the other case (b) into three separate narrow resonances. The nature of this effect, which appears at lowered initial pressures in the discharge tube, was investigated.

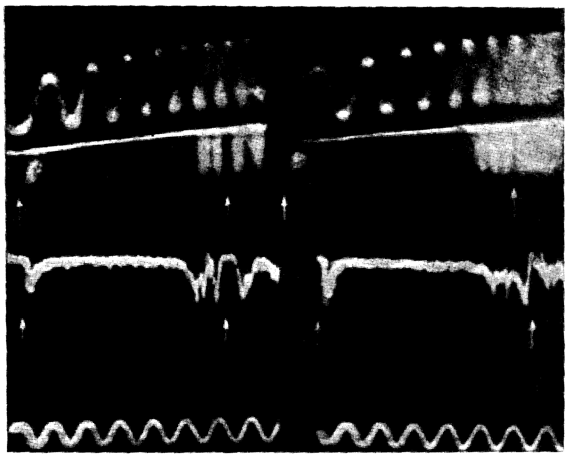

FIG. 6. Splitting of the resonance into two (a) and three (b) narrow resonances. I – streak photograph of the discharge obtained by means of the light amplifier. The photography was carried out in the direction perpendicular to H_0 through a narrow slit located perpendicular to the axis of the discharge tube; II – oscillogram of the signal from the photoelectric amplifier which records the light emission of the plasma in the center of the discharge tube. The pressure of the hydrogen: a – 3.5×10^{-5} mm mercury; b – 10^{-4} mm mercury. The amplitudes H_0 and $\tilde{H}$ are respectively equal to 3.43 koe and 74 oe. The arrows indicate the times of passage of H_0 through zero. The time scale (period of the sinusoidal oscillations) in all the photographs is equal to 0.5 msec.

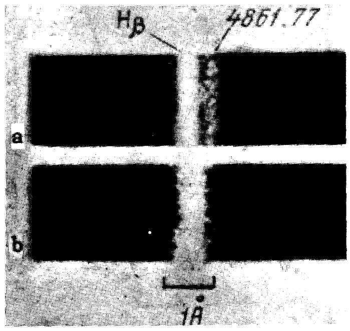

FIG. 7. Photograph of the H_β line obtained by means of the light amplifier and the ISP-51 spectrograph (focal length of the camera 1300 mm); a – in the spectrum of a standard DVS-25 hydrogen tube; b – in the high-frequency discharge (without the field H_0).

An estimate of the high-frequency energy absorbed at resonance was carried out in the arrangement with frequency 12.5 Mc/sec. At a generator power of 20 kw, the plasma absorbed about 10 kw of energy. This power is evidently mainly expended in ionization of the gas.

In the energy balance an important role must be played by the charge exchange with neutral atoms by means of which the energy absorbed by the plasma reaches the wall of the discharge chamber. From this point of view there is interest in the measurement of the temperature of neutral atoms in the discharge. Such measurements, based on the Doppler width of the H_β line, were carried out with the aid of a light amplifier for the high-frequency discharge outside the resonance conditions (in the absence of the field H_0).* The results of the measurements are shown in Figs. 7 and 8. In this case the Doppler broadening of the H_β line in the discharge was shown to be equal to ~ 0.6 A, which corresponds to a gas temperature of 2.5 ev (in energy units).

3. The experimental material just given makes it possible to draw the conclusion that a magnetoacoustic resonance was observed in the experi-

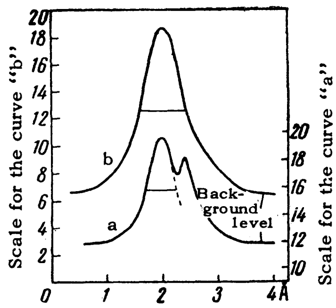

FIG. 8. Results of photometry of the negative of photographs shown in Figs. 7a and b. Light intensity is plotted along the ordinate in arbitrary units (the same for a and b). Thin horizontal lines indicate the half-width of the spectral lines.

*In this case the ion density in the discharge was $\lesssim 10^{12}$ cm^{-3} and the Stark broadening of the line was much smaller than the Doppler broadening.

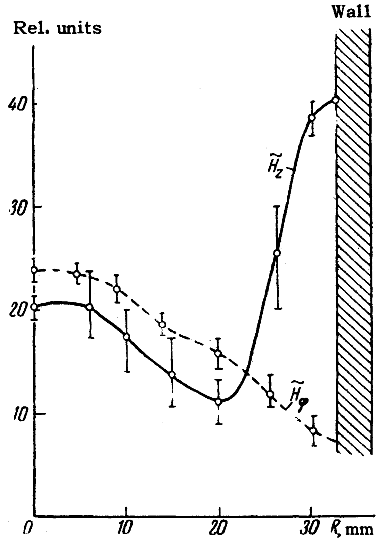

FIG. 9. Radial distribution of the components $\tilde{H}_z$ and $\tilde{H}_\varphi$ of the amplitude of the high-frequency magnetic field obtained in the arrangement with frequency 50 Mc/sec for $H_p \sim 800$ oe in hydrogen ($p = 9 \times 10^{-4}$ mm of mercury).

ments we have described. The phenomenon can be ascribed neither to electronic nor to ionic cyclotron resonance, since the observed resonance frequency lies far from the corresponding cyclotron frequencies. The dependence of the resonance field H_p on the amplitude of the variable field $\tilde{H}$ becomes understandable if we keep it in mind that the preliminary ionization in our experiments was brought about by the same high-frequency field whose interaction with the plasma was studied. This means that the change of the amplitude of the high-frequency field should lead to a change in the density n of charged particles which was established before the initial resonance. Consequently, the experimental results given above qualitatively reflect the dependence of H_p on the density n according to Eq. (1). The observed dependence of H_p on the mass M of the ion agrees qualitatively with this formula.

For quantitative comparison of Eq. (1) with experiment, an exact measurement of the quantity $\rho = nM$ is required. Such measurements were not carried out. The microwave testing made it possible to establish only the limiting values of the electron density, equal to 10^{12} and $1.6 \times 10^{13}\ \text{cm}^{-3}$, respectively, for the three-centimeter and eight-millimeter probes. An even larger inaccuracy is attributable to the mass M, inasmuch as in the process of discharge a considerable amount of impurity gas from the walls of the chamber enters into the discharge.

It can be assumed that qualitative agreement with theory is obtained also for the radial distribution of amplitude of the high frequency magnetic field at resonance (Fig. 5a), if we assume that the damping is sufficiently large (a Q of ~ 3).

Experiments with argon shown in Fig. 5b are of interest inasmuch as they were carried out in a range of frequencies known to be above the "hybrid." In the case of purely radial vibrations in this region there should be no penetration of the variable field into the cold plasma. However, experiment shows that penetration does exist and in its character it differs slightly from what takes place at a frequency below the "hybrid." One can therefore draw the conclusion that under experimental conditions transverse magnetoacoustic vibrations are observed with the direction of propagation not exactly perpendicular to the field H_0. This is confirmed by probe measurements of the azimuthal magnetic field $\tilde{H}_\varphi$ (see Fig. 9). One should note one more fact of qualitative agreement of theory with experiment which takes place behind the region of magnetoacoustic resonance, on the side of higher magnetic fields. Here, as follows from the evidence of the magnetic probe, for an increase of H_0 above a certain limiting value, the variable field begins to penetrate freely into the region of the discharge chamber, as in a vacuum. Simultaneously, the power loss to the plasma and the intensity of the radiation of the plasma falls off sharply.

The limiting field corresponds approximately to the conditions in which the azimuthal drift velocity of the electrons

$$v_\varphi = (\omega / \omega_i)\, \tilde{H} / \sqrt{4\pi\rho}$$

becomes insufficient for effective ionization.

In conclusion, the hope can be expressed that the observed magnetoacoustic resonance in which an intensive penetration of the high frequency vibrations into the plasma takes place is of interest from the point of view of the heating of a dense plasma.

The authors take note of the constant interest and cooperation displayed by Academician I. V. Kurchatov toward the completion of the present work.

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