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SPATIAL AMPLIFICATION OF VARIABLE MAGNETIC FIELDS DURING MAGNETIC-SOUND RESONANCE IN A PLASMA

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Magnetic-sound resonance under linear conditions is investigated experimentally. It is shown that under resonance conditions the variable magnetic field in a plasma increases several fold in comparison with its initial value.

INTRODUCTION

IN the first researches devoted to the study of magnetic-sound resonance in a plasma, the simplest arrangement was usually used, in which the production of the plasma column and the study of resonance phenomena were carried out with the same generator.[1-3] In such an experimental setup, the plasma concentration changes during the course of the experiment because of the variable field applied to it, and the experiment is not linear in this sense.

For the study of forced magnetic-sound oscillations under strictly linear conditions, a cold plasma source was constructed, which made it possible to obtain a plasma pinch in a constant magnetic field with a diameter of ~ 5 cm and with concentrations of charged particles $\sim 10^{13}$ cm^{-3}. The degree of ionization amounted to several tenths of one per cent.

The excitation of the resonance investigated was brought about by a low-power generator at fixed values of the concentration and diameter of the pinch.

CONSTRUCTION OF THE APPARATUS

The apparatus consisted of a glass tube, in which the discharge took place and the interaction of the plasma with a variable magnetic field was studied (see Fig. 1).

The tube was placed in a constant magnetic field which could have different intensities in the ionization and measurement spaces, since it was created by two independent constant voltage sources.1) The intensity of the magnetic field in the ionization space could change in the range from 0 to 1000 Oe, while the maximum value of the intensity of the magnetic field in the measurement space amounted to 3000 Oe.

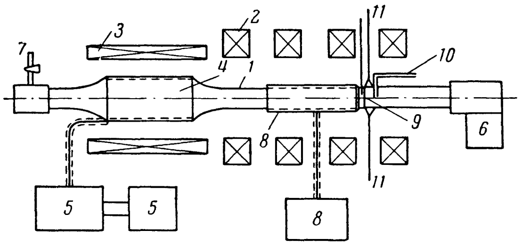

FIG. 1. Block diagram: 1 – glass tube, 2 – coils for magnetic field of the measurement space, 3 – solenoid for magnetic field of source, 4 – hf circuit of source, 5 – generator and modulator, 6 – diffusion pump, 7 – gas leak valve, 8 – measurement generator and circuit, 9 – magnetic probe, 10 – double electric probe, 11 – probing antennas for 8 mm waves.

The diameter of the ionization space was 10 cm. A resonant circuit fed from a generator with a frequency of 50 Mc and with nominal power of 150 kW was placed over this part of the glass tube.

The plasma, produced by the hf discharge in the ionization space, flowed along the magnetic force lines into a region with a large constant magnetic field intensity. Accordingly, the diameter of the glass tube was narrowed to 6.0 cm in this part.

For magnetic field intensities of 350 Oe in the ionization space and 1500 Oe in the measurement space, a plasma column of 5 cm diameter is obtained in the latter region with a concentration above 10^{13} cm^{-3}. The discharge takes place in hydrogen at an initial pressure of $(1-2)\times 10^{-3}$ mm.

The limiting vacuum in the working region amounted to 5×10^{-7} mm Hg. No change of hydrogen pressure was observed during the discharge. The discharge spectrum obtained in the visible region showed that the intensity of radiation of the impurity lines was small.

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1) The portion of the vacuum tube in which the ionization was produced will be called in what follows the ionization space, and the portion of the tube in which excitation of the investigated resonance takes place will be called the measurement space.

The operation of the hf generator was pulsed; the shape of the pulse was exponentially decaying. (The pulse amplitude fell off by a factor e in 10 micro-seconds. The plasma concentration likewise fell off in time.)

A nonresonant circuit in the form of a long coil of length 25 cm and diameter 6 cm was placed over the narrow part of the glass tube (measurement space). The hf field of the circuit was directed parallel to the constant magnetic field. The operating frequency range was 2 — 25 Mc; a GSS-6 exciting generator was used. Induction of resonance in the plasma was brought about by a magnetic probe which could be moved in the glass tube along its radius. The magnetic probe consisted of a coil of small dimensions which was screened on the outside by an electrostatic shield. The coil was connected by a short length of shielded two-conductor line to a coaxial cable RK-1. Such a connection guaranteed the maximum stability in operation over the frequency range. The signal from the magnetic probe was amplified by means of a superheterodyne line receiver "Klen" and fed to an IO-4 oscilloscope. A block diagram of the arrangements is shown in Fig. 2.

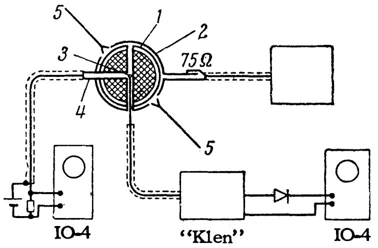

FIG. 2. Circuit for excitation and detection of resonance: 1 – glass tube, 2 – exciting loop, 3 – magnetic probe, 4 – double electric probe, 5 – probing antennas for 8 mm waves.

DESCRIPTION OF THE EXPERIMENT

At the instant of application of the hf pulse to the circuit of the ionization space, ionization takes place in the chamber and the plasma flows along the magnetic force lines into the measurement space. Concentration was monitored with a microwave probe at a wavelength of 8 mm, and also by means of an 8 mm Wharton interferometer.[4]

Simultaneously, one could monitor the concentration by means of a twin electric probe,[5] calibrated by blocking of the 8 mm signal. The operation of the electric probe in the magnetic field was tested by A. I. Makov in his diploma research in 1961 with the help of the 8 mm interferometer in this same setup. The ratio of the intensities of the constant magnetic fields was chosen in such a fashion that the plasma column did not touch the walls of the chamber in the measurement space.

The intensity of the variable magnetic field in the measurement space amounted to a value of the order of 10^{-5} of the constant field, i.e., the measurement generator did not disturb the plasma. The magnetic measurement probe was located on the end of the exciting circuit and, being placed on the axis of the plasma column, could fix the penetration of the hf field inside the plasma. A typical picture of the magnetic-sound resonance is shown in Fig. 3, in which the oscillograms of the hf signal from the magnetic probe and the current of the double electric probe are shown as the concentration varies with time.

The excitation frequency was 17×10^6 cps. The readings of the double probe were monitored with the interferometer; it was noted that the readings of the interferometer in the concentration range $2 \times 10^{12} - 10^{13}$ cm^{-3} agreed with the readings of the double probe within the limits of experimental accuracy (see Fig. 4). This result is also proof that the concentration distribution over the cross section does not differ too much from the equilibrium distribution.

As is seen from the oscillogram of the signal from the magnetic probe, several fold amplification of the variable magnetic field, compared with the original signal, takes place at the maximum of resonance. A "screening" effect is noted during damping of the discharge, at small plasma concen-

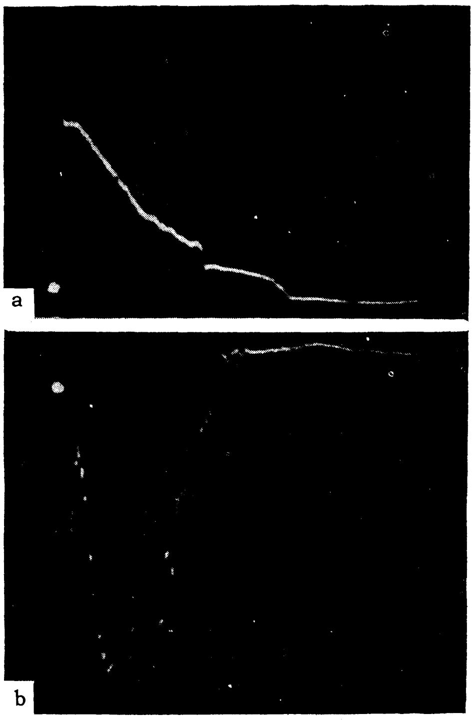

FIG. 3. Oscillograms of the current in the double electric probe and of the emf from the magnetic probe. $H_0 = 1500$ Oe, $p_0 = 2 \times 10^{-3}$ mm Hg, concentration at initial instant, $n_{max} = 1.6 \times 10^{13}$ cm^{-3}, $f = 17 \times 10^6$ cps, length of sweep ~15 microseconds.

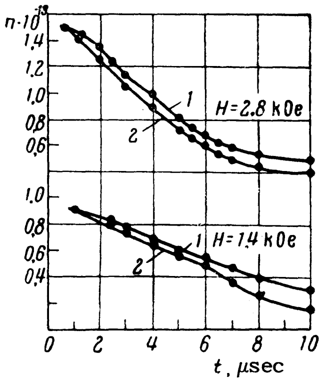

FIG. 4. Calibration of double electric probe by microwave interferometer: 1 – readings of interferometer, 2 – readings of double electric probe.

trations, i.e., the signal at the probe becomes smaller than in the absence of the plasma. The effect of the screening cannot be observed during growth of the concentration, since the ionization takes place too rapidly.

The radial distributions of the components $\tilde{H}_z$ and $\tilde{H}_\varphi$ of the variable magnetic field were obtained by means of the magnetic probe. These are shown in Fig. 5. In the limits of the plasma column, the character of the distribution of $\tilde{H}_z$ is close to that of the Bessel function $J_0(kr)$. The variation of $\tilde{H}_\varphi$ is qualitatively similar to that of the function $J_1(kr)$. The radial dependence has this character until the system becomes close to resonance; $\tilde{H}_\varphi = 0$ in the region of screening.

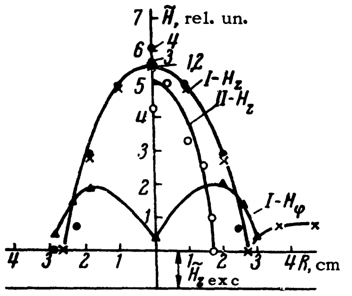

FIG. 5. Distribution of the components $\tilde{H}_z$ and $\tilde{H}_\varphi$ of the magnetic field along the radius for two values of the diameter of the plasma column: 5.6 cm (curve I) and 3.4 cm (curve II). H_0 = 1500 Oe, $n = 10^{13}$ cm^{-3}, $f = 1.7 \times 10^7$ cps.

The radial dependences for $\tilde{H}_z$ were obtained for two values of the radius of the plasma column: R_1 = 2.8 cm and R_2 = 1.7 cm. As is seen from Fig. 5, the radial dependence does not depend on the radius of the column within the limit of experimental accuracy.

The experimental data obtained allowed us to construct the resonance curve of the frequency dependence of the amplitude of the magnetic sound under otherwise constant conditions. The curve was constructed in the following fashion: for each fixed value of the excitation frequency (from 2 to 25 Mc) the time variation of the signal was studied with a magnetic probe placed at the center of the plasma column; simultaneously, the time variation of the concentration of the plasma was monitored. From the given oscillograms, one could construct the frequency dependence of the magnetic-sound resonance for fixed concentration, dimensions of the plasma column and of the magnetic field. The approximate variation of the frequency dependence of the amplitude of the magnetic sound for concentration $n = 1.3 \times 10^{13}$ cm^{-3} and column dimension R = 2.8 cm, in a field H = 1500 Oe, is shown in Fig. 6. Two resonant maxima are clearly noted on the curve.

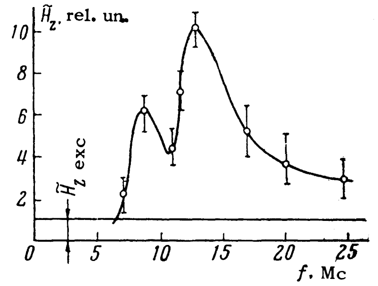

FIG. 6. Dependence of the field $\tilde{H}_z$ at the center of the plasma column on the frequency of excitation, H_0 = 1500 Oe, $p_0 = 9 \times 10^{-4}$ mm Hg, $n = 1.3 \times 10^{13}$ cm^{-3}, wave numbers $k_1 = 2.4/R$, $k_3 = 0.06$ cm^{-1}.

DISCUSSION OF RESULTS

As is seen from Fig. 5, the radial distribution of the field component $\tilde{H}_z$ is close to the function $J_0(kr)$, while that of $\tilde{H}_\varphi$ is close to $J_1(kr)$. It can therefore be assumed that oscillations were excited in the experiment with an azimuthal number m = 0 and radial number n = 1. For such oscillations, the boundary condition has the form $k_1R = 2.4$ for a cylinder with a free boundary,[6] and $k_1R = 3.83$ for a closed plasma resonator surrounded by ideally conducting walls.[7] In accord with the curve of Fig. 5, the longitudinal component $\tilde{H}_z$ is close to zero on the boundary of the plasma pinch. From this, the conclusion can be drawn that the picture of the oscillations in the experiment described was evidently close to the case of a cylinder with free boundaries.[2] Therefore, in the comparison of the value of the resonant frequency with theory, we take $k_1R = 2.4$.

By making use of the formula of Frank-Kamenetskiĭ[7] for a long cylinder, we get

$$f=\frac{V_A}{2}\sqrt{\left(\frac{2,4}{\pi R}\right)^2+\frac{M}{\Pi^* m}\left(\frac{l}{L}\right)^2},$$

where M is the mass of the ion, m is the electron mass, l the longitudinal number, L the length of the oscillating plasma volume, R the radius of the plasma column, V the Alfvén velocity, $\Pi^* = \omega_0^2/k_1^2c^2$. In our case, $\Pi^* \geq 30$.

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[2] This can be hypothetically attributed to the free radiation of electromagnetic waves from the ends and through the gap which served for excitation of the oscillations.

If we set the longitudinal number $l = 1$, then, for the given parameters ($n = 10^{13}$ cm^{-3}, $H_0 = 1500$, $L = 50$ cm, $R = 2.8$ cm), we get $f = 16$ Mc. The experimental value of the resonant frequency is $f = 17$ Mc for these conditions. Consequently, we can draw the conclusion that in our case the picture of the oscillations was close to the case with longitudinal number $l = 1$. This derivation is in qualitative agreement with the direct measurement of the distribution of amplitudes along the length of the cylinder.

Special interest is attached to the observation of the effect of spatial amplification of a variable magnetic field in a magnetized plasma. It was found experimentally that the amplitude of the field inside the plasma was 5 — 7 times larger than the signal in the absence of plasma. Obviously, this quantity must depend on the physical state of the plasma, and must be connected with its quality factor.

It is probable that this effect can have practical interest.

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