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## *OSCILLATIONS OF A PLASMA IN A MAGNETIC FIELD AT FREQUENCIES CLOSE TO THE CYCLOTRON FREQUENCY*

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A description is given of a method used to observe oscillations of a plasma in a longitudinal magnetic field at frequencies several times smaller than the ion cyclotron frequencies. The method makes it possible to observe the oscillation spectrum in the form of a series of narrow lines with very high signal-to-noise ratio. It is suggested that the observed oscillations are analogous to the waves known from the hydromagnetic analysis.

THE instabilities of plasmas in magnetic fields have been considered theoretically by many authors.[1] However a number of the questions in this field have not been answered in as much detail as might be desired. This situation is due to the fact that there is a large variety of complicated effects which make it essentially impossible to carry out a systematic theoretical investigation of the problem and the fact that the experimental data are very scanty and are not always amenable to theoretical interpretation. The latter circumstance arises from the difficulties involved in realizing the conditions of observation required by the theory. The instabilities of plasmas in magnetic fields are of the utmost importance, particularly as regards practical applications. In this connection the observations described below may be of interest. The results reported here are to be considered of preliminary nature only.

## APPARATUS AND METHOD OF OBSERVATION

A diagram of the apparatus, which was originally intended for the observation of ion cyclotron resonances in helium plasmas and hydrogen plasmas, is shown in Fig. 1. The principle of operation is similar to that used for the observation

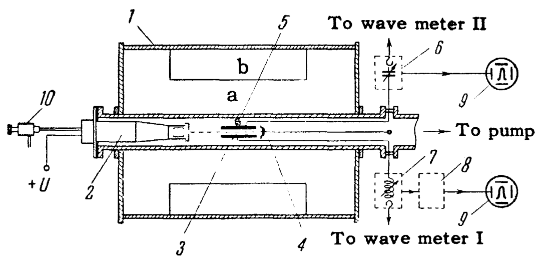


FIG. 1. Diagram of the apparatus. 1) solenoid: a) magnetizing winding, b) modulation winding; 2) ion source; 3) condenser; 4) collector; 5) proton probe; 6) magnetometer oscillator; 7) cyclotron resonance oscillator; 8) amplifier; 9) oscilloscopes; 10) needle valve for admitting gas.

nuclear magnetic resonance effects:[2,3] the absorption of radio frequency power by ions which rotate in a magnetic field is detected by the change in Q of an oscillator circuit. A powerful oil-cooled solenoid produces an axial magnetic field and the cold-cathode source is located at the axis of the field;* the source is a Penning discharge (Fig. 2). Collisions of ions extracted from the discharge chamber with gas molecules along the axis of the solenoid lead to the formation of a

*The source was designed by V. G. Gel'kovskiĭ and built under his direction at one of the Institutes of the Academy of Sciences, U.S.S.R.

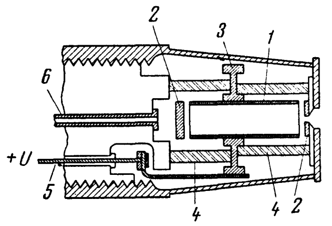


FIG. 2. Diagram of the ion source. 1) molybdenum cathode; 2) magnesium anodes; 3) rod cathode; 4) quartz insulators; 5) feed-through for cathode voltage; 6 gas inlet.

pinched plasma 3 — 5 mm in diameter and approximately 20 cm long. The pinch passes between the plates of a long plane condenser which is connected to the oscillator circuit; the plasma beam then strikes a collector which is connected to meters which measure the ion current and the electron current of the pinch. These measurements indicate that both currents are equal, varying from 10 to 35 $\mu$a depending on the mode of operation of the system. When the oscillator frequency coincides with the rotational frequency of ions of a given mass in the applied magnetic field a fraction of the radio frequency power is absorbed by the ions located between the plates of the condenser at a given instant of time. This absorption causes a reduction in the Q of the circuit and this effect is detected by the usual radio spectroscopy method: the magnetic field is modulated and the detected signal is applied to an oscilloscope whose sweep is synchronized with the modulation. On the outer side of one of the plates of the condenser there is a probe which is used to make proton measurements of the magnetic field strength. Measurements show that at the discharge (between the source and the collector) the field inhomogeneity is less than 1 — 1.5% (for fields of 2,000 to 3,000 oersteds); in the section occupied by the condenser the magnetic field variation is less than 0.25%. The magnetic field is modulated at 50 cps at an amplitude of 70 oersteds. A controlled leak (needle valve) of simple design is used to control the admission of gas into the system, making it possible to vary the pressure over wide limits and to maintain the pressure at a given value when desired.

The first observations in the hydrogen plasma showed that in addition to the very wide cyclotron resonances (due to the atomic and molcecular hydrogen ions) there were strong narrow signals (Fig. 3) which could be observed at lower values of the magnetic field. These lines are observed in groups, with different spacings between neighboring lines, with intensities which fall off uniformly with increasing frequency. It is also observed that similar signals appear on the screen of the oscilloscope used for the proton measurement of the magnetic field (Fig. 4). We believe that the observed signals, which are different

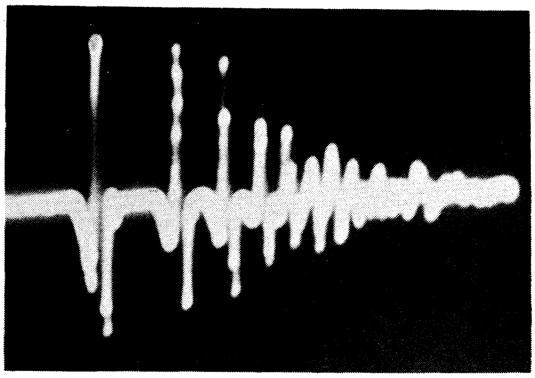

FIG. 3. Signals observed together with the cyclotron resonance signals in a hydrogen plasma. $p = 6 \times 10^{-4}$ mm Hg; H = 1276 oersteds; U = 560 v.

from the cyclotron resonance signals, are due to oscillations of the plasma. The alternating electric fields produced in the vicinity of the plasma as a result of these oscillations are picked up by the oscillator condenser used to detect the plasma resonance by the probe of the proton magnetometer, which operate as antennas; the oscillators themselves, under favorable conditions, act as narrow-band tunable receivers.

In order to obtain more meaningful measurements the following changes were made in the detection system. The condenser was replaced by antennas in the form of rods or loops: these antennas were oriented in different positions with respect to the beam. The antennas were placed at distances such that they could not be struck by electrons or ions from the beam. The antennas were connected to a narrow-band receiver or to a wide-band amplifier. In order to avoid the effect of the above-mentioned parasitic signals on the screen of the proton magnetometer oscilloscope the probe of this unit was shielded.

In the observations made with the first method, when the magnetic field modulation was applied signals similar to those shown in Fig. 3 were

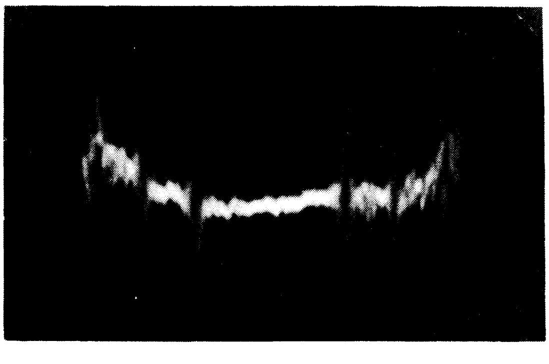

FIG. 4. View of the signals on the screen of the proton magnetometer oscilloscope. $p = 6 \times 10^{-4}$ mm Hg; H = 1180 oersteds; U = 530 v.

observed. In the observations made with the second method, in which no magnetic field modulation was used, reproducible periodic sinusoidal or saw-tooth curves were obtained on the screen. It was observed that the saw-tooth pulses of different intensity were produced only when the magnetic field modulation was applied in certain cases. The oscillation frequencies were measured by means of the receiver frequency meter or by making comparisons with a frequency standard. The intensities of the lines were determined by measurements of the heights of the signals on the screen of an oscilloscope to the input of which a current divider was connected.

## RESULTS OF THE OBSERVATIONS

The signals shown in Fig. 3 were first observed in a hydrogen plasma at pressures of the order of $10^{-5}$ mm Hg (the pressure in the source discharge was a half an order of magnitude higher). Using the improved methods of detection described above it was possible to obtain a well-defined spectral pattern (Figs. 5 and 6) and to carry out the measurements reported here.

It was found that the signals were produced at pressures ranging from $10^{-1}$ to $10^{-5}$ mm Hg over a relatively narrow range of magnetic field values (900 to 1600 oersteds); no signals were observed beyond these limits. In the hydrogen plasma there are three clearly defined series of lines which are superimposed on each other but are very different in intensity. Within each series the intensity of the lines falls off approximately linearly with frequency; within a given series the lines are equally spaced. By varying the magnetic field with the detection system fixed at a given frequency or by tuning the detection system with the magnetic field fixed it is possible to observe the entire spectra. Several tens of lines are observed in the total spectrum. An idea of the shape of a line can be obtained from Fig. 7. In the region in which the signals are observed there is almost no noise but beyond this region the noise level is generally high. At certain values of pressure and magnetic field the intensity of the most sharply defined signals has a signal-to-noise ratio of $10^3 - 10^4$.

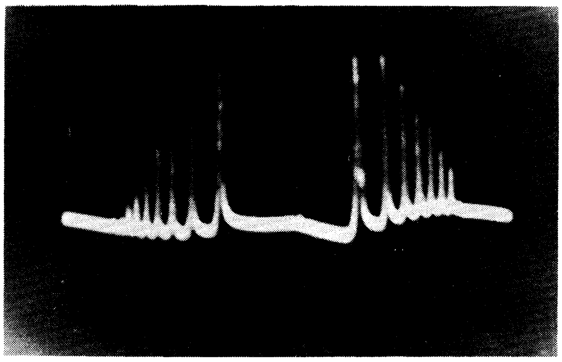

FIG. 5. Higher harmonics observed with a narrow-band receiver; $p = 2 \times 10^{-4}$ mm Hg, H = 1523 oersteds, U = 560 v; modulation amplitude 60 oersteds.

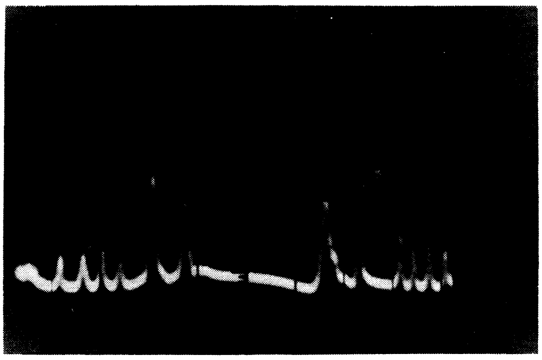

FIG. 6. The same but at a pressure of $5 \times 10^{-3}$ mm Hg.

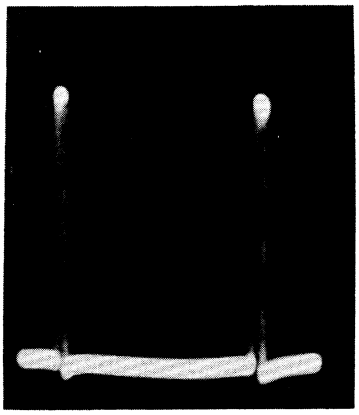

FIG. 7 One of the harmonics ($\nu$ = 1,440 Mcs) of the oscillations in the field of 1,420 oersteds; $p = 5 \times 10^{-4}$ mm Hg; U = 650 v; modulation amplitude approximately 15 oersteds.

The measurements indicate that within the limits of the experimental accuracy the frequencies for lines of a given series are multiples of some base frequency. The intensities of the lines of the same series falls off approximately linearly while the intensity of nearby lines, associated with different series, is very different. In Table I

TABLE I

| Line number | Frequency, Mcs | Relative intensity | Line number | Frequency, Mcs | Relative intensity |
|---|---|---|---|---|---|
| 1 | 0.121 | 0.008 | 10 | 1.270 | 0.001 |
| 2 | 0.1816 | 0.012 | 11 | 1.453 | 0.650 |
| 3 | 0.242 | 0.005 | 12 | 1.815 | 0.540 |
| 4 | 0.363 | 1.000 | 13 | 2.172 | 0.453 |
| 5 | 0.484 | 0.003 | 14 | 2.541 | 0.365 |
| 6 | 0.544 | 0.003 | 15 | 2.912 | 0.244 |
| 7 | 0.726 | 0.880 | 16 | 3.270 | 0.140 |
| 8 | 0.908 | 0.002 | 17 | 3.643 | 0.048 |
| 9 | 1.088 | 0.740 | | | |

we show the frequencies of the first seventeen lines of the spectrum observed in a hydrogen plasma at a pressure of $2 \times 10^{-4}$ mm Hg in a field of 1523 oersteds; estimates of the relative intensities are also given. It is apparent that the frequencies of the most intense lines are multiples of 0.363 Mcs, i.e., the frequency of the first line (line 4 of Table I), and that in addition to these harmonics there are much weaker lines whose frequencies do not fall in this series. These lines are to be associated with two other series in the spectrum. At pressures an order of magnitude lower, by a suitable choice of source cathode voltage it is possible to obtain still weaker lines; the frequencies of these lines are so close to the fundamental frequency that they are not considered multiples.

The frequencies of all lines are found to be highly dependent on the parameters characterizing the mode of operation of the system. The frequency increases nonlinearly with pressure. The relation between these quantities in the region of most rapid change is shown in Fig. 8. The dependence of frequency on the potential of the cathode in the source is almost linear, as is apparent from Fig. 9. At the present time, because of instrumental uncertainties it is impossible to determine the dependence of frequency on magnetic field; it is known, however, that the frequency increases very rapidly with field. The spacing between neighboring lines in the same series increases linearly with magnetic field (Fig. 10).

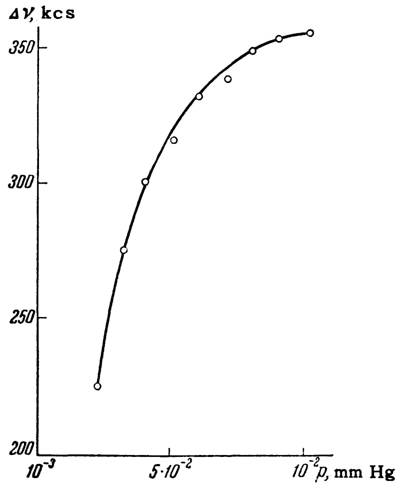


FIG. 8. Dependence of frequency on pressure. H = 1523 oersteds; U = 560 v.

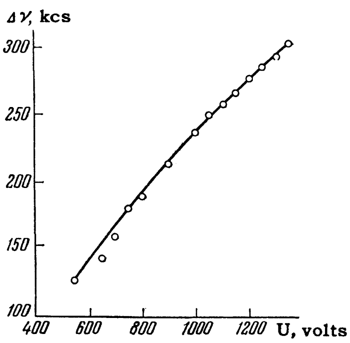


FIG. 9. Dependence of frequency on the potential of the cathode in the source. H = 1523 oersteds; p × 10⁻⁴ mm Hg.

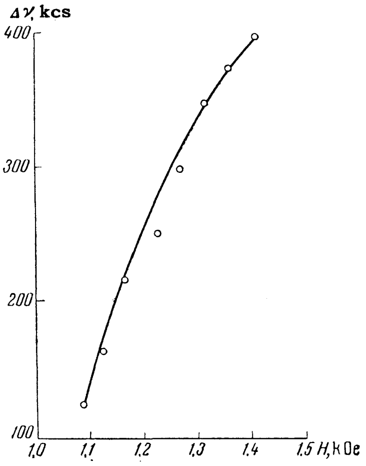


FIG. 10. Dependence of the frequency difference between neighboring lines on magnetic field. $p = 5 \times 10^{-4}$ mm Hg.

## DISCUSSION OF THE RESULTS

Among the oscillation modes of a plasma in a magnetic field which are predicted by theory[4] there are oscillations at frequencies which are only slightly different from the ion cyclotron frequencies. Thus, Stix,[5] in considering the behavior of a plasma in a longitudinal magnetic field, has shown that it is possible to produce hydrodynamic Alfven waves,[6] which, at wavelengths much less than the wavelength of light in vacuum, degenerate into waves of frequency

$$\omega^2 = \omega_c\left(1 - \frac{\omega_p^2}{k^2c^2}\right), \qquad (1)$$

close to $\omega_c = eH/m_ic$, the ion cyclotron frequency. Here $\omega_p$ is the ion plasma frequency and k is the wave number. The difference in frequency from the cyclotron frequency is due to the electric field in the plasma; this field gives rise to a centrifugal force which acts in addition to the force due to the magnetic field. The effect leads to a slowing down of ion rotation.

Essentially the same result has been derived by Ferraro[7] who has shown that in a rarified plasma there should be waves similar to the hydromagnetic waves at frequencies which approach a cyclotron frequency as the plasma density approaches zero. These waves are circularly polarized and can only exist in magnetic fields which are smaller than some critical value. The critical value is proportional to the square root of the product of the plasma density and the sum of the ion and electron masses.

It follows from the analyses of Stix and Ferraro

TABLE II

| Frequency, Mcs | Proportionality number | Harmonic number and ion | Frequency, Mcs | Proportionality number | Harmonic number and ion |
|---|---|---|---|---|---|
| 0.121 | 2 | 0; $H_3^+$ | 0.908 | 15 | 4; $H_2^+$ |
| 0.1815 | 3 | 0; $H_2^+$ | 1.088 | 18 | 4; $H_1^+$<br>5; $H_2^+$ |
| 0.242 | 4 | 1; $H_3^+$ | 1.270 | 21 | 6; $H_2^+$ |
| 0.363 | 6 | 0; $H_1^+$<br>1; $H_2^+$<br>2; $H_3^+$ | 1.453 | 24 | 3; $H_1^+$ |
| 0.484 | 8 | 3; $H_3^+$ | 1.815 | 30 | 4; $H_1^+$ |
| 0.544 | 9 | 4; $H_2^+$ | 2.170 | 36 | 5; $H_1^+$ |
| 0.726 | 12 | 1; $H_1^+$<br>3; $H_2^+$<br>5; $H_3^+$ | 2.540 | 42 | 6; $H_1^+$ |
| | | | 2.910 | 48 | 7; $H_1^+$ |
| | | | 3.270 | 54 | 8; $H_1^+$ |
| | | | 3.640 | 60 | 9; $H_1^+$ |

that the difference in frequency between the described oscillations and the cyclotron oscillations should be very small for a rarified plasma. In this connection the difference observed in the present measurements is extremely significant; thus, in a field H = 1520 oersteds, $\nu_c = 2.3$ Mcs while the frequency of the strongest harmonic which can be assigned to the atomic hydrogen ion is 0.363 Mcs, i.e., approximately six times smaller. This appreciable difference can be understood[4] if one notes that the ions move in a plane (perpendicular to the wave vector) which forms an angle $\varphi$ with the direction of the magnetic field. This situation results in a frequency $\omega = \omega_c \cos \varphi$. If account is taken of the electric field the frequency should be determined by Eq. (1), with the right side multiplied by the factor $\cos \varphi$.

The theory does not exclude the possibility of the production in a plasma in a magnetic field of an oscillation spectrum of equally spaced lines:[8] $\omega = \omega_0 n$ $(n = 1, 2, 3 \ldots)$ where $\omega_0$ is determined by the plasma density and the product of the magnetic field and electric field of the beam. However, as has been shown in the work cited, the frequencies given by this formula are 3 to 4 orders of magnitude lower than the observed frequencies.

If we assume that the observed lines are harmonics of a given fundamental it is possible to make a comparison of the experimental results with the theory so far as the dependence of frequency on ion mass is concerned.

If we assume $\omega = \omega_c \cos \varphi$, the departure from simple multiplicity shown in Table I is amenable to a simple explanation. Under the conditions of the present experiment the following ions should be present: $H_1^+$, $H_2^+$, and $H_3^+$. The frequencies associated with these ions should be in the ratio 2 : 3 : 6. The first harmonics should be in the ratio 4 : 6 : 12 etc. Consequently the entire spectrum should consist of lines whose frequencies go as the numbers 2 : 3 : 4 : 6 : 8 : 10 : 12 : 14 : 15 etc. In a number of cases the higher harmonics of the heavier ions will coincide with the lower harmonics of the lighter ions. Thus, the second harmonic of the $H_3^+$ ion and the first harmonic of the $H_2^+$ should coincide with the fundamental frequency of the $H_1^+$ ion. This effect leads to a departure from a uniform diminution of the line intensity with increasing frequency. The intensities of the first lines of the various ions should be different, corresponding to the different abundances of these ions in the plasma.

Applying these considerations to the data of Table I, we see (cf. Table II) that the frequencies of the observed lines are proportional to the numbers of the series enumerated above. From a comparison of the frequencies we may conclude that the first line (0.121 Mcs) is due to $H_3^+$ ion, the second line (0.1815 Mcs) is due to $H_2^+$ ion, the third line is the first harmonic of the $H_3^+$ ion while the fourth is the resultant of the superposition of the second harmonic of $H_3^+$ and the first harmonic of $H_2^+$ are the fundamental frequency of the $H_1^+$ ion and so on.

The differences in the intensities of the series of different ions also means that the lines of different series become lost in the noise background at different values of the harmonic number. Thus, the lines of $H_3^+$ are no longer observed after the second harmonic (0.484 Mcs) while the last observable harmonic of $H_2^+$ is the sixth (1.270 Mcs). On the other hand the lines of $H_1^+$ are observable up to the fifteenth harmonic.

If one assumes that the relative intensities of the lines in the spectrum makes it possible to estimate the relative abundances of various ions in the beam we may conclude that in the present case the fundamental effect in the plasma is due to $H_1^+$ ions and that the $H_2^+$ and $H_3^+$ content is only a fraction of a percent.

From the point of view of the explanation which has been proposed the oscillations and their dependence on ion mass obtained from the present experimental data represent a hydrogen mass spectrum; the apparatus which has been used is essentially a radio-frequency plasma mass spectrometer with a linear dispersion of approximately 1,000 cps per 1% relative difference of mass and a rather high resolving power.

The weak lines which are sometimes observed are possibly due to deuterium or to higher harmonics of the hydrogen mixtures. If this assumption is correct, with further improvement of this method of observation of plasma oscillations it may be possible to build a device which will be useful in mass spectrometry.

The author is highly indebted to V. G. Gel'kovskiĭ for his help in the construction of the apparatus and a number of valuable comments. The author is also indebted to Mechanic N. A. Matsuev and Technician N. I. Naumkin for their skill in the construction of this apparatus.

[1] L. Spitzer, Physics of Completely Ionized Gases, (Russ. Transl.) IIL, Moscow, 1957. A. Guthrie, and R. K. Wakerling, The Characteristics of Electrical Discharges in Magnetic Fields, McGraw Hill, New York, 1949. See also Проблемы современной физики (Problems of Contemporary Physics), No. 11, 1952; No. 2, 1956; No. 7, 1955; No. 7, 1957; and No. 1, 1958, which contains a comprehensive bibliography.

[2] H. J. Woodford and I. H. Gardner, Rev. Sci. Instrl, **27**, 378 (1956).

[3] E. Andrew, Nuclear Magnetic Resonance, (Russ. Transl.) IIL, Moscow, 1957.

[4] S. I. Braginskiĭ, Dokl. Akad. Nauk SSSR **115**, 475 (1958). Soviet Phys. Doklady **2**, 345 (1957).

[5] T. H. Stix, Phys. Rev. **106**, 1146 (1957).

[6] H. Alfven, Cosmical Electrodynamics, Oxford, 1950 (Russ. Transl. IIL, Moscow, 1955).

[7] V. Ferraro, Proc. Roy. Soc. (London), **A233**, 310 (1955), see also Проблемы современной физики (Problems of Contemporary Physics), No. 7, 1957.

[8] Chao K'ei-Hua, Dissertation, Moscow State Univ. 1958.

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