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# *INVESTIGATION OF SOLENOIDAL DRIFT WAVES IN A STATIONARY MAGNETOACOUSTIC PLASMA*

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We have investigated magnetic noise in an apparatus in which the plasma is produced by the magnetoacoustic method in a glass tube located in a fixed magnetic field. The plasma flows continuously along the axis into the measurement volume; the magnetic field varies from 700 to 2500 Oe. A hydrogen plasma has been investigated in the pressure range $1 \times 10^{-3}$—$5 \times 10^{-3}$ torr. The real rf power introduced into the discharge is 4 kw. In this pressure range the electron temperature varies from 4 to 10 eV. The electron density at the center of the chamber is $5 \times 10^{11}$—$5 \times 10^{12}$ cm$^{-3}$. In the frequency range 50—500 KHz magnetic probes show strong (approximately 0.05 Oe) solenoidal electric noise whose fundamental frequency is of the order of 100 KHz. The dependence of this noise on the plasma parameters has been investigated. The results are discussed from the point of view of possible excitation of "Alfvén" drift waves in the inhomogeneous plasma.

## 1. INTRODUCTION

MOST of the experimental work devoted to the investigation of drift waves[1-4] has been concerned with the investigation of irrotational low-frequency oscillations by means of electric probes. However, the theory also predicts the excitation of solenoidal fluctuations of a drift nature in an inhomogeneous plasma.[5] Physically these waves are similar to Alfvén waves in a uniform plasma since they involve the bending of lines of force of the static magnetic field. For this reason, any method of investigating solenoidal oscillations must make use of magnetic probes. An investigation of this kind is the subject of the present work.

These experiments were carried out with a device shown schematically in Fig. 1. The apparatus consists of a cylindrical glass vacuum chamber (overall length 200 cm and diameter 10 cm) located in a longitudinal magnetic field. In the uniform region (approximately 100 cm) the strength of the magnetic field can be varied from 700 to 2500 Oe.

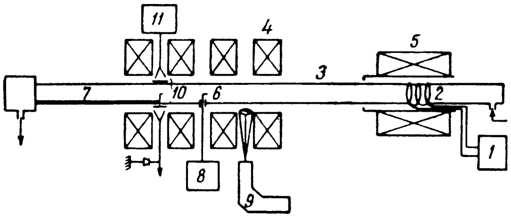


FIG. 1 Diagram of the experimental apparatus: 1) RF generator, 2) RF coil, 3) glass tube, 4) coil for the main magnetic field, 5) coil for the auxiliary magnetic field, 6) radial movable electric probe, 7) longitudinal movable electric probe, 8) spectrum analyzer, 9) monochromator, 10) Fabry-Perot interferometer λ = 8 mm, 11) 8 mm signal generator.

The plasma is produced by an rf generator which operates at 25 MHz. The applied magnetic field is parallel to the static field and the real power introduced into the plasma can be as high as 4 kw. The generator is coupled to the plasma by means of a three-turn coil which is located at one end of the vacuum chamber. Effective ionization in the region of the coil requires the application of a longitudinal magnetic field of 200—300 Oe which is produced by a separate coil. The discharge chamber is pumped to a pressure of $10^{-6}$ torr by means of oil diffusion pumps. Most of the experiments are carried out in hydrogen in the pressure range $10^{-3}$—$5 \times 10^{-3}$ torr. The following diagnostic techniques are used in these experiments.

1. The electron density is determined by means of a double electric probe and by means of a microwave Fabry-Perot interferometer which operates at $\lambda = 8$ mm. The maximum density is $5 \times 10^{12}$ cm$^{-3}$.

2. The electron temperature is determined by double electric probes and by an optical method (comparison of the relative intensities of the 5047 and 4713 Å lines in neutral helium which is added for this purpose).

The discrepancies in the temperature values as obtained by the different methods are less than 30%.

## 2. EXPERIMENTAL RESULTS

The electron density and temperature distributions in the radial direction at the center of the chamber are determined by means of a double electric probe. These measurements show that the density of the center of the plasma column varies from $5 \times 10^{11}$ to $5 \times 10^{12}$ cm$^{-3}$ depending on the experimental conditions.

The density distribution of charged particles for different magnetic fields is shown in Fig. 2. The density increases toward the axis of the discharge, reaching a maximum at $r = r_0$, and then diminishes somewhat at the axis itself. This double-humped distribution is a consequence of the magnetoacoustic method used to produce the plasma in which the maximum electric field of the ionizing waves occurs at the peripheral part of the plasma column.

The electron temperature distribution in the same cross section is also determined by means of a probe. Within the limits of experimental error the temperature at this cross-section is found to be constant, varying between 3.5 and 10 eV for various modes of operation of the generator and various pressures. For purposes of comparison the temperature is also measured optically from the relative intensities of the spectral lines at 5047 and 4713 Å in neutral helium. The relative intensities of these lines as functions of temperature are given in [6]. This pair of lines has been chosen because the error in the determination of temperature due to collisions between electrons and neutral atoms is a minimum for this pair.[7] The values of the electron temperature as obtained by these lines agree with those obtained by the probe measurements to within 30%.

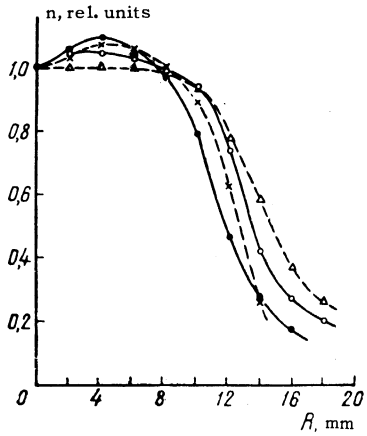


FIG. 2. Density distribution of charged particles over the radius of the column for various magnetic fields: ● – H = 2300 Oe, x – H = 1800 Oe, o – H = 1500 Oe, △ – H = 1000 Oe.

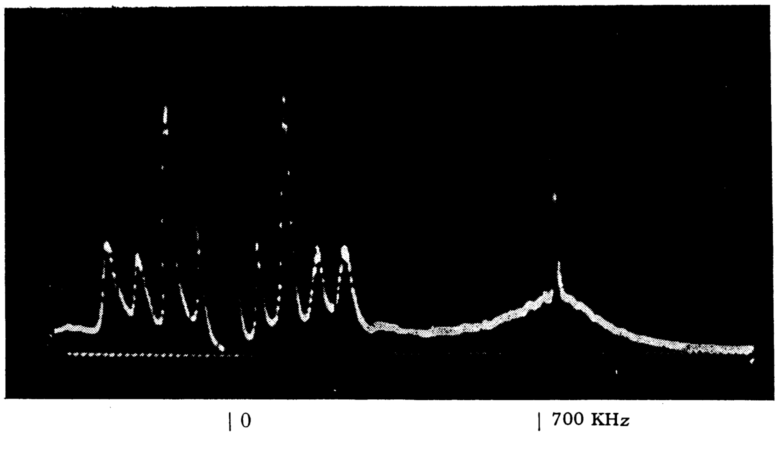
## 3. MEASUREMENT OF MAGNETIC NOISE

The spectral measurement of the magnetic noise is carried out by means of a noise spectrum analyzer (S4-8) which can be used to analyze noise between 10 KHz and 30 MHz. Most of the measurements are carried out in the range 50—500 KHz, but the spectrum is examined qualitatively between 500 KHz and 5 MHz.

The signals are investigated with a magnetic probe which is enclosed in an electrostatic shield. The probe signal is fed to a high-frequency filter and an amplifier and then to the input of the spectrum analyzer. The measurements are carried out both inside and outside the plasma. Greatest interest attaches to the spectrum in the range 50—500 KHz. In this region one observes strong oscillations (approximately 0.05 Oe) for which the fundamental frequency is approximately 100 KHz.

In Fig. 3 we show a typical spectrum of the magnetic field in the plasma (a quantity proportional to $\sqrt{H_\omega^2 \Delta\omega}$ is plotted along the ordinate). The peak near 700 KHz corresponds to a resonance in the frequency characteristic of the probe. On the spectrum one sees clearly four narrow peaks at

FIG. 3. Typical spectrum of the magnetic noise in the plasma. $n_e = 10^{12}$ cm$^{-3}$, $H_0 = 1.5$ kOe, $p = 3 \times 10^{-3}$ torr. The sharp peak to the right is a frequency marker at 700 KHz.



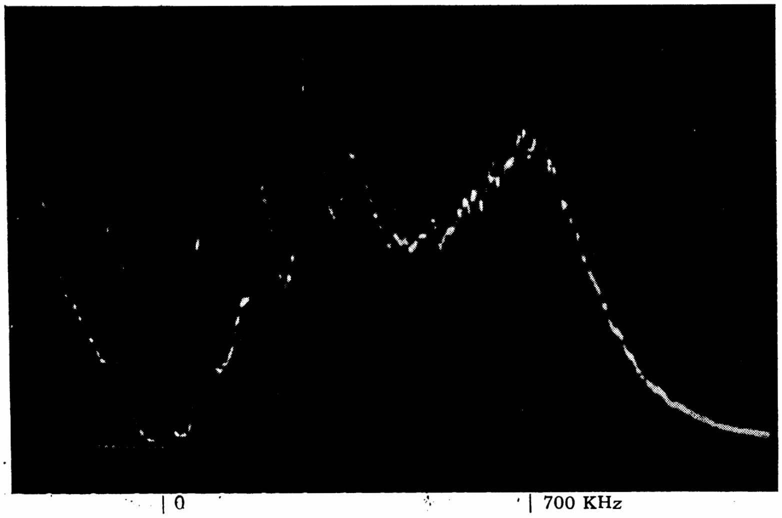


FIG. 4. Spectrum of magnetic noise for $p = 8 \times 10^{-4}$ torr, $H_0 = 1.5$ kOe, $T_e = 9$ eV and $n_e = 9 \times 10^{11}$ cm$^{-3}$.

harmonic frequencies. The position, magnitude, and number of peaks depends on the magnetic field, the plasma parameters and the pressure. The spectral measurements are carried out as functions of these parameters.

A characteristic feature of the spectrum is the excitation of harmonics; at low pressures most of the noise power appears in these harmonics. In Fig. 4 we show a spectogram taken at $p = 8 \times 10^{-4}$ torr, $H = 1500$ Oe, $T = 9$ eV, and $n_e = 9 \times 10^{11}$ cm$^{-3}$.

### A. Spatial Distribution of $H_r$, $H_\varphi$, and $H_z$

The ratio of the components $H_r$, $H_\varphi$, and $H_z$ in the fluctuating magnetic field is determined by changing the polarization of the probe. It is found that $H_\varphi$ is three or four times greater than $H_r$ while $H_z$ is at least ten times smaller than $H_r$. Thus, in these oscillations $H_z$ is negligible.

In order to examine the nature of the excitation of the low-frequency oscillations in the plasma a movable probe is used to determine the distribution of the magnetic field components $H_r$ and $H_\varphi$ over the radius of the plasma. The results are shown in Fig. 5. The distribution exhibits a peak at the edge of the plasma, that is to say, the oscillations are excited intensely in a region where the plasma density exhibits a strong gradient. The longitudinal distribution of $H_r$ and $H_\varphi$ in the uniform region of magnetic field is essentially uniform and only falls off at the metal end plates.

### B. Dependence of Frequency on Magnetic Field

In these experiments we have also investigated the dependence of the fundamental frequency on the strength of the fixed magnetic field for a fixed density. This functional relation (for pressures of $1.5 \times 10^{-3}$ and $3.5 \times 10^{-3}$ torr) is shown in Fig. 6. The frequency of the oscillations increases linearly with increasing magnetic field. It is evident from the same figure that the frequency varies inversely with the pressure.

### C. Phase Measurements

Great interest attaches to the propagation of these oscillations in space. For this purpose we have taken phase measurements. Signals from two identical magnetic probes located some distance from each other are applied to a summing

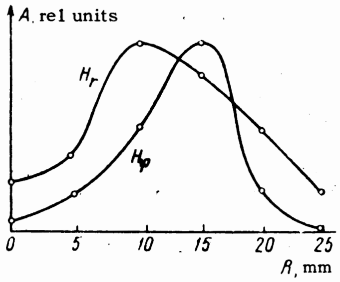


FIG. 5. Spatial distribution of the noise-field components $H_r$ and $H_\varphi$ in the plasma.

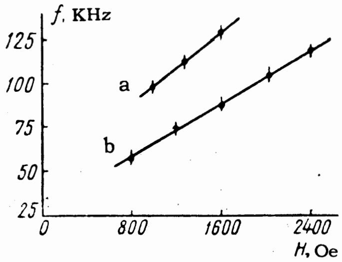


FIG. 6. Fundamental frequency as a function of static magnetic field: a) at a pressure $1.5 \times 10^{-3}$ torr. b) at a pressure $3.5 \times 10^{-3}$ torr.

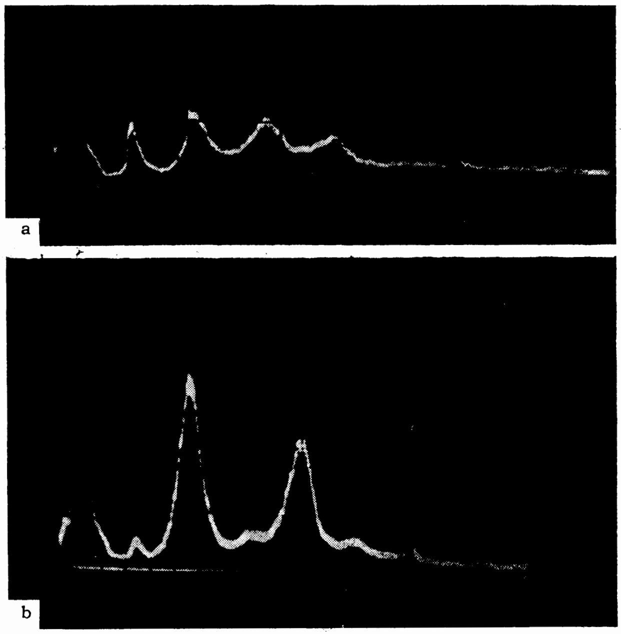


FIG. 7. Phase measurements: a) signal from one probe, b) summed signal from two probes located at opposite ends of a diameter.

circuit and then to the spectrum analyzer. Results of the measurements of the azimuthal phase velocity are shown in Fig. 7. The spectrogram marked a shows the signal from a single magnetic probe while the spectrogram marked b shows the summed signals from two magnetic probes located at opposite ends of a diameter at the surface of the tube. It is clearly evident from b that the first and third harmonics disappear (these are in antiphase) while the second and fourth harmonics add constructively. On the basis of these results we conclude that these are azimuthal travelling waves. The azimuthal phase velocity at the fundamental is estimated as follows: the wavelength (referred to the radius of the column $r = 1.5$ cm) $\lambda_\varphi = 10$ cm, the frequency $f = 100$ kHz and $v_\varphi = 10^6$ cm/sec.

The phase measurements along the magnetic field exhibit no discernible phase shifts. Thus, a standing wave is excited along the z-axis.

In addition to the low-frequency measurements we have taken a series of measurements at high frequencies. A rather broad maximum in the magnetic fluctuations is observed in the region between 3 and 5 MHz. In contrast with the low frequency oscillations the rf noise has a component $H_z$ which is large compared with $H_r$ and $H_\varphi$.

In addition to the magnetic noise there simultaneously exists intense (approximately 1 V) irrotational electric fluctuations which have been investigated in detail by the present authors in an earlier publication.[4] The characteristic frequency of these electrical oscillations is 20–30 KHz and the frequency is inversely proportional to the static magnetic field. Thus, we conclude that the plasma fluctuations investigated in the present work are not the magnetic component of the irrotational fluctuations which have been investigated earlier.

## 4. DISCUSSION

The solenoidal oscillations which have been observed are low-frequency oscillations ($f \approx 100$ kHz) which are excited in a region of high density gradient. The dependence of the frequency on $H_0$ and the transverse nature of the variable fields ($\tilde{H}_z = 0$) are reminiscent of Alfvên waves but the corresponding theoretical frequency ($n_e = 10^{12}$ cm$^{-3}$, $L_z = 200$ cm, $H_0 = 1.5$ kOe, $f = 2$ MHz) is much too large.

The low-frequency nature of the waves indicates the need for taking account of collisions between ions and neutral gas molecules. Under the present experimental conditions the collision frequency $\nu_{in} \approx (1-5) \times 10^5$ sec$^{-1}$ so that $f \lesssim \nu_{in}$. In this case the entire gas participates in the Alfvên wave motion. For neutral particle densities $n_n \gg n_i$ the Alfvên velocity is found to be $v_{An} = H_0/\sqrt{4\pi n_n M}$ that is to say, the frequency is reduced considerably.[8]

The fact that the fluctuations are excited at the boundary of the plasma indicates the need for taking gradient terms into account. If we consider a three-component inhomogeneous plasma and take account of the inertia of the neutral particles, in the semiclassical approximation the frequency of the excited waves is found to be

$$\omega = -\frac{\omega^*}{2} \pm \left(\frac{\omega^{*2}}{4} + k_z^2 v_{An}^2\right)^{1/2}, \quad \omega^* = k_y \frac{cT_e}{eH} \frac{\nabla n}{n}. \tag{1}$$

The frequency of the Alfvên waves ($H_0 = 1.5$ kOe, $n_e = 10^{12}$ cm$^{-3}$, $p = 2 \times 10^{-3}$ torr) in hydrogen $f_{An} = 260$ kHz ($\omega^* = 30$ kHz) so that (1) assumes the form

$$\omega \approx -{}^1\!/_2\omega^* \pm k_z v_{An}.$$

This formula reproduces the observed experimental dependence of frequency on magnetic field and neutral gas pressure p ($v_{An} \sim H_0/\sqrt{p}$). In general, one can write $\omega \approx k_z v_{An}$, neglecting the gradient term in the frequency expression in a first approximation. The effect of the gradient term is important in the growth rate. In a cylindrical geometry one expects excitation of the harmonic terms as well: $m\lambda = 2\pi r$, $m = 1, 2, 3, \ldots$.

An important feature is the effect of viscosity and the friction of the neutral gas with the walls of the chamber. However, under the present experimental conditions the frequency of neutral-neutral collisions is small ($\nu_{\mathrm{nn}} \approx (1-3) \times 10^3$ sec$^{-1}$) and can be neglected compared with the ion-neutral collision frequency ($\nu_{\mathrm{ni}} \approx 2 \times 10^4$ sec$^{-1}$). On the other hand the frequency of collisions between the neutrals and the walls of the discharge chamber $\nu_{\mathrm{W}} = 2 \times 10^4$ sec$^{-1}$ is many times smaller than the frequency of the oscillations observed here so that the friction of the neutral gas with the walls can also be neglected. Thus, the neutral particles are trapped by the plasma column and execute oscillations together with the ions.

Thus, it may be assumed that the low-frequency branch of the magnetic noise observed here is due to the excitation of Alfvén drift waves in the inhomogeneous plasma.

The high-frequency magnetic noise described in these experiments (3—5 MHz) is of a magnetoacoustic nature: There is a well defined $H_z$ component. In this case again we must invoke the entrainment of the neutral gas in order to obtain a reasonable theoretical value of the frequency. However the nature of the excitation of the magnetoacoustic wave is still not clear.

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