

# OBSERVATION OF ION SOUND IN A PLASMA OF TOROIDAL CONFIGURATION UNDER TURBULENT HEATING

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**Abstract**

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*PHYSICS*

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**OBSERVATION OF ION SOUND IN A PLASMA OF TOROIDAL CONFIGURATION UNDER TURBULENT HEATING**

*(Presented by Academician E. K. Zavoisky, 7 IV 1969)*

It was shown earlier <sup>(1,2)</sup> that the anomalous resistance of a plasma in experiments on turbulent heating in closed systems is due to collective interactions of current-carrying electrons. Superthermal plasma oscillations were observed in the region of the electron plasma frequency  $\omega_{pe}$ , and indications were obtained of the development of intense oscillations in the region of the ion plasma frequency  $\omega_{pi}$  <sup>(3)</sup>. The purpose of the present work is the direct observation of plasma noise in the range  $\omega \leq \omega_{pi}$ .

**1. Measurement arrangement.** The experiments were carried out on the toroidal device "Vikhr-2," described in <sup>(2,4)</sup>. A vortex electric field  $E_\theta$ , much exceeding the critical Dreicer field, was produced along the circumference of the annular plasma cord. The observed plasma resistance was anomalously large. The field  $E_\theta$  excited a current flowing along the magnetic field and heated the plasma to  $nT \sim 10^{15}$  eV/cm<sup>3</sup>. Observation of noise in the range  $\omega_{pi} \geq \omega \simeq 50 \div 10^3$  MHz was carried out at densities

**Table 1**

**Methods for observing the spectrum of plasma oscillations**

No.	Signal sensor	Receiver	Method of registration	Ratio signal/noise
1	Single-turn magnetic probe, $d = 5$ mm	Video amplifier, sensitivity $30 \mu V$ , band 0.8-100 MHz	Multichannel spectrum analyzer with frequency range 250- $10^3$ MHz	50

No.	Signal sensor	Receiver	Method of registration	Ratio signal/noise
2	Double electric probe, pin length 4 mm, distance between them 2 mm, $d = 0.2$ mm	Same video amplifier as in No. 1; oscilloscope amplifier, sensitivity 10 mV, band 40-220 MHz	Same analyzer as in No. 1. Direct oscillography	50
3	Combined scattering of a wave $\lambda_0 = 8.15$ mm from an external source through an angle $\pm 15^\circ$	Direct-amplification receiver with homodyne frequency conversion in the 8-mm wave range, sensitivity $\sim 3 \times 10^{-6}$ W, band 30-150 MHz	Selection of the difference frequency of the scattering by a band-pass filter	10
4	Plasma radiation in the range $\lambda = 8$ mm, 19 mm	Same as in No. 3. Traveling-wave-tube amplifier	Same as in No. 3; spectrum analyzer same as in No. 1	5; 50

No.	Signal sensor	Receiver	Method of registration	Ratio signal/noise
5	Same as in No. 3, for $\lambda_0 = 2.3$ mm	Superheterodyne receiver of the 2-mm range with double frequency conversion, sensitivity $\sim 10^{-7}$ W	Homodyne conversion in the 2-mm range, second heterodyning in the frequency interval $f_{\text{het}} = 200 \div 800$ MHz, IF band 60 MHz	5

$(2 \div 7) \cdot 10^{12} \text{ cm}^{-3}$ . The measurements were carried out with electric and magnetic probes, by the method of combination scattering of millimeter-range waves, and also by analyzing the modulation by “low-frequency” oscillations of the plasma’s own radiation in the region of  $\omega_{pe}$  (5). Data on the measurement technique are given in Table 1. Without going into detail, we note that analysis of the oscillation spectrum in the range  $250 \div 10^3$  MHz was performed with an analyzer based on band-pass filters, with simultaneous recording of the signals in three channels.

**2. Experimental results.** Figure 1 presents a selection of typical oscillograms of the readings of the four diagnostic methods listed above, on a common time scale.\* Oscillograms 5  $\div$  7 directly show oscillations in the plasma in the frequency range 50  $\div$  200 MHz. Oscillograms 2  $\div$  4 show the time variation of the amplitude of plasma oscillations in the frequency range 250  $\div$  800 MHz. All observation methods register a broad spectrum of oscillations. These oscillations (at the sensitivity of the receivers used) were observed only while current was flowing in the plasma in the anomalous-resistance regime.

Study of the entire complex of measurement results made it possible to reveal a general regularity, which is also clearly visible in Fig. 1. It turned out that all experimental values of  $\tau_{\text{delay}}$  (the moment at which an oscillation of one frequency  $f$  or another appears in the spectrum) lie on a single curve, independently of the method used to observe the oscillations (see Fig. 2). Such agreement of the readings of the four methods of investigation (two of them contact methods, the other two non-contact methods) indicates: 1) the signals observed by the different methods are indeed plasma oscillations; 2) the spectrum of low-frequency plasma oscillations is at first rather narrow, and then gradually broadens. The

Fig. 1

Figure 1: Fig. 1

Figure 2

Figure 2: Figure 2

data in Fig. 2 refer to experimental conditions in which the plasma density at the observation point\*\* corresponded to  $\omega_{pi} \simeq 700$  MHz. The oscillations  $\omega_{pi}$  arose with the minimum measurable delay.

**Fig. 1.** Oscillations of plasma with density  $\sim 6 \cdot 10^{12} \text{ cm}^{-3}$  in the “Vikhr-2” device in the regime of turbulent heating of the plasma by current. 1—external electric field  $E_0$ ; 2 and 4—envelope of oscillations in the frequency range  $760 \pm 15$  MHz (2) and  $250 \pm 15$  MHz (4), recorded by a magnetic probe; 3—envelope of oscillations in the frequency range  $290 \pm 30$  MHz, recorded during combination scattering of a wave  $\lambda_0 = 2.3$  mm (effective scattering angle  $\sim 5 \cdot 10^{-4}$ ); 5—signal of a double electric probe located at floating potential; 6—difference-frequency signal during combination scattering of a wave  $\lambda_0 = 8.15$  mm (effective scattering angle  $\sim 10^{-2}$ ); 7—signal of modulation of the plasma’s own 8-millimeter radiation. Oscillograms 5 ÷ 7 were obtained with a passband of the channel  $30 \div 150$  MHz.

0.35  $\mu\text{s}$

\* The impedance of the plasma cord is purely active, and the shape of the current repeats the shape of the electric field  $E_0$ .

\*\* In the region of probe 8 in Fig. 1 of work (4).

The probes were used to record “instantaneous” spectra of oscillations for different instants of time and different initial densities. The histograms in Fig. 3 were constructed from the readings of a broadband magnetic probe (with an upper frequency limit of  $2 \cdot 10^9$  Hz). The maximum power  $P_{\text{magn}}$  of the signal recorded by the magnetic probe was 10 mW. On the histograms, circles indicate experimental points obtained under the same conditions with an electric probe. They are in good agreement with the magnetic-measurement data.

**Fig. 2.** Delay in the moment of appearance in the spectrum of plasma oscillations at frequency  $f$ .  $a$ —magnetic probe,  $b$ —electric probe,  $c$ —microwave measurements

Comparison of histograms 1 and 2 shows that, when the plasma density changes, the oscillation spectrum shifts in accordance with the change in  $\omega_{pi} \sim \sqrt{n}$ . The frequency corresponding to the maximum of the spectrum is in satisfactory agreement with the calculated value  $\omega_{pi}^*$  and does not depend on the magnitude of the constant magnetic field. Consequently, the maximum of the

plasma-oscillation spectrum under conditions of turbulent current heating may be identified with the ion plasma frequency.

Comparison of spectra 1 and 3, plotted on the same scale, clearly illustrates the broadening of the spectrum in time (see also Fig. 2). It is seen that the growth of the low-frequency “tail” is accompanied by a decrease in the maximum of the spectrum.\*\* The change of the spectrum in time is clearly manifested in the different behavior of the signals at frequencies 760 and 250 MHz (Figs. 1, 2, 4).

We now turn to the experimental data on the lowest-frequency part of the oscillation spectrum (50–250 MHz). From consideration of oscillograms 6, 7 in Fig. 1, obtained by contactless microwave methods, it is seen that the spectrum of the observed signal is considerably narrower than the receiver passband. At first sight, the discreteness of the combination-scattering spectrum contradicts the readings of the electric probe (oscillogram 5 in Fig. 1) and the continuity of the spectrum in the high-frequency region. However, the delay in the moment of appearance of the discrete frequencies agrees well with the value  $\tau_{\text{del}}$  for the same frequencies observed by the probes. It may therefore be supposed that oscillations of the same nature are observed by the contactless and probe methods. To check whether the observed oscillations are connected with displacement of the boundary of the plasma column, the reflection from the plasma of a wave  $\lambda_0 = 3$  cm was investigated. Analysis of the spectrum of the reflected signal showed that, in the frequency range of interest to us, 50–250 MHz, boundary oscillations are absent.

In experiments on combination scattering of millimeter waves by plasma oscillations it was established: 1) the frequency shift  $\Delta f$  upon scattering does not depend on the direction of scattering; 2) upon scattering of waves with  $\lambda_0 = 8.15$  mm under the specified experimental conditions, the frequency shift  $\Delta f$  has a quite definite value; 3) the frequency shift  $\Delta f$  increases with an increase in the electric field  $E_\theta$  producing the heating (Fig. 4).

The data from analysis of the low-frequency modulation of the plasma’s own emission correspond qualitatively to the results of experiments on combination scattering in plasma of electromagnetic waves from an external source, with the only difference that the depth of modulation of the ultrahigh-frequency signal by the low-frequency one in the first case is almost an order of magnitude greater than in the second.

\* In calculating  $\omega_{pi}$ , it should be taken into account that the plasma density in the “Vikhr-2” device is strongly nonuniform both in radius and along the length of the plasma column.

\*\* According to radiointerferometer readings at wavelengths of 2, 4, and 8 mm, the plasma density remains constant to within 10%.

### 3. Discussion of Results

**A.** The most significant experimental result should be considered the direct observation of plasma oscillations near the ion plasma frequency, clearly correlated with the manifestation of the effect of anomalous plasma resistance.

From the agreement of the results obtained it follows that not only the electrostatic probe, but also the magnetic probe in some way registered ion-acoustic oscillations. A possible mechanism for the appearance of magnetic signals at ion-sound frequencies reduces to a nonlinear transformation of ion-acoustic oscillations into waves of the “whistler” type. Processing the data of Fig. 3 by the theoretical formulas of work <sup>(6)</sup> makes it possible to estimate the relative energy of the ion-acoustic oscillations as

$$W_i/nT \sim 10^{-2}.$$

**Fig. 3.** Spectrum of oscillations recorded in the plasma by various methods, *a*—initial spectrum,  $\tau_{\text{del}} = 0.02 \mu\text{sec}$ : 1—magnetic-measurement data at  $n \simeq 6 \cdot 10^{12} \text{ cm}^{-3}$ ; 2—the same at  $n \simeq 2 \cdot 10^{12} \text{ cm}^{-3}$ ; 4—spectrum of modulation of the plasma’s own emission with  $\lambda \simeq 1.9 \text{ cm}$ ,  $n \simeq 6 \cdot 10^{12} \text{ cm}^{-3}$ . *b*—spectrum at the time  $\tau_{\text{del}} = 0.08 \mu\text{sec}$ : 3—magnetic and 5—microwave measurements at  $n \simeq 6 \cdot 10^{12} \text{ cm}^{-3}$ .

**Fig. 4.** Frequency shift  $\Delta f$  under combination scattering in the plasma of a wave with  $\lambda = 8.15 \text{ mm}$  as a function of the field  $E_0$ .

**B.** In the low-frequency region of the spectrum, the results on scattering of electromagnetic waves are in qualitative agreement with the conclusions of the theory of combination scattering by ion-acoustic oscillations of a bounded plasma. In this case, according to (7), the frequency shift does not depend on the scattering direction and corresponds to the frequencies of ion-acoustic oscillations whose wavelengths are multiples of the transverse size of the system  $d_0$ . For a given  $d_0$ , the resonant wavelength of ion sound must be constant, while the frequency must vary directly proportionally to  $c_s \sim \sqrt{T_e}$ . This could explain the experimental dependence  $\Delta f(E_\theta)$ , since it is known <sup>(5)</sup> that with increasing  $E_\theta$ ,  $T_e$  also increases. However, there is a certain quantitative discrepancy between the experimental value  $\Delta f \simeq 60 \div 80 \text{ MHz}$  and estimates of the discrete frequency shift according to the theory.

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