EXPERIMENTAL STUDY OF THE COLLECTIVE PROCESSES AND TURBULENT HEATINGS OF A PLASMA IN ANNIHILATION OF OPPOSING MAGNETIC FIELDS

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Submitted May 12, 1970

Zh. Eksp. Teor. Fiz. 60, 345–355 (January, 1971)

The turbulent state of a plasma and the possibility of turbulent heating by energy dissipation of opposing magnetic fields was investigated in a geometry analogous to that of a θ pinch. The experiments revealed a threshold value of the plasma density, which depends on the alternating magnetic field intensity, below which instabilities develop effectively. The measured spectrum of the plasma oscillations points to the occurrence of both perturbations of the magnetic field relative to large-scale instabilities of the "whistler" type, and of high-frequency small-scale fluctuations, with frequencies in the region ω_{pi} and $2\omega_{pi}$, resulting from nonlinear transformation of the ion-acoustic waves into "whistlers." As a result of the development of the instability, the lifetime of the captured magnetic field in the plasma is greatly reduced. Radiation of electromagnetic waves from the plasma, in the microwave bands 3.2 and 1.6 cm, is observed together with the appearance of fast electrons, thus indicating that the plasma becomes heated.

In order for a turbulent state to arise in a current layer separating opposing magnetic fields of given magnitude, the number of particles in this layer should be smaller than a certain critical value, so that the current velocity of the electrons exceeds the threshold for the occurrence of the instability[1]. Under conditions when the current flows across the magnetic field, the small-scale instability connected with the flow of the current can develop even in an isothermal plasma, if the current velocity of the electrons u_j exceeds by 1.5–2 times the quantity $[(T_e + T_i)/M]^{1/2}$ [2]. When the current velocity increases above this threshold, the increment increases rapidly and at a velocity exceeding the thermal velocity of the electrons, $u_j > (2T_e/m)^{1/2}$ (the Budker-Buneman instability), the increment reaches a value

$$\gamma_{max} \approx 0.69 (m/M)^{1/3} \omega_{pe}.$$

The instability produces in the current layer an anomalous resistance, which increases together with the energy density of the ion-acoustic noise until the friction force of the electrons balances the action of the electric field. This occurs when the noise energy density satisfies the relation[2]

$$W \geqslant nT_e \left(\frac{F^2}{8\pi n T_e}\frac{M}{m}\right)^{1/2} \frac{c_s}{u_j}$$

(c_s is the velocity of the ion sound). As a result of the occurrence of anomalous resistance, the magnetic field captured in the plasma dissipates its energy into heat.

Besides the indicated instabilities, in the presence of a magnetic-field gradient in a magnetized plasma there can build up large-scale oscillations of the "whistler" type with frequency $\Omega = k^2c^2\omega_{He}/\omega_{pe}^2$ [4] lying in the frequency interval $\omega_{Hi} \ll \omega \ll \omega_{He}$. The increment of this instability is

$$\gamma \sim \omega_{He}\frac{c^2}{\delta^2\omega_{pe}}\left(\frac{\nu}{\omega_{He}}\right)^{1/2}(k_z\delta)^{1/2}.$$

Here ν is the collision frequency, and δ the width of the transition layer where there is a gradient of the magnetic field. This instability is a continuation of the "tearing mode" instability into the region of higher frequencies.

EXPERIMENTAL SETUP AND MEASUREMENT METHODS

The experiments were performed with a setup constituting an open magnetic trap with a mirror ratio 2[5]. A constant magnetic field up to 3 kOe was produced by two coils mounted at a distance 1.2 m from each other (Fig. 1).

The pre-ionized plasma had the geometry of a hollow cylinder with outside diameter 14 cm and layer thickness 0.5–1 cm. The source of the pre-ionized plasma was a Penning discharge with hot electrodes in the form of rings. The discharge was ignited in the continuously flowing neutral gas. The alternating magnetic field with amplitude up to 4 kOe was produced by a high-frequency discharge circuit with frequency 0.84 MHz.

To investigate the collective processes and the turbulent heating of the plasma in annihilation of opposing magnetic fields, we used different diagnostic methods.

1. The behavior of the alternating magnetic field

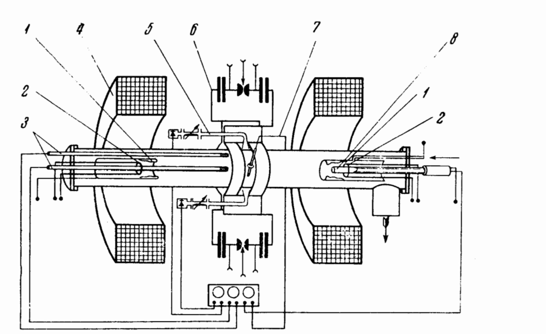

FIG. 1. Diagram of the "Dimpol" setup: 1–anode of Penning discharge, 2–cathodes, 3–magnetic probes, 4–coils of constant magnetic field, 5–microwave-noise pickups, 6–high-frequency circuit, 7–radial magnetic probe, 8–pickup for bremsstrahlung x-radiation from the target.

penetrating into the plasma was investigated with the aid of a magnetic probe screened against electrostatic fields, with L/R integration ($L/R > \tau$, $\tau = 1.2 \times 10^{-6}$ sec, where τ is the period of the oscillations of the high-frequency circuit). The probe consisted of 140 turns of wire of 0.2 mm diameter, had a cross section area 0.3 cm^2, an inductance $L = 8 \times 10^{-6}$ H, and was shunted by resistors of $R = 2$ Ohms. The probe was located along the axis of the vacuum chamber and measured the H_z component of the magnetic field.

Oscillation in the frequency range 10—400 MHz were registered with a screened magnetic probe that measured the derivative dH_z/dt. It consisted of five turns of wire 0.2 mm in diameter, had an inductance 5×10^{-8} H, and a time constant $\tau = 6 \times 10^{-10}$ sec. By moving the probe along the radius of the chamber it was possible to measure dH_r/dt.

2. The radiation of the high-frequency oscillations in the frequency ranges ω_{pi} and $2\omega_{pi}$ was investigated with a single-term magnetic probe with inductance $L = 9 \times 10^{-9}$ H, which measured the rate of change of the H_φ components of the high-frequency magnetic field.

3. To obtain the spectrum of the oscillations registered by the oscilloscope, we used the method of converting the signal recorded on the oscilloscope into a low-frequency signal[6] with subsequent analysis of this signal with a low-frequency spectrum analyzer ASChKh-1 (Fig. 2). The frequency range and the sensitivity of the system were calibrated by recording the spectrum of a standard calibration signal constituting a sinusoid or a signal with a known spectrum, for example a sawtooth curve.

4. The concentration of the preliminary plasma was measured with a microwave interferometer at a wavelength 8 mm. The concentration of the plasma after the operation of the discharge circuit was estimated from the blocking of the microwave signal at the wavelengths 16, 8, and 4 mm. The noise radiation from the plasma in the microwave band at the wavelengths 32, 16, and 8 mm was investigated with the aid of horn antennas.

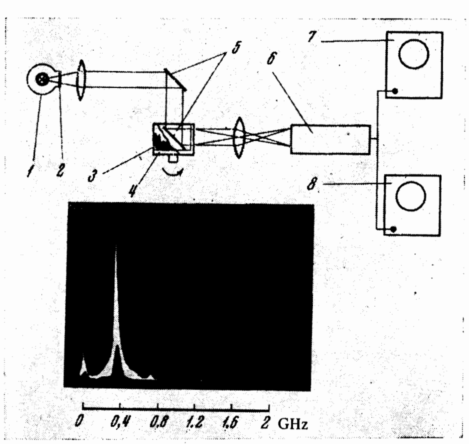

FIG. 2. Diagram of the setup for the analysis of oscillations recorded on the oscilloscopes: 1—light source, 2—ground glass, 3—oscillogram pattern, 4—cylinder of organic glass, 5—mirror, 6—photomultiplier, 7—oscilloscope for controlling the form of the oscillations, 8—spectrum analyzer ASChKh-1.

5. The appearance of fast electrons emerging from the magnetic mirrors was observed by means of a scintillation pickup that registered the bremsstrahlung x-radiation from an electron-bombarded target. The scintillation pickup consisted of a receiving target foil, absorbers serving to estimate the temperature of the electrons by means of the absorption, a CsI(Tl) crystal or polystyrene, a lightpipe, and a photomultiplier (Fig. 3). The scintillation pickup was placed in a screen cooled with water, since the pickup passed through the annular incandescent cathode of the Penning discharge.

RESULTS OF EXPERIMENT

As shown in[5], there exists a critical concentration that separates two principally different operating regimes with different behaviors of the magnetic field inside the plasma (Fig. 4). For a neutral-hydrogen density 4×10^{13} cm^{-3}, the axial magnetic field registers the capture of the magnetic field of the first half-period, which is retained in the plasma for 2—3 μsec. When the density drops below critical, the alternating magnetic field is also captured but is rapidly dissipated (within 50—100 nsec).

During the dissipation time there are observed in the plasma high-frequency oscillations in the range from 10 to 1500 MHz, indicating the onset of an instability accompanying the fast dissipation of the magnetic field. This dissipation causes the plasma to become heated. Measurements of the electron temperature, determined from absorption of the bremsstrahlung x-rays from the target by beryllium foils 0.1—0.5 mm thick, shows that at a neutral-gas density 10^{13} cm^{-3} and an alternating-magnetic-field intensity 3 kOe, the electron temperature as a result of the dissipation of the

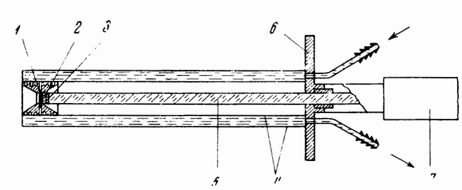

FIG. 3. Scintillation pickup for bremsstrahlung x rays from the target: 1—target, 2—absorber-filter, 3—scintillator CsI(T1), 4—cooled screen, 5—lightpipe, 6—flange, 7—FEU-13 photomultiplier.

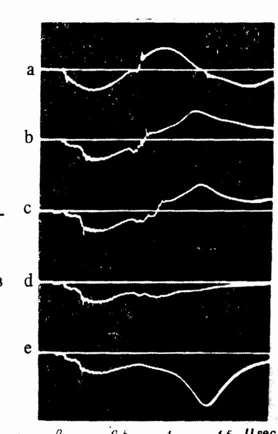

FIG. 4. Oscillograms of the readings of the microwave field, illustrating the dependence of the lifetime of the frozen-in magnetic field during the second half-cycle on the concentration of the neutral gas. Penning-discharge current 34 A, alternating magnetic-field amplitude H = 3.5 kOe, probe with L/R integration. a—$n_0 = 10^{13}$ cm^{-3}, H_0 = 175 Oe; b—$n_0 = 4 \times 10^{13}$ cm^{-3}, H_0 = 1400 Oe; c—$n_0 = 4 \times 10^{13}$ cm^{-3}, H_0 = 1225 Oe; d—$n_0 = 5 \times 10^{13}$ cm^{-3}, H_0 = 1400 Oe; e—n_0 7.5×10^{13} cm^{-3}, H_0 = 1400 Oe.

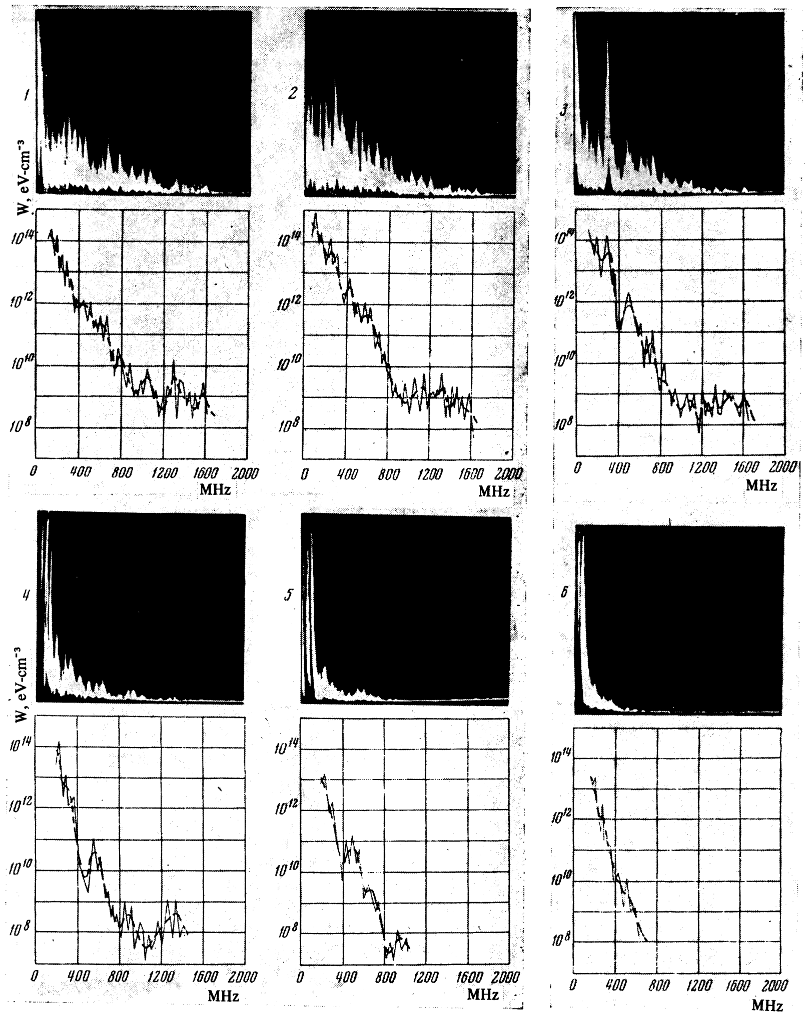

FIG. 5. Evolution of oscillations of turbulent plasma. Intensity of constant magnetic field H_0 = 700 Oe, intensity of magnetic field of high-frequency circuit H = 3 kOe. The ordinates represent the energy density of the "whistler" oscillations. 1–n_0 = 4.2 X 10^{12} cm^{-3}, 2–4.7 X 10^{12} cm^{-3}, 3–1.4 X 10^{13} cm^{-3}, 4–2.3 X 10^{13} cm^{-3}, 5–3.3 X 10^{13} cm^{-3}, 6–3.6 X 10^{13} cm^{-3}.

energy of the magnetic field is $T_e \sim 1-2$ keV during the first half-cycle and $T_e \sim 5-7$ keV in the second half-cycle.

We investigated also the spectrum of the plasma oscillations in the region of ion plasma frequencies, by a method similar to that employed in[6,7]. Figure 5 shows the evolution of the spectrum of oscillations of the turbulent plasma with increasing concentration of neutral hydrogen. It follows from the figure that a wide spectrum of oscillations builds up both in the interval of relatively narrow frequencies from 10 to 400 MHz, and in the region of ion plasma frequency ω_{pi} and double the ion plasma frequency $2\omega_{pi}$. At a neutral hydrogen concentration exceeding 4×10^{13} cm^{-3}, there are no oscillations.

Figure 6 shows the typical oscillogram of the oscillations, and Fig. 7 the frequency characteristic of the measuring circuit.

We investigated also radiation at microwave wavelengths from the plasma. We observed radiation at the wavelengths 32 and 16 mm. No radiation was observed in the 8 mm band. It should be noted that the microwave noise is delayed by several dozen nanoseconds relative to the fast electrons, which appear simultaneously with the development of the high-frequency oscillations.

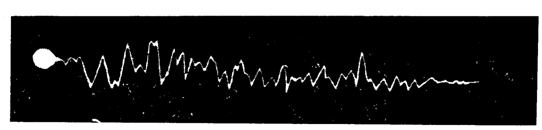

FIG. 6. Characteristic oscillogram of high-frequency oscillations.

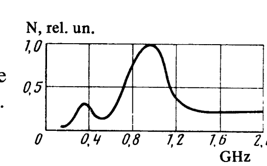

FIG. 7. Frequency characteristic of the probe-plus-oscilloscope measuring channel.

DISCUSSION OF RESULTS

1. The experimental data indicate that when the plasma density decreases below a definite limit, the lifetime of the captured magnetic field decreases sharply. This phenomenon can be attributed to the development in the current layer of small-scale instability when the current velocity becomes larger than a certain critical value $u_j = j/ne > u_{cr}$. It was investigated in detail in experiments with collisionless shock waves and on turbulent heating of plasma by direct current[8,9]. The proof of this explanation in our case may be the estimated current velocity, listed in the

table[1], and measurements of the plasma noise spectrum.

The thickness of the current layer was not monitored in the experiments, so that the estimate of the current velocity was made for two layer thicknesses: $\delta \sim 1$ cm, which is close to the thickness of the layer of the preliminary plasma, and $\delta \sim 7$ cm, which is close to the radius of the chamber and consequently is the upper limit of the layer thickness. It can be seen from the table that for a plasma density $n_0 = 4.7 \times 10^{13}$ cm^{-3} the current velocities turn out to be very low even for a layer thickness on the order of 1 cm. This indicates that the critical velocity at which the instability develops is closest to the velocity of the ion sound as calculated for a temperature on the order of 1 keV. The current velocities obtained in accordance with these estimates can be larger than the thermal velocity of the electrons only at a very low plasma temperature, on the order of 5–10 eV. This makes it possible to conclude that the main phenomena observed in the experiment can be attributed to the development of oscillations of the ion-sound type.

n_0, cm^{-3}	n_e, cm^{-3}	δ, cm	j, A-cm^{-2}	u_j, cm-sec^{-1}	T_e, eV	
					$u_j = v_{Te}$	$u_j = 2c_s$
$9 \cdot 10^{12}$	10^{13}	1	10^3	$6 \cdot 10^8$	10^2	10^5
		7	130	$8.4 \cdot 10^7$	2	$1.8 \cdot 10^3$
$2 \cdot 10^{13}$	10^{13}	1	$1.2 \cdot 10^3$	$7.2 \cdot 10^8$	$1.5 \cdot 10^2$	$1.3 \cdot 10^5$
		7	170	10^8	3	$2.5 \cdot 10^3$
$4.7 \cdot 10^{13}$	$5 \cdot 10^{13}$	1	700	$8.4 \cdot 10^7$	2	$1.8 \cdot 10^3$
		7	100	$1.2 \cdot 10^7$	$4 \cdot 10^{-2}$	36

Figure 8 shows the readings of the magnetic probe oriented along the chamber, and oscillograms of the cutoff of the sounding microwave signal at wavelengths 8 and 4 mm, which make it possible to estimate the plasma density. It follows from the oscillograms that at a neutral-hydrogen density 9×10^{12} cm^{-3} the alternating magnetic field penetrates freely into the plasma during all halfcycles (Fig. 8, Ia), and when the gas density is increased to 2×10^{13} cm^{-3}, after the second half-cycle there is observed a prolonged capture of the alternating magnetic field (Fig. 8, IIa). The plasma density during the second half-cycle, estimated from the cutoff of the microwave signal of 4-mm wavelength reaches 7×10^{13} cm^{-3} (Fig. 8, IIc). At a hydrogen density 4.7×10^{13} cm^{-3}, the magnetic field is trapped and contained for a long time already after the first half-cycle. The critical plasma density, above which no instability arises and the trapped magnetic field has a long lifetime, is $n_{cr} = 5 \times 10^{13}$ cm^{-3} (the 8-mm signal is blocked, and the 4-mm signal cuts off shortly after the passage of the external magnetic field through zero; Fig. III). With increasing circuit voltage (120 kV), the value of n_{cr} shifts towards larger concentrations.

The main experimental data pertain to the instant of passage through zero between the first and second half-cycles of the current. This is connected with the fact that the Penning discharge does not permit the plasma concentration to be varied in a wide range and makes it impossible to carry out a detailed investigation during the first half-cycle. In the second half-cycle, as a result of ionization of the neutral gas during the first half-cycle, the concentration of the plasma can increase appreciably and reach the concentration of the initial neutral gas. Therefore the plasma density at the start of the second half-cycle is easier to vary, but it is

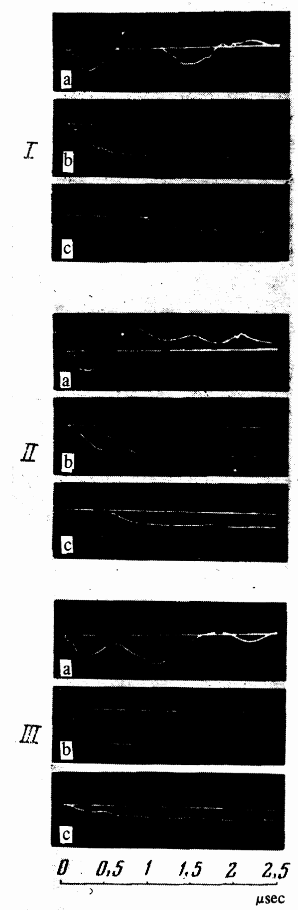

FIG. 8. Oscillograms of signals of axial magnetic probe (a) and of microwave sounding radiation at wavelengths 8 mm (b) and 4 mm (c) at different plasma densities: I–$n_0 = 9 \times 10^{12}$ cm^{-3}, II–2×10^{13} cm^{-3}, III–4.7×10^{13} cm^{-3}. $H_0 = 700$ Oe, H - 3 kOe.

more difficult to monitor, and in addition we do not know the thickness of the current layer. The plasma density was estimated from the cutoff of the microwave signals at three wavelengths: 16, 8, and 4 mm.

It is known that an electromagnetic wave passing through a turbulent plasma experiences attenuation as a result of scattering by the turbulent fluctuations, and this can introduce an error in the measurement of the plasma concentration. Let us estimate the attenuation of the intensity of the sounding microwave signal in scattering by ion-acoustic fluctuations of the plasma. The power dissipated per unit volume of the plasma is

$$P_\omega \approx S_0 \frac{\omega_{pe}}{c} \left(\frac{\omega_{pe}}{kc}\right)^2 \left(\frac{\omega_{pe}}{v_{Te} k_0}\right)^2 \frac{W_i}{mnc^2},$$

where S_0 is the flux density of the incident electromagnetic radiation power, W_i is the energy density of the ion-acoustic oscillations. At $T_e \sim 1$ keV, $W_i \sim 10^{14}$ eV-cm^{-3} and $n \sim 10^{13}$ cm^{-3} the power of the sounding electromagnetic waves changes after passing through a

[1]The estimates of the current velocities given in the table pertain to a series of experiments aimed at determining the critical plasma density under the following conditions: constant magnetic field intensity $H_0 = 700$ Oe, intensity of magnetic field of the high-frequency circuit H = 3 kOe, circuit voltage V = 84 kV.

layer of turbulent plasma width ~10 cm by not more than 10^{-6} of P_0.

2. The appearance of intense oscillations (10–400 MHz) cannot be attributed to magnetosonic resonance or to excitation of natural oscillations of the plasma sheath[10,11] for the following reasons:

a) the frequency of the magnetosonic oscillations is much lower than the frequency of the observed oscillations[5],

b) the scale of the oscillations along z is much smaller than the dimensions of the microwave circuit[5],

c) the frequency of the oscillations does not depend on the ion mass (Fig. 9).

The experimental data indicate that the wave excited is not magnetosonic. One of the possible types of the oscillations that develop here are oscillations of the "whistler" type[4]. The reason for the buildup of such oscillations is the sharp gradient of the magnetic field, and the increment of the instability turns out to be large because of the increased collision frequency ν as a result of the occurrence of small-scale instabilities. This instability is a continuation of the well known "tearing mode" instability into the high-frequency region. As is well known, the current in the magnetic field tends to a force-free configuration $j \times H = 0$. In the region of the gradient of the magnetic field, such a configuration can be established only if the magnetic force lines become demagnetized, a fact ensured by a large collision frequency owing to the development of small-scale instabilities.

Investigations of the high-frequency oscillations by magnetic probes with large band widths have shown that the spectrum of the observed oscillations extends up to frequencies on the order of ω_{pi} and $2\omega_{pi}$. Although the magnetic probe is not sensitive to small-scale fluctuations of electric fields of ion-acoustic oscillations, the appearance of fluctuations of the magnetic field in the frequency band can be attributed to processes of nonlinear transformation of the ion-acoustic waves in the plasma into "whistlers," which are the natural oscillations of the plasma.

As is well known, the dispersion equations for ion-acoustic oscillations and "whistlers" are of the form

$$\omega_s = \omega_{pi}[1 + (kr_{De})^{-2}]^{-1/2}, \quad \Omega = q^2c^2\omega_{He} / \omega_{pe}, \quad \omega_{He} \gg \omega \gg \omega_{Hi}.$$

It follows therefore that when the "whistlers" and the ion sound have the same frequency, $\Omega(q) \sim \omega(k)$, the "whistlers" have longer wavelengths $q \ll k$, a fact used in the experiment to register ion-acoustic oscillations. The processes of coalescence of ion-acoustic oscillations leads to accumulation of the "whistler" energy in the frequency band $\leq 2\omega_{pi}$, in accordance with the law[6]

$$\frac{H^2}{8\pi} = \frac{W_s^2}{Mnc^2}\omega_{pi}t,$$

where W_s is the energy density of the ion-acoustic oscillations in the frequency band ω_{pi}.

Such measurements were carried out in the experiments of[6,7], where the ion plasma oscillations were registered by the appearance of electromagnetic fluctuations at the frequency $2\omega_{pi}$. A similar method of observing the turbulence by means of the radiation at the frequency $2\omega_{pe}$, produced as a result of the

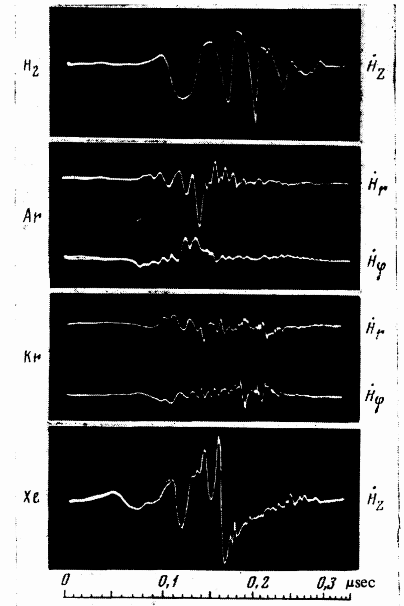

FIG. 9. Oscillograms illustrating the independence of the high-frequency oscillations of the mass. Hydrogen—$n_0 = 2 \times 10^{13}$ cm^{-3}, argon—$n_0 = 2.4 \times 10^{13}$ cm^{-3}, krypton—$n_0 = 2.7 \times 10^{13}$ cm^{-3}, xenon—$n_0 = 1.7 \times 10^{13}$ cm^{-3}.

"nonlinear coalescence" of Langmuir oscillations, was used by Demidov and Fanchenko[12]. The measured energy density of the ion-acoustic oscillations corresponding to fluctuations of the magnetic field of the "whistlers" is 10^{13}–10^{14} eV-cm^{-3}, amounting to approximately 10^{-3}, of nT_e. n

In summary, we can draw the following conclusions:

1. At a plasma density below critical, the annihilation of opposing magnetic fields occurs very rapidly and is accompanied by plasma heating. The observed heating can be explained as being due to the development of intense turbulence as a result of the occurrence of ion-acoustic instability, since the current velocity of the electrons in the plasma layer separating the opposing magnetic fields is larger than the velocity of the ion sound but is smaller than the thermal velocity of the electrons.

2. When opposing magnetic fields are annihilated, intense oscillations develop in the plasma in a wide frequency range. Observation of fluctuations of the magnetic field with frequency $2\omega_{pi}$, resulting from the nonlinear coalescence of ion-acoustic plasmons with frequencies close to ω_{pi}, proves the existence of ion-acoustic instability.

3. The experimentally observed relatively low-frequency oscillations of the magnetic field (10–400 MHz) can be identified with the instability considered theoretically by Aref'ev, Gordeev, and Rudakov[4].

The authors consider it their pleasant duty to thank E. K. Zavoĭskiĭ, L. I. Rudakov, A. V. Gordeev, and V. A. Aref'ev for interest in the work and for useful remarks, and also Yu. G. Kalinin, D. M. Lin, and V. D. Ryutov for numerous discussions.

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Translated by J. G. Adashko
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