dimensional and two-dimensional vortices. A connection exists between their amplitude and the characteristic dimensions. It turns out that magnetosonic vortices are three-dimensional, and in an unstable medium they expand until their Fourier spectrum goes out of the instability region in the wave-number space. Alfven vortices are two-dimensional, and in a homogenous unstable plasma their amplitude increases and the dimensions decrease.

In a recent paper, Hasegawa and Mima[15] also investigated one-dimensional Alfven solitons. The nonlinearity obtained by them is proportional to the longitudinal electric field. It has been shown by others,[16,17] however, that the longitudinal electric field in Alfven waves is $\sim k_\perp^2 \rho_s^2$ ($\rho_s = c_s/\Omega$, where c_s is the speed of the ion sound), a quantity regarded in[15] as the small expansion parameter. Consequently, the equilibrium between the dispersion and nonlinearity, which must take place in the soliton, is reached at $k_\perp^2 \rho_s^2 \approx 1$, in contradiction to the initial assumptions of Hasegawa and Mima.[15]

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Experimental investigation of the mechanism of turbulent heating of a plasma carrying a transverse current

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A stationary model of a plasma with a transverse current was realized in a system consisting of an electron-ionized ion beam moving perpendicular to a magnetic field. It is established that the produced turbulence is due to excitation of ion-sound oscillations that propagate across the magnetic field. The oscillations are unstable in a wide wavelength range bounded from below by the average Larmor radius of the electrons. The characteristics of the instability are investigated in the saturation regime. It is established that effective linear transformation of the noise spectrum takes place in the direction towards decreasing frequencies (wave numbers). The structure of the wave process in k-space is experimentally investigated, and it is established that the excited oscillations are three dimensional and that their phase correlation is disturbed. At large wave numbers, the steady-state nonlinear spectrum is characterized by an exponential decrease of the noise amplitude with increasing k. In the case of advanced instability, the ions and electrons are found to be heated. The final state of the plasma is characterized by a relation $T_i \lesssim T_e$ between the ion and electron thermal energies, owing to the rapid heating of the ions as a result of capture by the ion-sound waves.

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The turbulence produced by development of instability in a current-carrying plasma (anomalous resistance) can lead to heating of the electrons and ions. In systems in which the current flows across the magnetic field, these effects are attributed to excitation of low-frequency oscillations.[1–10] Plasma heating by a transverse current was observed in experiments with shock, magnetosonic, and ion-cyclotron waves of large am-

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plitude, in induction pinches, and in plasma accelerators. Under conditions of fast nonstationary processes, investigations of small-scale turbulence are difficult. At the same time, they are of great interest, since no rigorous nonlinear description of the anomalous resistance to transverse current in a plasma has been found to this day.[7–9] A stationary experimental model of a plasma with current, i.e., with relative motion of the charged components, can be taken to be an ion beam whose volume charge is neutralized by electrons. The first results of an investigation of low-frequency instability in such a system are given in[11, 12]. Spatial growth of the oscillation amplitude was observed under conditions of initial modulation of the ion beam in the region of ion-sound frequencies, at a rate that agreed with the linear theory.[5] In the present paper we investigate, under conditions of an electron-neutralized ion beam moving across a magnetic field, the nature and structure of the excited low-frequency waves, the dynamics of establishment of the nonlinear spectrum, the correlation characteristics of the oscillations, and the heating of the ions and electrons under conditions of instability saturation.

The theory of potential oscillations in a low-pressure plasma with a transverse current indicates that at a sufficiently high particle density ($\omega_{pi} \gg \omega_{Hi}$; ω_{pi} and ω_{Hi} are the plasma and cyclotron ion frequencies) and at a translational velocity V of the ions relative to the electrons in the interval v_{Ti}, $v_s \ll V \ll v_{te}$ ($v_{Ti,e}$ are the thermal velocities of the ions and electrons, and v_s is the velocity of the ion sound), oscillations are excited and propagate almost perpendicular to the magnetic field. In the low-frequency region ($\omega_{Hi} \ll \omega \ll \omega_{He}$) and at angles $\cos\theta \sim (m/M)^{1/2}$ they correspond to the lower hybrid branch of the plasma oscillations, with frequencies

$$\omega \approx \omega_{pi}\left(1+\frac{\omega_{pe}^2}{\omega_{He}^2}\right)^{-1/2} = \omega_{LH},$$

growth rates $\gamma \sim \omega_{LH}$, and wave numbers $k \sim \omega_{LH}/V$ (ω_{pe} and ω_{He} are the electron plasma and cyclotron frequencies, θ is the angle between the direction of the wave vector **k** and the magnetic field **H**; m and M are the masses of the electron and the ion). In the case $\cos\theta \sim V/v_{Te}$, the theory predicts excitation of magnetized ion-sound oscillations $\omega \approx k(V - v_s)$ with maximum growth rates $\gamma \sim \omega_{LH}$ of perturbations with $k\rho_e \sim 1$ ($kd_e < 1$); here ρ_e and d_e are the Larmor and Debye radii of the electrons.

Nonlinear estimates of the energy density of the noise in the saturation regime were obtained for the indicated types of waves in a number of papers.[7–9] Under the conditions $k\rho_e \gg 1$, the magnetic field in the low-frequency region is immaterial and the kinetic instability of the "oblique" ion-sound waves propagating at large angles to the direction of the transverse current has much smaller growth rates $\gamma \sim \omega_{pi} V/v_{Te}$ ($\omega_{pe} > \omega_{He}$). A quasilinear theory of the anomalous resistance was developed for this case in[13, 14].

In the experiments described below, with a neutralized ion beam, there is no translational motion of the

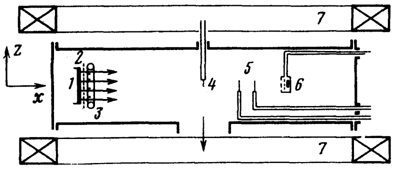

FIG. 1. Diagram of experimental setup.

electrons across the magnetic field (in the laboratory coordinate frame), and the transverse current is due to the flow of ions. A magnetic field hardly alters the trajectories of the motion in this case.

EXPERIMENTAL SETUP

The experimental setup (Fig. 1) comprised a cylindrical copper chamber with a surface-ionization potassium ion source on its end face. The source consisted of an incandescent flat tungsten disk (emitter) 1, a unit 3 that bombarded the emitter surface with potassium atoms, and a grid 2 to accelerate the ions. The grid was electrically connected to the chamber, and the accelerating voltage was applied to the emitter. The chamber was 36 cm long and 10 cm in diameter. The tungsten disk diameter was 4 cm, the potassium ion energy in the beam was 50–200 eV, and the beam current reached 3 mA (ion density $n \sim 4\times10^8$ cm^{-3}), and the gas pressure in the chamber under operating conditions was $\sim 10^{-5}$ mm Hg. The diagnostic devices were movable electrostatic probes 4 and 5, and emission probe to measure the potentials in the plasma, and a movable miniature electrostatic ion-beam energy analyzer 6 with a retarding field. Rectangular coils 7 produced in the volume a uniform magnetic field ($H = 0$ to 100 Oe) perpendicular to the system axis. The probe measurements have shown that a quasineutral state with an electron temperature $T_e \sim 1.5$ eV is realized in the space where the ion beam moves. The electrons produced by ionization of the residual gas and by secondary emission from the grid accumulate in the potential well of the positive space charge of the ion beam; the potential in the volume is +10–30 V relative to the potential of the chamber walls. The ion temperature in the thus obtained synthesized ion-beam plasma is determined by the heating of the tungsten emitter and amounts to ~0.15 eV. Measurements have shown that the density of the slow ions produced in the volume upon ionization of the gas did not exceed 0.1 of the concentration of the potassium-beam ions.

The spectra of the excited oscillations were investigated with an S4-8 frequency analyzer and a narrow-band amplifier. The spatial and temporal correlations of the RF-probe signals were investigated with a correlator. The shape of the wave front and the phase velocities (i.e., the corresponding components of the wave vectors) of the oscillations were measured with two movable probes whose spatial separation was oriented in a specified direction, and whose signals at the specified frequency were separated by an adjustable time delay in the circuit of one of the probes.

The typical experimental conditions thus corre-

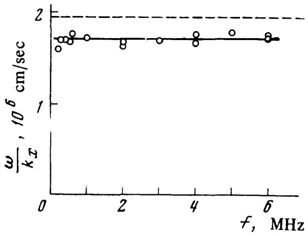

FIG. 2. Dispersion of the excited oscillations (the dashed line shows the velocity of the ion beam).

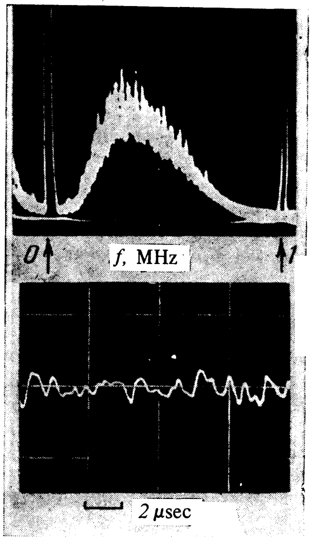

FIG. 4. Nonlinear spectrum of excited oscillations in the region of small wave numbers ($k_x\rho_e > 1$).

sponded to the following ratios of the initial system parameters $\omega_{pe}/\omega_{He} \sim 1.5$, $T_e/T_i \approx 10$, $v_{Te}/V \approx 50$, $V/v_s \approx 10$, and to a ratio $V_A/V \sim 40$ of the Alfven and beam velocities, so that the instability in question can be regarded as electrostatic.

We assume from now on that the beam propagates along the x axis and the magnetic field is directed along the z axis. The origin (x, y, z) is placed at the center of the ion source (emitter).

RESULTS OF EXPERIMENTS

The investigations have shown that the relative motion of the ions and electrons across the magnetic field is accompanied by excitation of a continuous oscillation spectrum in a wide frequency range. The phase velocities of the waves in the direction of the relative motion differ from the ion-beam velocity by an amount close to the ion-sound velocity $v_s \approx 3\times 10^5$ cm/sec, independently of the frequency (Fig. 2) and of the beam energy $\omega \approx k_x(V - v_s)$. The k_x spectrum has upper end points $k_x \approx (3-5)\rho_e^{-1}$. For example, in Fig. 2 the condition $k_x\rho_e = 1$ corresponds to a frequency $f = 2$ MHz. An investigation of the development and establishment of the nonlinear oscillation spectrum with increasing ion flight path x in the system has revealed the following: At the start of the flight path the waves grow rapidly in the high-frequency region ($k_x\rho_e \gtrsim 1$), and then their amplitudes saturate and decrease. The growth rate obtained, e.g., for $f = 3$ MHz, $H = 40$ Oe, and $V = 2\times 10^6$ cm/sec is $\gamma \approx 4\times 10^6$ sec$^{-1} \approx 1.5\omega_{LH}$.

The development and saturation of the longer-wavelength perturbation extends over larger distances. Figure 3 shows the results of the reduction of the amplitude dependences for different frequencies (i.e., different values of k_x). The vertical lines indicate the range of values of x within which the amplitude of oscillations at a given frequency exceeds half the corresponding maximum amplitude. The values of the maximum amplitudes $\tilde{\varphi}$ for different frequencies are shown in the same figure. The region bounded by the dashed lines shows the change of the effective spectral composition of the noise as the instability develops. It follows from Fig. 3 that the evolution of the nonlinear oscillation spectrum takes place under these conditions over a flight distance 15–20 cm.

The experiments have shown that this distance decreases with increasing magnetic field intensity and with increasing density of the charged particles. Figure 4 shows the steady-state spectrum ($x = 25$ cm) and a time scan of the signal. The linearity of the scale in Fig. 4 does not make it possible to resolve the behavior of the amplitude at high frequencies. Measurements with a selective receiver have shown that at high frequencies ($k_x\rho_e > 1$) the amplitude of the oscillations in the steady-state spectrum falls off exponentially with increasing frequency. Figure 5 shows the corresponding plots obtained at different values of the magnetic field intensity.

Phase measurements at fixed frequencies, with the aid of two probes separated in space (along the coordinate axes) have made it possible to determine the values of the components of the wave vectors of the oscillations and the shape of the wave front. By way of example, Fig. 6 (lower part) shows the measured values of k_x, k_y, and k_z under the conditions of advanced instability. The experiments have shown that the front of the excited waves is convex in the x direction, while the wave vector **k** varies both in space and with changing frequency. The upper part of Fig. 6 shows the shape of the wave front in the xz plane ($y = 0$, $x = 15$ cm). The

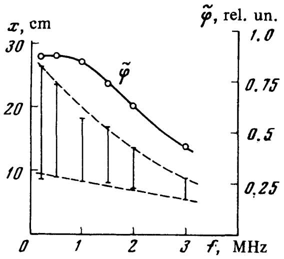

FIG. 3. Regions of spatial localization (x) of the maximum amplitudes in the oscillation spectrum ($\tilde{\varphi}$) for different frequencies ($H = 40$ Oe, $V = 2\times 10^6$ cm/sec, beam-ion current 2.5 mA).

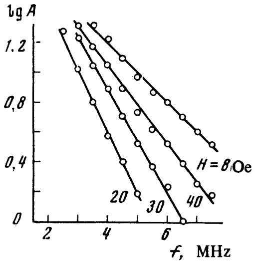

FIG. 5. Nonlinear spectrum of excited oscillations in the region of large wave numbers ($k_x\rho_e > 1$).

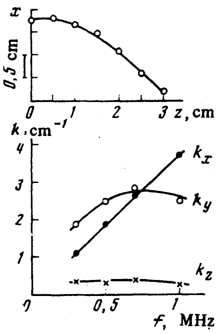

FIG. 6. Shape of wave front (top, $f = 0.3$ MHz, $V = 2\times10^6$ cm/sec, $H = 45$ Oe). Structure of waves in the region of the maximum amplitudes of the nonlinear spectrum (bottom, $x = 15$, $y = 1$, $z = 1$ cm).

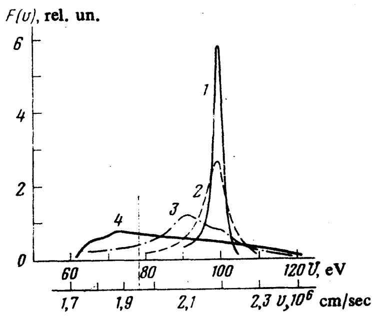

FIG. 8. Distribution functions of the ion velocities, obtained for different flight distances of the beam ($1-x=7$, $2-14$, $3-19$, $4-35$ cm. Initial beam energy 100 eV).

phase measurements have shown at the same time that the spatial correlation of the signals is violated already when the displacement along the y axis is comparable with the wavelength $2\pi/k_y$. The phase relations are violated along the direction of motion of the beam (i.e., the interference pattern vanishes when the signals of the reference and moving probes are added) at distances $\sim(4-6)2\pi/k_x$. In accord with the effective width of the excited frequency spectrum, the autocorrelation function of the investigated noise is practically damped out after 0.7–1.0 μsec. Thus, three-dimensional oscillations are realized in the steady-state spectrum of the instability, and have comparable values of the components k_x and k_y of the wave vector in a plane perpendicular to the magnetic-field direction.

The self-consistent set of waves excited in the plasma stream propagates transversely to the magnetic field even if the velocity of the ion beam is inclined by a small angle to the plane perpendicular to H. By rotating the magnetic coils it was possible to vary the angle between the beam-velocity and magnetic-field directions in a range $90°\pm15°$. Two probes placed at the center of the chamber and separated by a distance $d=2$ cm in a direction perpendicular to the beam motion, in the xz plane, were used to determine the rotation of the wave front (Fig. 7). Rotation of the wave front through an angle α produces a phase shift $\omega\Delta\tau = kd\sin\alpha$ between the signals from the two probes. This relation is shown in Fig. 7 by the dashed line. The experimental points were obtained from measurements of the phase velocity and the temporal signal shift obtained at different rotation angles α of the magnetic coils. As seen from Fig. 7, in the indicated range of the angles α the excited oscillations propagate across the magnetic field regardless of the direction of the ion-beam velocity.

Measurements of the amplitudes of the oscillations with the aid of an electrostatic analyzer have shown that the ratio of the alternating and constant components of the ion density at the end of the flight path was $n_i/n = (2-5)\times10^{-2}$. The amplitude of the oscillating potential in the plasma was estimated from the value of the alternating voltage measured in the probe circuit and increased by a factor C_1/C_2, where C_1 is the capacitance of the probe circuit and C_2 is the capacitance of the probe relative to the plasma. C_2 was assumed to equal the capacitance of a cylindrical layer of thickness equal to the electron Debye radius (the amplitudes were measured with floating probes without drawing current from the plasma). The amplitudes $\tilde{\varphi}$ of the alternating potentials in the plasma, estimated in this manner, were of the order of a volt.

The excitation of the oscillations is accompanied by heating of the ions and the electrons. Figure 8 shows the distribution functions of the ion-beam velocities, obtained at various flight distances under the conditions of advanced instability. The collisionless broadening of the energy spectrum of the ion beam increases in space (i.e., in the coordinate system that moves together with the beam across the magnetic field), and ion heating takes place. Measurements with the aid of electrostatic probes show that the electron temperature increases when the system goes into the turbulent regime.

The value of T_e increases in this case from ~1.5 to ~5 eV. Figure 9 shows the corresponding probe characteristics, obtained in the regime of advanced instability (2) and in the absence of oscillations (1).

DISCUSSION OF RESULTS

1. The experiments have established that the relative motion of the ions and electrons in the plasma across

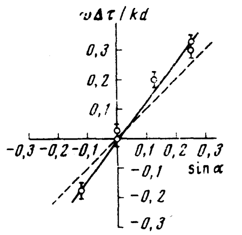

FIG. 7. Rotation of the front of the excited waves with changing direction of the magnetic field in the (V, H) plane.

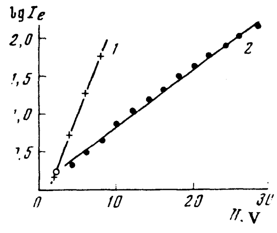

FIG. 9. Dependences of the electron probe current on the potential, plotted in the stable (1) and turbulent (2) regimes: 1—$T_e = 1.6$ eV, 2—$T_e = 5.1$ eV.

the magnetic field, in the indicated range of conditions, is accompanied by excitation of oscillations with a continuous spectrum in a broad frequency band. The spatial structure of the alternating electric fields (Fig. 6) shows that oscillations in a wide range of angles θ are represented in a self-consistent manner in the wave process. They are grouped around $\theta = \pi/2$ and are not affected by small deviations of the current direction (**V**) from the plane perpendicular to **H**. The range of wave numbers k_x of the excited oscillations includes both the values $k_x \sim \omega_{LH}/V$ which are typical of the hydrodynamic (modified two-stream) instability, and $k_x \gtrsim 1/\rho_e$ which correspond to ion-sound instability of the transverse current. The phase velocity ω/k_x, in a coordinate system moving with the ions, is close to the velocity of ion sound at all values of the wave numbers. The width of the spectrum of the excited frequencies and the characteristic shape of the wave front (Fig. 6) indicate that the phase velocities of the oscillations along the magnetic field directions (ω/k_z) have a wide range of values, including practically the entire spectrum of the electron thermal velocities. It can thus be concluded that under the described conditions the instability of a plasma with a transverse current is due to the predominant excitation of ion-sound oscillations that propagate across the magnetic field.

2. In the presently accepted theory[7, 9] the mechanism of the saturation of the instability in question is connected with the three-dimensional character of the excited oscillations, and particularly with the presence of a finite angle width of the spectrum in a plane perpendicular to H ($k_y \neq 0$). At electric-field amplitudes when the drift velocity of the electrons in the x-axis direction

$$\tilde{v}_x = c\tilde{E}_y/H = ck_y\tilde{\varphi}/H$$

(c is the speed of light) becomes comparable with phase velocity $\omega/k_x = V$ of the wave, elimination of the instability is natural. The corresponding nonlinear estimates lead in this case to an oscillation energy density

$$W \sim \frac{H^2}{8\pi}\left(\frac{V}{c}\right)^2 \approx mnV^2$$

at $k\rho_e \sim 1$. It is proposed in[8], where a modified Buneman instability is considered, that this mechanism should lead primarily to an effective nonlinear transformation of the three-dimensional wave spectrum into a two-dimensional one ($k_y \approx 0$). The subsequent elimination of the instability is connected in this case with effects of capture of electrons and ions by the waves. Under the conditions of the described experiments, the energy density of the oscillations agrees with the value of W. Thus, if the value of the electric field is estimated from measurements of the amplitude of the oscillations of the potential and the characteristic wavelength in the regime of the steady-state nonlinear spectrum $\tilde{E} \sim k_x\tilde{\varphi}$, then at typical parameters ($n = 4\times 10^8$ cm^{-3}, $V = 2\times 10^6$ cm/sec, $\tilde{\varphi} = 1$ V, and $k_x = 2$ cm^{-1}) we have the ratio $\tilde{E}^2/8\pi mnV^2 \approx 1$.

The experimental data point to the following picture of the instability development. In accord with the linear theory, the initial stage constitute a growth of ion-sound perturbations with $k\rho_e \gtrsim 1$, with a growth rate $\gamma \sim \omega_{LH}$ and with an amplitude that saturates quite rapidly at a level comparable with W. Perturbations with smaller values of k saturate later, so that the evolution of the nonlinear spectrum is accompanied by an effective transfer of the noise energy into the low-frequency region ($k\rho_e < 1$) and establishment of an exponentially decreasing amplitude in the region $k\rho_e > 1$. The variation of the ratio of the quantities k_x/k_y over the spectrum (Fig. 6.) points to a tendency of the wave spectrum to compress in k-space in the xz plane, as predicted in[8].

3. The instability leads to a rapid slowing down and broadening of the ion velocity spectrum (Fig. 8). The measured value of the oscillation phase velocity (dashed line) shows that a regime in which the ions are captured by the waves is reached. The average translational velocity of the ion beam, whose distribution function is represented by curve 4 (Fig. 8), is 2×10^6 cm/sec, i.e., it is close to the phase velocity of the oscillations. The half-width of the velocity spectrum corresponds, the coordinate system moving with the ions, to an energy 2.5 eV. The characteristic capture time $\tau_i \sim (M/e\tilde{\varphi}k^2)^{1/2} \approx 3\cdot 10^{-6}$ sec correspond to an ion flight path $x = V\tau_i = 6$ cm (for $k = 2$ cm^{-1}; e is the electron charge), which is much less then the length of the experimental setup. Thus, the phase mixing of the ions captured by the ion-sound waves leads to the appearance of an effective ion temperature $T_i \lesssim T_e$ that is transverse relative to the magnetic field. In the laboratory frame, this corresponds to the ion-beam energy-spectrum broadening observed in experiment.

The electrons are contained in the investigated plasma by the field of the electrostatic trap produced by the space charge of the ion beam. It appears that the stationary drift of the fastest electrons to the walls are maintained by Coulomb collisions. The average lifetimes of the electrons in the volume can then be estimated to equal the time of Maxwellization of the electron gas $\tau_M \approx T_e^{3/2}m^{1/2}L_C e^4 n \sim 4\times 10^{-3}$ sec under typical experimental conditions (L_C is the Coulomb logarithm). The phase velocities of the oscillations along the direction of the magnetic field lie in a wide interval $\omega/k_z > 2\times 10^6$ cm/sec, which includes the thermal velocities of the electrons. The observed electron heating can therefore be attributed to resonant interaction with the waves. A quasilinear estimate[7] of the characteristic electron heating time $\tau_e \sim (v_{Te}/V)^3/\omega_H$ leads, under the described experimental conditions, to a value $\sim 10^{-4}$ sec $< \tau_M$, i.e., the increase of the average thermal energy takes place in the course of a repeated ($\sim 10^3$ times) passage of the electrons through the turbulent-field zone.

In concluding the discussion, attention must be called to the fact that in[8], where the saturation of plasma instability with a transverse current was considered theoretically and by numerical simulations, assuming the ion and electron capture mechanism, the obtained turbulence level and degree of particle heating exceeded substantially the corresponding values in our experiment. The amplitude of the oscillations of the potential in the ion-capture regime is determined primarily by the phase velocity $\tilde{\varphi} \gtrsim M(V-\omega/k)^2/2e$ of the waves. In the cited paper it was assumed that $V-\omega/k_x = V/2 \gg v_s$, as follows from the hydrodynamic dispersion equation. Experiment yields $V-\omega/k_x \approx v_s$, which jointly with the condition $\tau_e > \tau_i$ can explain the disparity between the conclusions of the theory[8] and the described experiment.

The purpose of the present paper was to simulate the evolution of the turbulence of a plasma with a transverse current by investigating the instabilities of an ion beam that moves through a magnetized electron gas in a direction perpendicular to the magnetic field. Such a simulation is possible because, from the point of view of the excitation and development of the investigated instability (which are determined by the character of the vibrational motion of the electrons), the nature of the transverse current in the plasma is immaterial. In experiments on high-frequency heating of a plasma by large-amplitude waves (see, e.g., [2,7]) the transverse current is due to the drift motion of the electrons relative to the ions in the crossed electric and magnetic pump-wave fields. Under the conditions of these experiments, the nonstationary character of the process and the inhomogeneity of the magnetic field are of no importance from the point of view of development of ion-sound turbulence, since $\gamma \gg \omega_{Hi}$ and $\omega \gg \omega_{Hi}$, and the characteristic wavelengths are small compared with the inhomogeneity scale $k \gg H^{-1}dH/dx$. In the present paper we simulated the instability of the transverse current under conditions of a uniform magnetic field in order to be able to compare the experimental results with the existing theories of anomalous resistance.

We have thus investigated experimentally the dynamics of the development and saturation of the instability of ion-sound oscillations propagating across a magnetic field in a plasma with a transverse current. The ion-sound turbulence is an effective mechanism for rapid collisionless heating of ions and electrons, leading to a near-isothermal plasma state.

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