

*DISINTEGRATION OF THE FRONT OF A STRAIGHT MAGNETIC-SOUND SHOCK WAVE IN
A RAREFIED PLASMA AT HIGH MACH NUMBERS*

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Experiments on large amplitude straight cylindrical magnetic-sound waves in a rarefied plasma are described. At relatively small magnetic Mach numbers ($\mu < \mu_{CR}$), waves with a steep front are observed, their duration being of the order of $\tau_e \approx 11 c \sqrt{mM}/eH$ and width $\delta_e = (10-12) c/\omega_{pe}$. When $\mu > \mu_{CR}$, a wave with a steep front is first formed on the initial part of the path, its duration being $\sim \tau_e$ and width $\sim \delta_e$; subsequently these parameters sharply increase, by one order of magnitude, in the central region of the plasma column. The observed effect is interpreted as a disintegration of the magnetic-sound waves as a result of formation of oppositely moving ion beams and buildup of ion-ion instability at Mach numbers $\mu > \mu_{CR}$.

1. INTRODUCTION

It is known from the theory of straight magnetic-sound shock waves in a rarefied plasma that there exists a certain critical value of the magnetic Mach number, μ_{CR} , at which radical changes should take place both in the structure of the front and in the character of the dissipative processes in the wave^[1]. In the region $\mu < \mu_{CR}$ the front of the wave has a structure for which a laminar theory can be constructed^[1-3]. According to this theory, and according to the results of experimental measurements^[4-6], the width of this front is $\delta_e \approx (5-10)c/\omega_{pe}$, and the dissipation has a purely ohmic character and can be connected with the instability of the current^[1,7,8].

At Mach numbers $\mu > \mu_{CR}$ the ohmic dissipation is incapable of stopping the twisting of the ion velocity profile in the wave, and no laminar theory of the front structure can be constructed. A description of the shock wave is possible here only when account is taken of a new dissipative mechanism, such as ion viscosity.

In our case, the role of ion viscosity can be played, for example, by ion-ion instability^[9], inasmuch as the ion-velocity profile in the wave is not unique, and oppositely moving ion beams are produced in the plasma and move transversely to the magnetic field. This process, sometimes called in analogy with ordinary hydrodynamics the "toppling over" of the wave, should lead to an effective destruction of the front and to heating of the ions^[1]. The width of the wave front should then be deter-

mined by the magnitude of the Larmor radius of the ion in the wave after the "toppling over":

$$\delta_i \sim \frac{v_0 M c}{eH} \approx \frac{c}{\omega_{pi}}, \quad \omega_{pi}^2 = \frac{4\pi n_1 e^2}{M}. \quad (1)$$

Here v_0 is the relative velocity of the opposing ion beams and n_1 is the plasma density ahead of the wave front. The remaining symbols are standard.

The purpose of the present investigation was to observe the disintegration of the front of magnetic-sound wave at magnetic Mach numbers $\mu > \mu_{CR}$. Experimental realization of such waves, however, entails serious difficulties. This is precisely why observation of the structure of their front has become possible only recently^[5,6], although experiments on the investigation of collective processes in strong hydromagnetic waves were started back in 1961^[10] (see also^[8]).

To attain Mach numbers $\mu > \mu_{CR}$ it is necessary first that the amplitude of the pulsed magnetic field on the piston $\tilde{H} = H_2 - H_1$ increase to large values within a very short time interval τ_0 , satisfying the condition

$$\tau_0 < \Delta t = R/u = R/\mu u_A. \quad (2)$$

Here H_1 and H_2 are the magnetic fields ahead and behind the wave front, R the path traversed by the wave in the plasma, or the radius of the plasma cone in the case of cylindrical waves, u the velocity of the wave, u_A the Alfvén velocity. The table lists the values of Δt in units of 10^{-8} sec, calculated by means of formula (2) for a helium plasma of density $n_1 = 10^{13} \text{ cm}^{-3}$ at $R = 4 \text{ cm}$ ($M = 4$).

μ	H_1, Oe		
	350	500	1000
3	13	9	4,5
4	8,3	5,8	2,9
5	6,7	4,6	2,3

The physical meaning of these requirements is obvious. If the magnetic field on the boundary of the plasma does not increase sufficiently rapidly, then the wave, whose velocity exceeds that of the piston, can become detached from the piston before the desired Mach number μ is realized.

Another important feature of experiments of this kind under laboratory conditions is the essentially nonstationary nature of the wave process. According to (1), the width of the wave front should increase as a result of the "toppling over" by approximately one order of magnitude compared with the laminar case, and may turn out to be comparable with the radius R of the discharge chamber or even exceed it. In this case, of course, we can no longer speak of a stationary wave. However, the process of disintegration of the front can be observed even under such nonstationary conditions, provided the condition $\delta_e \ll R$ is satisfied for the wave with $\mu < \mu_{cr}$. Indeed, when \tilde{H} increases sufficiently rapidly, the magnetic piston should have time to deform the wave during its initial section of the path, and to impart the ions of the peripheral regions of the plasma cone a momentum sufficient for the formation of the opposing ion beams. Then we can expect the effects connected with the "toppling over" to appear in the central region of the plasma cone.

From this point of view, it is of interest to estimate the possible densities of the opposing ion beams. The pre-ionized plasma has a radial density distribution corresponding to diffusion. If the volume of the plasma cone is separated into two parts, one outside the cylinder with radius $r = R/2$ and the other inside the cylinder, then the average plasma density in the outer region turns out to be approximately half as large as in the central region. However, owing to the cylindrical nature of the plasma, the total number of particles in the outer region turns out to be even larger (approximately double) than in the central region. Consequently, if the formation and twisting of the wave front take place when $\mu > \mu_{cr}$ over distances comparable with $R/2$, and if the opposing ion beams are produced in the region $r < R/2$, then we can assume that the densities of these beams are of the same order of magnitude.

We note, finally, that in experiments with an incompletely ionized plasma the structure of the wave front can in general be greatly influenced by dissipative effects (charge exchange, ionization) due to collisions between charged particles and neutral atoms on the wave front^[4,11]. It was therefore desirable to realize conditions under which the collision-free dissipation effect connected with the disintegration of the wave front could be separated from the collision effects connected with the presence of neutral atoms.

2. EXPERIMENTAL SETUP AND TIME TABLE OF EXPERIMENTS

The experimental setup is shown in Fig. 1. The plasma is produced in a glass tube 1 of diameter $2R = 7.5$ cm and of length 85 cm, by a dc discharge between electrodes 2 and 3. The discharge was initiated by a supplementary electrode 3n. The central section of the discharge chamber, 45 cm long, was in a longitudinal constant magnetic field H_1 produced by coils 4 (the inhomogeneity of the field H_1 was less than 1% in this region). Converging cylindrical magnetic-sound waves were excited in this region by trapezoidal pulses of the magnetic field \tilde{H} , produced on the boundary of the plasma column by the discharge circuit 6. The pulses had a rise time $\tau_0 = 4 \times 10^{-8}$ sec and an amplitude $|\tilde{H}| = 1500$ Oe. The field H_1 ranged from 0 to ~ 3 kOe. It was possible to turn on magnetic mirrors with the aid of coils 5. The dashed lines in the center of the figure shows the configuration of the magnetic field in the region of the surge circuit with the magnetic mirrors turned on and off.

On the right side of the figure is shown the cross section of the discharge chamber with schematically marked cylindrical wave, and a diagram of the surge circuit with the artificial line shaping the pulses of the field H . The circuit is closed by a three-electrode discharge gap K after the lapse an adjustable time interval following the instant of ignition of the pre-ionization. The idea is to have the surge circuit generate a train of pulses of magnetic field H , alternating in sign and having trapezoidal wave form, as shown by the solid line in the lower part of the figure. The dashed line denotes the derivative dH/dt . The actual shape of the H and dH/dt pulses will be discussed later.

The time table of the experiment was as follows. Pre-ionization was first produced by a direct discharge current. The current lasted several microseconds and produced an initial concentration $n_0 \approx 4 \times 10^{13} \text{ cm}^{-3}$ at a neutral-helium density $N_0 \approx 10^{14} \text{ cm}^{-3}$, or else $n_0 \approx 4 \times 10^{14} \text{ cm}^{-3}$ at N_0

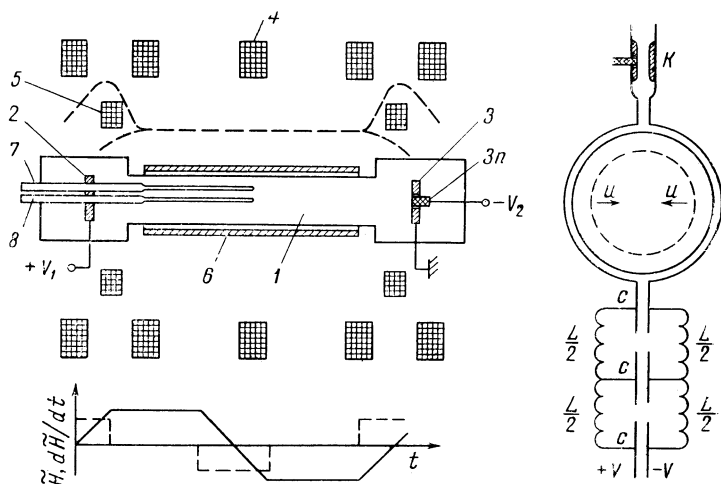


FIG. 1. Diagram of experimental setup: 1 – volume of discharge chamber, 2, 3, 3n – electrodes to obtain pre-ionized plasma; 4 – magnetic-field coils; 5 – magnetic-mirror coils; 6 – cylindrical surge-circuit loop; 7, 8 – miniature magnetic probes. The remaining details of the figure are discussed in the text.

$\approx 10^{15} \text{ cm}^{-3}$. The plasma density then decreased during several hundred microseconds in accordance with a certain law, down to a value $n_1 \sim 10^{12} \text{ cm}^{-3}$. The plot of the density against time was obtained with the aid of a microwave interferometer with wavelengths λ equal to 8 and 4 mm; in the region above $5 \times 10^{13} \text{ cm}^{-3}$, the Stark broadening of the Balmer line H_β was used^[12,13]. In the latter case, a Fabry-Perot interferometer (IT-51) in tandem with a ISP-51 spectrograph was used, together with high-speed spectrum scanning by an electron-optical converter. The time sweep of the spectrum made it also possible to estimate the electron temperature T_e in the pre-ionized plasma by determining the spectrum of the three-particle electron-ion recombination^[14]. In practically the entire time range, with the exception of the phase during which current flowed (approximately 5 μsec), the electron and ion temperatures were on the order of several electron volts and lower (see^[12-14]).

Thus, switching of the surge circuit at a definite delay following the initiation of the pre-ionization has made it possible to excite a wave in a plasma of no values of density n_1 and temperature T .

The disintegration of the magnetic-sound wave front was observed with the aid of two differentiating magnetic probes 7 and 8, located at distances $r = R/2$ and $r = R/8$ (the near-axis region) from the axis of the system. The probes, placed in an insulating glass tube of 3 mm outside diameter, were introduced from the end of the discharge chamber into the plasma region spanned by the surge-circuit loop. The upper limit of the pass band of the probes, f_{lim} , was higher than 10^8 Hz .

3. EXPERIMENTAL RESULTS

It turned out in experiment that by varying only the magnetic Mach number μ it was possible to

realize two operating modes, in which the structure of the front of the magnetic-sound perturbation and the character of the wave processes were essentially different.

Let us consider the oscillograms recorded simultaneously with the aid of two probes. Figure 2a shows oscillograms obtained at a distance $r = R/2$ from the axis. The corresponding oscillograms obtained at $r = R/8$ are shown in Fig. 2b. Oscillograms 1 on both figures were registered at a plasma density $n_1 = 0$ and represent the derivative $d\tilde{H}/dt$ of the pulsed magnetic field. The first (positive) peak on them corresponds to the rising front of the field \tilde{H} , parallel to the field H_1 , and the second (negative) corresponds to the decrease of the positive pulse and to the rise of the succeeding negative pulse of the magnetic field \tilde{H} .

Oscillograms 2 were obtained at a Mach number $\mu = 1.7$ ($H_1 = 1500 \text{ Oe}$) and a density $n_1 = 3 \times 10^{13} \text{ cm}^{-3}$, with the magnetic mirrors turned on. It is seen from oscillogram 2 of Fig. 2a that in this case the probe determines accurately the instant of passage of the wave through the point $r = R/2$ (first positive peak). The wave front then experiences a nonlinear twisting, although its width still does not reach its minimum value. The second positive peak, which appears on the same oscillogram, corresponds to the front of the reflected wave moving from the axis towards the periphery. The distance between the first and second positive peaks, as expected, depends on the density n_1 and on the magnitude of the magnetic field. There is no reflected wave front on oscillogram 2 of Fig. 2b. Nor should there be one, since the second probe is located near the axis of the discharge tube. The negative signal on oscillogram 2 of Fig. 2a and the corresponding section on the oscillogram 2 of Fig. 2b offer evidence of free penetration of the rarefac-

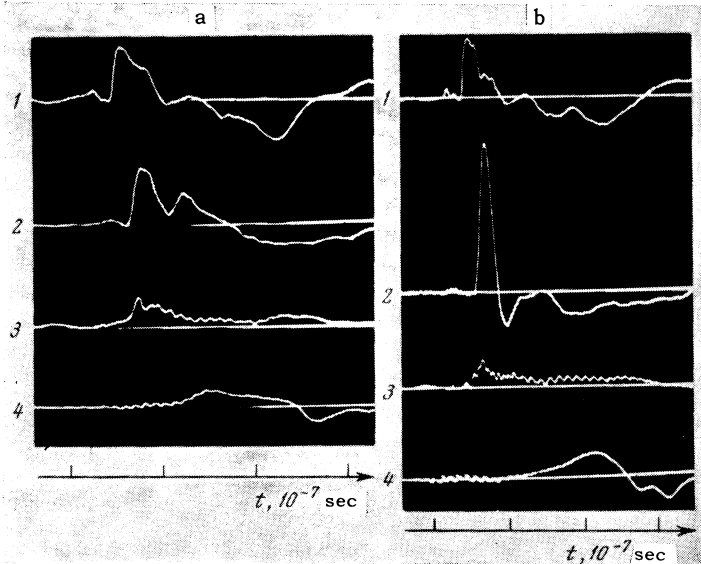


FIG. 2. Oscillograms of magnetic-probe signals: a – probe located at $r = R/2$; b – probe located near the axis of the discharge chamber ($r = R/8$): 1 – $n_1 = 0$; 2 – $\mu = 1/7$, $N_1 = 10^{14}$, $n_1 = 3 \times 10^{13} \text{ cm}^{-3}$; 3 – $\mu = 4.2$, $N_1 \approx 10^{14}$, $n_1 \approx 3 \times 10^{13} \text{ cm}^{-3}$; 4 – $\mu = 1.7$, $N_1 \approx 10^{15}$, $n_1 \approx 3 \times 10^{14} \text{ cm}^{-3}$.

tion wave^[15,16] into the plasma in this case ($\mu < \mu_{cr}$).

The transients have an entirely different character in oscillogram 3, obtained at $\mu = 4.2$ ($H_1 = 350 \text{ Oe}$), the other experimental conditions being the same. At the point $r = R/2$ we no longer observe the nonlinear twisting of the front. To the contrary, the width of the transition zone has increased by approximately ten times compared with the oscillograms in 2. Now can we speak with any assurance of the presence of a reflected wave. Finally, there is practically no negative signal corresponding to the rarefaction wave or to the decreasing section corresponding to the rarefaction wave or to the decreasing section of the vacuum pulse of magnetic field. The latter fact can apparently be interpreted to mean that the plasma captures the paramagnetic moment induced by the wave.

The indicated difference in the character of propagation and structure of the transition zone of the magnetic-sound perturbation in the two modes under consideration becomes particularly clearly manifest on the oscillograms of Fig. 2b, obtained

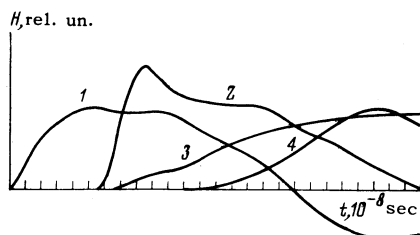


FIG. 3. Waveform of the magnetic field exciting the wave (1) and typical profiles of the buildup of the magnetic field in the region near the axis ($r = R/8$) (2, 3, 4) obtained by integrating the corresponding probe oscillograms; the values of μ , N_1 , and n_1 are the same as in Fig. 2.

in the near-axis region, and also on the corresponding magnetic-field profiles in Fig. 3, obtained by integrating these oscillograms. We see that in one case ($\mu = 1.7$) a wave with a steep front arrives in the near-axis region and in the other case ($\mu = 4.2$) the wave front is effectively disintegrated and the growth rate of the amplitude of the magnetic-sound perturbation becomes very small.

We present some quantitative characteristics of the structure of the transition zone, for the two modes under consideration. When $\mu = 1.7$ the front duration τ_e , determined by measuring the converging (Figs. 2a, b) and reflected (Fig. 2a) waves is approximately $2 \times 10^{-8} \text{ sec}$. This is equal to eleven cycles of the oscillations at a geometric-mean frequency $\omega_{g.m.}$ calculated from the magnetic field in the wave ($\tau_e = 11 \omega_{g.m.}^{-1}$) and amounts to approximately $1.5 \sqrt{mM/eH_1}$, which agrees with the result obtained in our earlier paper^[4].

The width of the front in this case ($\mu = 1.7$) can be defined as $\delta_e = u\tau_e$. The wave velocity u can be estimated with sufficient accuracy from experiments on the delay time Δt_d of the reflected wave relative to the primary converging wave. From oscillogram 2 of Fig. 2a we get $\Delta t_d = 4 \times 10^{-8} \text{ sec}$. The path covered by the primary and reflected waves during that time is $2(R/2 - R_0)$, where R_0 is the radius of the near-axis region of the plasma, into which the wave does not penetrate. By probe measurements we got $R_0 = 0.7-1 \text{ cm}$. Consequently, $u = (5-6) \times 10^7 \text{ cm/sec}$ and $\delta_e = (1-1.2) \text{ cm}$. For $n_1 = 3 \times 10^{13}$ this yields $\delta_e = (10-12) c/\omega_{pe}$ which agrees with the earlier results^[5,6].

The described method of measuring δ_e is quite convenient. Since the primary wave is converging and the reflected wave diverging, the cylindricity

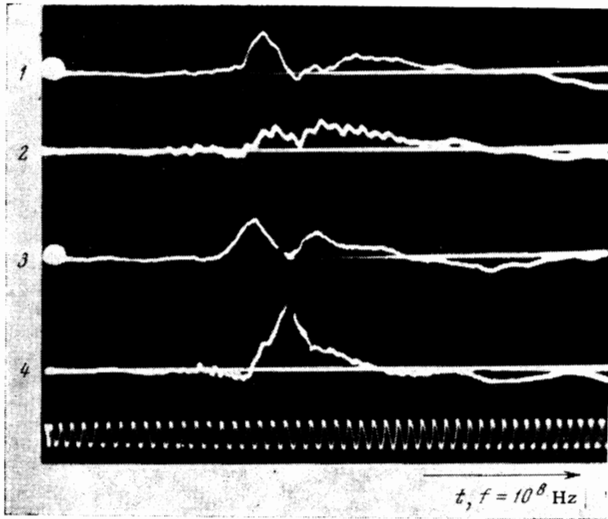


FIG. 4. Oscillograms of magnetic-probe signals, demonstrating the formation of the magnetic-sound wave on the periphery and its subsequent toppling over in the central region of the discharge tube: oscillograms 1 and 2 were obtained simultaneously, 1 – at $r = R/2$, 2 – at $r = R/8$, with $n_1 = (3 - 4) \times 10^{13} \text{ cm}^{-3}$ and $H_1 = 350 \text{ Oe}$; oscillograms 3 and 4 – also obtained simultaneously, 3 – at $r = R/2$ and 4 – at $r = R/8$, with $n_1 = 2 \times 10^{13} \text{ cm}^{-3}$ and $H_1 = 350 \text{ Oe}$.

effect in the measurements of δ_e is eliminated. By varying the constant magnetic field H_1 during the course of the experiments and keeping the amplitude \tilde{H} constant, we have found that the obtained front width $\delta_e = (10-12) c/\omega_{pe}$ remains essentially unchanged up to $\mu = 2.5-3$.

Before we present the quantitative characteristics of the structure of the transition zone for the second operating mode ($\mu = 4.2$), we must make use of additional experimental material, which enables us to refine the dynamics and the character of the wave processes in this case. The probe measurements showed that when $\mu = 4.2$ a magnetic-sound perturbation with a steep front was initially produced on the periphery, having a width δ_e just as when $\mu = 1.7$. The wave disintegrated only after it had time to take shape and cover a certain distance. Depending on the initial conditions, this process occurred either somewhere in the $r = R/2$ region or else in the near-axis region.

The foregoing is illustrated by the oscillograms of Fig. 4. The two upper oscillograms were obtained simultaneously for $n = (3-4) \times 10^{13} \text{ cm}^{-3}$ and $\mu = 4.2$ ($H_1 = 350 \text{ Oe}$) with the magnetic mirrors disconnected. The Oscillograms 1 and 2 correspond respectively to $r = R/2$ and $r = R/8$ from the axis. The signal sequence on these oscillograms was obviously the following: first the primary converging wave (first positive peak on oscillogram 1) traveled

past the probe, then the wave reached the near-axis region (oscillogram 2) and finally, the reflected wave reached the first probe (oscillogram 1). We see that the primary converging wave still had a steep front with width δ_e at the point $r = R/2$ (compared with oscillograms 2 and 3 of Fig. 2a). On the axis, however, the wave front disintegrated. Since, however, the disintegration of the front took place too late and was not very effective, oscillogram 1 shows also quite clearly the reflected wave. But the amplitude of the reflected wave is small in this case, and the front duration is very large.

A similar situation is observed on oscillograms 3 and 4, obtained at the lower density $n_1 \approx 2 \times 10^{13} \text{ cm}^{-3}$ ($H_1 = 350 \text{ Oe}$; magnetic mirrors disconnected). Oscillogram 3 corresponds to $r = R/2$, and oscillogram 4 to the radius $r = R/8$. We see that the dynamics of the wave process is in this case essentially the same as in the preceding pair of oscillograms. At first the primary converging steep-front wave travels through the point $r = R/2$, then disintegration of the front takes place on the axis (compare oscillogram 4 of Fig. 4 with oscillogram 2 of Fig. 2b), and finally, at the point $r = R/2$, the reflected wave appears. However, the disintegration process is here less effective than on oscillogram 2, and the reflected wave is more distinct. This can be easily explained. With decreasing plasma density, the velocity of the wave increases. The wave now becomes detached from the piston and reaches the system axis before the specified value of μ is realized. In other words, the disintegration of the wave front occurred at a lower value of μ in the case of oscillograms 3 and 4 than in the case of oscillograms 1 and 2.

The oscillograms demonstrate uniquely that at Mach numbers $\mu > \mu_{cr}$ a wave with a steep front of width δ_e is produced at first on the periphery, and only later does the wave front disintegrate in the central region of the plasma column.

It was noted in Sec. 1 that under the conditions of our experiments the concept of wave-front width becomes physically meaningless once the wave has toppled over, inasmuch as the width becomes larger than the radius of the discharge chamber. We can, however, speak with a certain degree of caution, of the duration of the corresponding transient process. For example, according to oscillogram 3 of Fig. 2b, of the time τ_i in which the magnetic-sound perturbation rises to a maximum value near the axis amounts to about 100 cycles of oscillations at the frequency $\omega_{g.m.}$ calculated from the magnetic field in the wave. It can be assumed that in the stationary case this would correspond to a front width δ_i of the same order of magnitude as c/ω_{pi} .

In concluding this section we note also the influence of the magnetic mirrors on the measurement results. Inclusion of the mirrors increased as a rule the effectiveness of wave-front disintegration and capture of the paramagnetic moment in the plasma by the induced wave (compare oscillograms 3 in Figs. 2a and b with the oscillograms in Fig. 4).

4. DISCUSSION

Thus, an effective disintegration of the front of the magnetic-sound waves, propagating in a rarefied plasma transversely to the magnetic field, takes place in our experiments at magnetic Mach number $\mu > \mu_{\text{CR}}$. This can only be caused by the development of some process of collective integrations in the plasma. The most probable is the appearance of ion viscosity as a result of the "toppling over" of the ion velocity profile in the wave and the build up of an ion-ion instability^[9]. One can, of course, attempt to interpret the results obtained here on the basis of the already known current instability modes (two-stream, ion-sound), or else on the basis of the appearance of some new mode of this instability.

However, current instability is hardly capable of leading to an abrupt increase in the width of the front when μ changes from 2.5–3 to 4. An instability of this type can influence only the azimuthal component of the momentum in the wave, a component connected with the electron current on the front, and can lead to a dissipation that has an ohmic character. It is known, however, that the energy of the current motion in the magnetic-sound wave amounts to less than 1/10 of the entire energy, which is connected principally with the translational motion of the ions^[17,18], and that ohmic dissipation, as noted in Sec. 1, is incapable of stopping the twisting of the velocity profile of the ions at Mach numbers $\mu > \mu_{\text{CR}}$.

Moreover, when the profile of the magnetic field broadens greatly in the wave (by approximately one order of magnitude), a corresponding decrease, of the same order of magnitude, should appear in the electron current velocities. Consequently, even if current instability could develop on the front of a wave with $\mu < \mu_{\text{CR}}$, it should apparently tend to zero in this case.

Kadomtsev^[9] has shown that if the relative velocities of the opposing ion beams in a homogeneous unbounded plasma exceeds the thermal velocity ($v_0 > \sqrt{T_i/M}$), then an ion-ion instability can set in, containing oscillations with different wave numbers k_x and k_z (the z axis is oriented along the magnetic field, the x axis along the ion motion). In particu-

lar, oscillations are present whose direction is strictly transverse to the magnetic field ($k_z/k_x \approx \sqrt{m/M}$), with wavelength $\sim c/\omega_{pe}$ and with increment $\sim \omega_{g.m.} = \sqrt{\omega_{H_i}\omega_{H_e}}$.

It can be shown that the main requirement for the buildup of ion-ion instability ($v_0 > \sqrt{T_i/M}$) is certainly satisfied under the conditions of our experiments. Indeed, the temperature of the pre-ionized plasma can at best be of the order of several electron volts. In the case when $\mu < \mu_{\text{CR}}$ the electron temperature T_e behind the front of the wave reaches, according to our earlier measurements^[4], ~ 100 eV. It is not very probable that the ions in such a wave would have a like temperature. If we assume arbitrarily $T_i = 20$ eV, we get $\sqrt{T_i/M} \approx 2 \times 10^6$ cm/sec, and we certainly get too high a thermal velocity if we assume $T_i = T_e = 100$ eV, namely $\sqrt{T_i/M} \approx 5 \times 10^6$ cm/sec.

On the other hand, at large Mach numbers the translational velocity of the ions in the wave is close to the velocity of the wave itself. The latter, as shown in Sec. 3, is $(5-6) \times 10^7$ cm/sec. Consequently, the requirement $v_0 > \sqrt{T_i/M}$ is satisfied with an ample margin under the conditions of our experiments.

Of course, other conditions for the buildup of ion-ion oscillations^[9] and for the toppling over of the wave^[1], which are assumed in the theory, differ from the conditions of our experiment (boundedness and inhomogeneity of the plasma, cylindricity). This can possibly lead to somewhat different quantitative results. It can be assumed, however, that the convergence of the cylindrical wave and its reflection on the axis should contribute to an effective formation of opposing ion beams, and consequently, to excitation of the instability.

The cylindricity, generally speaking, can influence the results of probe measurements of the front width in the near-axis region, owing to cumulation of the wave. But this effect has turned out to be insignificant. It came into play essentially only at the smaller Mach numbers. This can be deduced from the oscillogram 2 of Fig. 2b. The negative peak on this oscillogram, which follows directly the main positive peak, indicates that in this mode the magnetic field decreases rapidly after cumulation to the level of the amplitude of the field \tilde{H} (see also Fig. 3).

It was noted in Sec. 1 that in a partially ionized plasma an important source of broadening of the wave front can, in general, be dissipative processes connected with charge exchange and ionization^[4,11]. The role of these processes in the described experiments, which were carried out at a neutral-atom density ($N_1 \approx 10^{14}$ cm⁻³) corresponding to the initial pressure of the helium $p_0 = 3 \times 10^{-3}$ mm Hg,

turned out to be insignificant. Only an appreciable simultaneous increase of the densities of the neutral and charge particles had led, in the case of small μ , to a broadening of the wave front comparable with the "toppling over" effect. For example, oscillograms 4 in Figs. 2a and b were obtained at $\mu = 1.7$, $N_1 \approx 10^{15}$, and $n_1 \approx 3 \times 10^{14} \text{ cm}^{-3}$ (see also Fig. 3).

In conclusion, we wish to call attention to one characteristic feature of probe signals obtained in the "toppling over" mode. They show clearly high-frequency oscillations that extend over the entire front of the wave, whereas there are no such oscillations at $\mu = 1.7$. Moreover, the more effective the front disintegration, the more strongly pronounced are the high-frequency oscillations (compare oscillogram 4 with oscillogram 2 of Fig. 4 and compare the latter with oscillogram 3 of Fig. 2b). It can be further noted that the oscillations in the readings of the probe located at $r = R/2$ appear only if the "toppling over" has occurred prior to the arrival of the wave at this point (see oscillogram 3 of Fig. 2a). To the contrary, if the "toppling over" occurred after the passage of the wave through the location of the probe at $r = R/2$ (oscillogram 1 of Fig. 4), then the high frequency oscillations appear only on the oscillogram of the probe located near the axis (oscillogram 2 of Fig. 4). They are seen in part also on the front of the reflected wave produced after the "toppling over" (oscillogram 1 of Fig. 4).

We note that the oscillations have a frequency of the same order as $f_{g.m.}$ and may be a manifestation of the ion-ion instability considered above. A detailed study of the character of these oscillations calls for special experiments, which will be the subject of further research. It is also of interest to measure the energy of the plasma ions in the process of disintegration of the wave front.

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