INVESTIGATION OF TURBULENT PROCESSES IN THE FRONT OF A SHOCK WAVE IN A PLASMA

A. G. ES'KOV, R. Kh. KURTMULLAEV, A. I. MALYUTIN, V. I. PIL'SKIĬ and V. N. SEMENOV

Nuclear Physics Institute, Siberian Division, USSR Academy of Sciences

Submitted September 27, 1968

Zh. Eksp. Teor. Fiz. 56, 1480—1491 (May, 1969)

Results of investigation of microfluctuations of an electromagnetic field and the distribution of the electric and magnetic fields in the front of a shock wave are presented. It is found that electric field oscillations arise within the front when the plasma concentration increases. Their frequencies and wave lengths are consistent with the assumption of an ion-acoustic nature of the oscillations. The electric and magnetic field distributions, fluctuation level and measured value of the conductivity in the wave are in accordance with the assumption that resistive dissipation due to "friction" between the electrons and ion-acoustic waves is dominant in the wave front. It is shown that at large Mach numbers $M > M_c$ there occurs a change in the oscillation spectrum and of the macroscopic distribution of the electric field in the wave front. The experimental data are in agreement with the hypothesis that at $M > M_c$ the viscosity dissipation mechanism is operative; this dissipation is due to build-up of electromagnetic oscillations in opposite ion streams and is accompanied by ion heating.

1. INTRODUCTION

In experiments on collisionless shock waves in a plasma[1], it was observed that when the initial plasma concentration n_0 exceeds a certain critical value n_c, the width of the collisionless shock front (CSF) increases sharply from a value c/ω_0 (ω_0—electron Langmuir frequency) to a value approximately ten times larger (in a hydrogen plasma). Such a regular broadening of the CSF can be due either to anomalously high plasma resistance, or to anomalously high plasma viscosity, since the influence of pair collisions in typical experimental conditions can be neglected (at $n_0 \sim 10^{12}$—10^{14} cm^{-3}, a neutral atom concentration $n_a \sim 10^{13}$—10^{14} cm^{-3}, and electron and ion temperatures T_e, $T_i \sim 10^2$—10^4 eV, the characteristic times between the pair collisions of electrons, ions, and neutral atoms $\tau_{\text{pair}} \sim 10^{-6}$ sec, and the temporal width of the front $\tau_{\text{fr}} \sim 10^{-8}$—$10^{-7}$ sec, so that $\tau_{\text{fr}} \ll \tau_{\text{pair}}$). A theoretical analysis[2-4] has shown that the most probable process that can cause the anomalous dissipation is instability of the particle motion in the front against buildup of various oscillations.

The purpose of the present work was to study the nature of the turbulent processes and the ensuing character of the dissipative mechanism in the CSF. A study of the dissipation mechanism is also of practical interest, since it governs the features of plasma heating. For example, if the dissipation is due to a high plasma resistance, then the electronic component becomes predominantly heated, whereas ion viscosity leads mainly to ion heating.

The investigation of the processes that broaden the CSF was carried out in two directions: 1) study of the spectrum of the microfluctuations of the electric and magnetic fields and its dependence on the conditions, making it possible to establish the nature of the turbulent processes; 2) study of the distribution of the macroscopic electric and magnetic fields in the CSF. Knowledge of this distribution in itself can provide an indication of the type of the dissipative mechanism.

For example, if the prevailing mechanism in the CMF is the high resistance of the plasma, then the front width is $\Delta \approx c^2/4\pi\sigma u_0$, and the equation for the magnetic field is of the form[4]

$$\frac{H}{n}=\frac{H_0}{n_0}+\frac{c^2}{4\pi\sigma u_0 n_0}\frac{dH}{dx}, \tag{1}$$

whence

$$n(x)\propto H(x-\delta x),\quad \delta x\approx c^2/4\pi\sigma u_0\approx\Delta,$$

where n(x) and H(x) are the distributions of the density and of the magnetic field in the wave, σ is the conductivity, and u_0 is the velocity of the wave. In the other case, when the resistance is small, but the viscosity is large, the front width is $\Delta \approx \eta/u_0$ (η—viscosity coefficient), and Eq. (1) takes the form $H/n = H_0/n_0$, i.e., $H(x) \propto n(x)$. The potential distribution should have a similar dependence on the nature of the dissipative mechanism, since it is uniquely connected with the distribution of the plasma velocity, and consequently with its density distribution (see formula (3) below).

2. EXPERIMENTAL SETUP AND PROCEDURE

The described experiments were performed with the UN-4 setup[1]. Plasma with density $n_0 \sim 10^{12}$—10^{14} cm^{-3}, placed in a quasistationary magnetic field $H_0 \sim 100$—1000 Oe in a cylindrical volume, was subjected to fast compression ($\Delta t \sim 50$—300 nsec) by an alternating field $H_\sim \sim (2$—$3) \times 10^3$ Oe, applied to the boundary (Fig. 1). The perturbations of the electric and magnetic fields produced in the cylindrical shock wave were registered with electric and magnetic probes. The magnetic probe used in the measurements was described in[1]. The electric probe for the measurement of the local potential difference comprised two metallic prongs in contact with the plasma exciting a coaxial feeder of

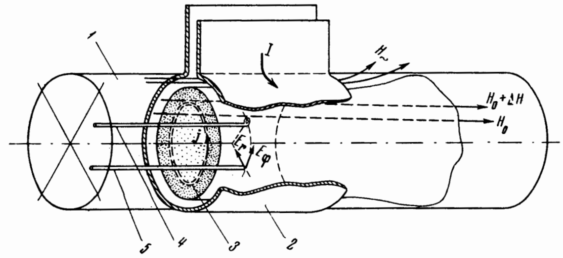

FIG. 1. Diagram of UN-4 setup: 1 – vacuum volume, 2 – shock loop, 3 – shock-wave front, 4 – magnetic probe, 5 – electric probes.

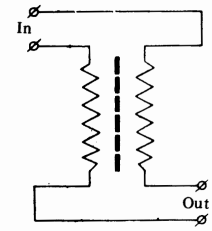

FIG. 3. Equivalent circuit of symmetrizing transformer.

small cross section (1 mm diameter) Fig. 2). The signal from the probe was fed to a broad-band oscilloscope with bandwidth 1000 MHz. The distance between the electrodes in contact with the plasma was 0.5–5 mm, the contact diameter was 0.2 mm, and the length 0.5–2 mm. The entire probe, with the exception of the electrodes, was encased in a glass insulator. To improve the frequency characteristic of the transmission channel, all the parts of the coaxial feeder were matched with an accuracy not worse than 10%. To avoid large high-frequency losses, quartz was used as the insulator in the coaxial cable.

The difficulties of measuring the local potential differences are due principally to the need for satisfying two requirements: 1) the probe in contact with the plasma must not short circuit the high potential produced on the shock discontinuity, and 2) the induced currents in the plasma, flowing through the external lead of the coaxial feeder, must not be diverted to the plasma. Satisfaction of these requirements excludes the possibility of transmitting the signal from the probe directly to the oscilloscope through a cable. It is also difficult to use the customary isolating transformer, owing to the small bandwidth and the large capacitive coupling between the windings. We therefore used a symmetrizing transformer, constructed in the following manner: the outer conductor of the coaxial cable, through which the signal was fed from the probe to the oscilloscope, was surrounded by ferrite rings, over which a conducting screen grounded near the probe was placed (Fig. 2). It can be verified that the equivalent circuit of such a transformer is that shown in Fig. 3. The "In" terminals were connected to the antennas of the probe, and the "Out" terminals to the oscilloscope; the core constitutes the ferrite ring. In this case, the impedance of the cable surrounded by the ferrite rings to the equalizing currents in grounding the plasma potential is large, since the currents flowing through the center and outer conductors of the coaxial cable, i.e., in both "windings" of the equivalent circuit, flow in the same direction, and the ferrite rings in their common magnetic field greatly increase the inductive reactance of the cable ($L\omega \gtrsim 1$ kohm). In this case the ferrite rings have no effect on the quality of the symmetrical signal fed to the input of the transformer, since the magnetic field of the symmetrical signal is contained inside the cable. The outer screen protects the transformer against external electromagnetic pickup. Such a scheme made it possible to decrease the noise to a negligible level.

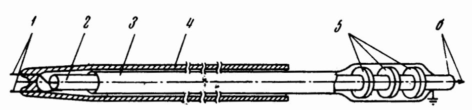

FIG. 2. Construction of electric probe: 1 – antennas in contact with the plasma, 2 – coaxial feeder, 3 – outer screen, 4 – glass insulator, 5 – –ferrite rings, 6 – coaxial output.

The question of the resistance of the plasma-probe transition layer was not investigated in detail, but it can be assumed, judging from the dependence of the measured value of the electric field on the distance between the probe antennas and from the closeness of this value to the expected one, that this resistance does not distort the result significantly (i.e., its value is smaller than the probe load resistance (75 ohm)).

For an exact temporal and spatial correlation of the electric and magnetic disturbances, we used a probe of combined construction, in which the output coaxial leads of the electric and magnetic probes were placed in a single glass tube.

To measure the correlations of the oscillations of the electric field, we used a triple electric probe comprising two probes of the construction described above and a single common electrode. In addition, to measure the wavelength of the electric oscillations, we used probes with different distances between electrodes (5–0.5 mm). The probe electrodes in contact with the plasma were located on a straight line oriented along the direction of the measured component of the electric field. The main experiments were performed with the aid of probes of the construction described above. To determine the extent to which these probes are subject to the influence of electric noise, we used a probe insulated from the conductors that were external with respect to the plasma. This probe constituted a crystal diode connected with the antennas in contact with the plasma, which glowed under the influence of the current. The light was transmitted through a dielectric light pipe and recorded with a photomultiplier. The experiments have demonstrated a good qualitative agreement between the signals from this probe and from the ordinary electric probe. A shortcoming of such a scheme is that the frequency band of the signal is limited both by the diode itself and by the photomultiplier.

3. EXPERIMENTAL RESULTS

A. Small Mach numbers $M = u_0/V_A < M_c$. (V_A—Alfven velocity, $M_c \sim 3–4$ is the critical Mach number). Figure 4 shows typical oscillograms obtained from the magnetic (b, e) and electric probes (a, c, d) following excitation of the shock wave in a plasma. Since the distance between the rods of the electric probes ($\sim 0.5–2$ mm) was much smaller than the spatial dimensions of the potential variation (~ 1 cm), the probes ac-

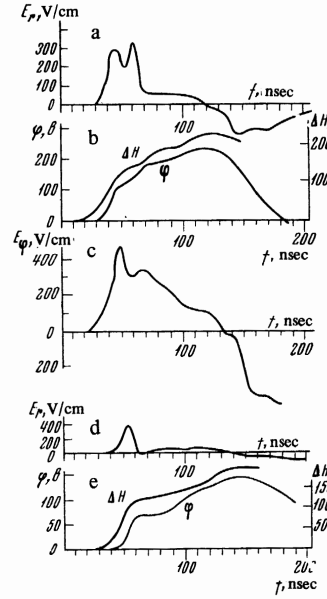

FIG. 4. Distribution of radial and azimuthal components of the electric field (a, c, d), and of the magnetic field and the potential (b, e) in the front of the shock wave. Hydrogen, $n_0 \sim 2 \times 10^{14}\,\mathrm{cm}^{-3}$ in cases a – c and $n_0 \sim 10^{14}\,\mathrm{cm}^{-3}$ in cases d and e. The signals a and d were obtained from probes with distances between prongs respectively 2 and 0.5 mm.

tually measured the electric field intensity (the potential difference between two close points).

The oscillograms (b, e) of Fig. 4 show the distribution of the potential φ in the wave, obtained by numerically integrating the signal from the probe that registered the radial component of the electric field E_r. We see that φ and the azimuthal component of the electric field E_φ, as well as the magnetic field, experience an abrupt jump connected with passage of the front. The width of the potential jump in E_φ is the same as the width of the magnetic field jump, and amounts to $10\ c/\omega_0$. The monotonic increase of H and φ behind the front is due to the adiabatic compression of the plasma layer behind the front, owing to the increase of the pressure of the magnetic piston. The compression is simultaneously accompanied by cumulation of the wave and its reflection from the axis. The variation of the electric field illustrates quite well the dynamics of the process. The negative peak of the radial component and the reversal of the sign of the azimuthal component of the electric field are connected with the reflection of the wave and with the change of direction of motion of the particles (due to the reflection of the wave and the diffusion expansion of the plasma column). The plasma velocity behind the wave front can be estimated from these oscillograms by various methods.

Indeed, knowing the azimuthal component of the electric field behind the wave, we can find the plasma drift velocity

$$v_i = cE_\varphi / H. \tag{2}$$

The same velocity can be determined from the equation of motion of the ions in the CSF (assuming them to be not magnetized): $m_i dv_i/dt = eE_r$, from which, in the laboratory frame,

$$v_i = u_0\left(1 - \sqrt{1 - \frac{2e\varphi}{m_i u_0^2}}\right), \quad \varphi = -\int_0^r E_r(\rho)\,d\rho \tag{3}$$

(φ—potential). If it is assumed that $Hv_i = H_0u_0$ behind the front (the freezing-in condition), where u_0 is the wave velocity and H_0 and H are the initial field and the field in the wave, then

$$v_i = u_0(1 - 1/h), \quad h = H/H_0. \tag{4}$$

For the oscillograms of Fig. 4, the velocities calculated from formulas (2)—(4) are respectively:

$$v_{i(2)} = 1.5\cdot10^7\ \mathrm{cm/sec}, v_{i(3)} = 1.3\cdot10^7\ \mathrm{cm/sec}, v_{i(4)} = 1.4 \times 10^7\ \mathrm{cm/sec}.$$

An essential feature of the distribution of the radial potential is the fact that it lags the profile of the magnetic field by an amount on the order of the front width. This gives grounds for stating that in this case the high resistance of the plasma plays an important role in the dissipation in the CSF.

Knowledge of the distribution of the electric and magnetic fields in the front makes it possible to determine the variation of the conductivity. Indeed, at each point of the front $j = \sigma(E_\varphi - v_iH/c)$, where j is the current density, E_φ is the azimuthal component of the electric field in the laboratory frame, which is measured by the probe, and v_i is the plasma velocity relative to the probe. We find the latter from (3). As a result

$$= \frac{j}{\left[E_\varphi - \frac{u_0}{c}H\left(1 - \sqrt{1 - \frac{2e\varphi}{m_i u_0^2}}\right)\right]} \approx \frac{\frac{c}{u_0}\frac{dH}{dt}}{4\pi\left[E_\varphi - \frac{u_0}{c}H\left(1 - \sqrt{1 - \frac{2e\varphi}{m_i u_0^2}}\right)\right]}$$

Another method of estimating σ is to measure the violation of the freezing-in of the magnetic field inside the shock discontinuity. Indeed, from Eq. (1) we get

$$\sigma \approx \frac{c^2 dH/dt}{4\pi u_0(vH - u_0H_0)}$$

(since $nv = n_0u_0$, where $v = (1 - 2e\varphi/m_iu_0^2)^{1/2}u_0$ is the plasma velocity in the coordinate system connected with the wave).

Generally speaking, the variation of σ in the front determines uniquely the profile of the magnetic field H, so that knowing the distribution of H in the wave we can plot the distribution of the conductivity. As shown in[4]

$$\frac{dH}{dx} = \frac{4\pi}{c^2}\sigma f(H),$$

from which we can find $\sigma(x) = F(H(x), dH(x)/dx)$. However, in the derivation of this formula it is necessary to use the conservation laws on the jump (the Hugoniot relations), which are valid only in the stationary case and can lead to an appreciable error if they are applied to a nonstationary process. In this sense, the first two methods of estimating σ are preferable.

Owing to the relatively small width of the front in a hydrogen plasma ($\Delta \sim 1$ cm), it is difficult to determine in detail the variation of the conductivity from the distribution of the electric fields. Such an investigation was carried out in an argon plasma, where the spatial and temporal widths of the front, at the same wave velocity, are much larger than in a hydrogen plasma.

Figure 5 shows characteristic oscillograms of the distributions of the magnetic and electric fields in a shock discontinuity in an argon plasma (a, b, c) and of the conductivity estimated by various methods (d). It is seen from the figure that the average level of the resistance in the CSF is precisely sufficient to explain the width of the latter, so that it can be concluded that the main contribution to the dissipation of the front is made by the resistance. As to its microscopic cause, it lies more readily, in accordance with the theoretical prediction[2-4], in the instability of the current in the CSF against buildup of various oscillations: either electrostatic (ion sound) or relatively low-frequency electromagnetic waves of the "whistler" type.

Experiments show that the presence of electric-field oscillations inside the front is typical mostly of a "dissipative" profile. These oscillations are clearly seen in Figs. 5b and 5c. An important attribute that makes it possible to establish the physical nature of these oscillations is the correlation length. To estimate this length, we recorded these oscillations with the triple probe described above. It turned that there were no phase correlations between the oscillations plotted with such a probe (its prongs were spaced 2 mm apart).

Another way of establishing the nature of the oscillations is to measure the wavelength. An exact measurement of the wavelength with electric probes is impossible if the wavelength is smaller than the distance between the probe antennas, but it is possible to determine its upper or lower limit from the dependence of the level of the oscillations, simultaneously received by two probes with different antenna spacings, on this distance. Experiments performed with probes having antenna spacings 2 and 0.5 mm have shown that the oscillation level received by the probes is the same. This means that the fluctuation wavelength is at least smaller than 0.5 mm (in this case the width of the front is $\Delta \sim 1-2$ cm and the Debye radius is $\sim 10^{-2}-10^{-5}$ cm). So small a wavelength excludes unambiguously the possibility that these oscillations are "whistlers," since $\lambda \sim \Delta$ for the latter[3].

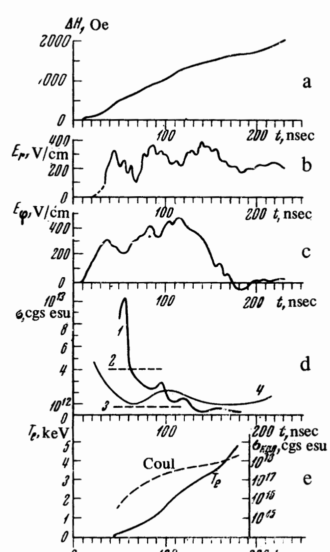

FIG. 5. Distribution of the magnetic field (a), of the radial and azimuthal components of the electric field (b, c), of the temperature (d), and of the conductivity (e) in the wave front: curve 1 – $\sigma = [c^2 dH / dx] / 4\pi(\nu H - u_0 H_0)$, 4 – $\sigma = j / (E_\varphi - \nu_i H / c)$, 2 – $\sigma = ne^2 / m_e \nu_{eff}$ (φ), 3 – $\sigma = c^2 / 4\pi u_0 \Delta$ (the level needed to ensure the front width Δ). σ_{Coul} – conductivity due to the electron-ion collisions. Argon, $n_0 \sim 2 \times 10^{13}$ cm^{-3}.

In addition, further evidence in favor of the ion-acoustic origin of the oscillations is the fact that their frequency is close to the ion Langmuir frequency $f \sim \Omega_0/2\pi$ (50–200 MHz at $n \sim 5 \times 10^{12} - 5 \times 10^{13}$ cm^{-3}), and also the fact that there are no oscillations of the magnetic field at this frequency (i.e., the observed oscillations are electrostatic). Other conditions needed for the excitation of ion sound are also satisfied, namely $v_e/c_s \gg 1$ (for argon, the ion-sound velocity is $c_s = \sqrt{T_e/m_i} \lesssim 2 \times 10^7$ cm/sec even at $T_e \sim 10$ kV, and $v_e > 10^8$ cm/sec).

As indicated in[4], at the ion-acoustic instability the electron temperature rises more rapidly than the ion temperature, with

$$\frac{d}{dt} T_e \Big/ \frac{d}{dt} T_i \gtrsim \frac{v_e}{c_s} \gg 1,$$

that is to say, in this sense this instability is self-maintaining. Experiments on the measurement of T_e and T_i[5,6] confirm the relation $T_e/T_i > 1$. This condition is unfavorable for the buildup of other types of oscillations, for example the magnetized ion sound considered in[7]. The fact that they were not registered in the CSF in a hydrogen plasma (Fig. 3) is apparently due to the excessively high oscillation frequency. Indeed, in the conditions under which these oscillograms were obtained ($n_0 \sim 10^{14}$ cm^{-3}), the frequency should be $f > 1{,}000$ MHz, which is higher than the limiting frequency of the transmission channels. In a hydrogen plasma, the fluctuations of the electric field with characteristic frequency $f \sim \Omega_0/2\pi$ were observed at a low density ($n_0 \sim 10^{12}$ cm^{-3}), i.e., under conditions close to critical at which the broadening of the CSF begins.

The level of the fluctuations of the electric field makes it possible to obtain the resistance due to the interaction between the electrons and the ion-acoustic waves (phonon friction), and consequently also the width of the front. Generally speaking, the level of the oscillations picked up by the probes may differ from the actual level of the fluctuations of φ in the plasma because $l \gg r_D$ and $d \gg r_D$ (l—length of probe antenna, d—its diameter, r_D—the Debye radius, which is the characteristic scale of the oscillations), and the estimate of $\tilde{\varphi}$ may include the factor $N = ld/2\pi r_D^2$. Different methods of taking this factor into account yield for the effective collision frequency, estimated by means of formula[4]

$$\nu_{eff} = k^3 \tilde{\varphi}^2 / 4\pi m_e v_e n, \quad k \sim 1/r_D, \tag{5}$$

values of the same order of magnitude as the experimental ones obtained from the expression

$$\nu_{eff} = 4\pi n e^2 u \Delta / c^2 m_e. \tag{6}$$

For example, in the typical case $n \sim 2 \times 10^{13}$ cm^{-3}, $T_e \sim 2$ keV, $r_D \sim 0.7 \times 10^{-2}$ cm, $N \sim 6-7$, $v_e \sim 2 \times 10^8$ cm/sec, $u_0 \sim 2.5 \times 10^7$ cm/sec, $\Delta \sim 3$ cm, the measured value $\varphi_{meas} \sim 15$ V. If it is assumed that $\tilde{\varphi} \sim N\varphi_{meas}$, then we get from (5) $\nu_{eff} \sim 1.5 \times 10^9$ sec^{-1}, and from (6) we get $\nu \sim 5 \times 10^9$ sec^{-1}.

We can note an interesting regularity in the variation of the conductivity in the CSF: it decreases sharply upon appearance of electric-field oscillations, within a time on the order of $(10-20)/\gamma$, where γ is the increment of the ion-acoustic instability. This agrees with the hypothesis that the buildup of ion-acoustic waves leads to the dissipation in the CSF.

The experimentally obtained values of j and σ inside the discontinuity make it possible to calculate the turbulent heating j^2/σ and the temperature T_e behind the front. The variation of T_e in the front is shown in Fig. 5e. The value of T_e agrees with the value measured from the diamagnetism of the electrons[5], and the value obtained by an electronic-computer solution of the corresponding problem.

It must be emphasized that the established regularities in the distribution of the parameters in the shock-wave front depend very little on the method of the shock-wave excitation, in agreement with[1]. A change in the character of the "piston" can lead to additional effects, which occur principally on the plasma boundary. Thus, in the case when the orientations of the fields $\mathbf{H}_0$ and $\mathbf{H}_\sim$ are opposite, during the earlier stage of formation of the piston there were observed intense oscillations of the electric field, localized in the region where the sign of the magnetic field is reversed. This effect, however, is connected mainly with the development of turbulent resistance in the current layer and with establishment of its effective width. The large magnitude of the current in the layer and its localization during the entire process in the peripheral region of the plasma make the mechanism of collisionless dissipation highly effective. But from the point of view of wave processes, this effect is principally manifest in the transient phenomena (prior to the detachment of the wave from the piston) and in the limitation of the region of conditional plasma parameters in which wave formation is possible.

Summarizing the foregoing results, we can state the following: when $n_0 > n_c$ and the amplitudes are sufficiently small ($M < M_c$), the main dissipation mechanism broadening the front is the high plasma resistance. The experimental results do not contradict the hypothesis advanced in[4] that the cause of such a superresistance is "phonon friction."

B. Large Mach numbers $M > M_c$. Let us examine the results pertaining to large Mach numbers. Earlier experiments[1,8] have shown that when $M > M_c$ there appears ahead of the front an elongated gently sloping section, a "pedestal," which broadens with increasing M. An important result of the described experiments is the establishment of a variation of the character of the distribution of the electric fields inside the jump when $M \sim M_c$. Thus, when the wave amplitude approaches the critical value, a decrease was observed in the lag of the potential profile relative to the magnetic field profile (Fig. 6), and a section with large slope (larger than the slope of the magnetic-field profile) appeared on the potential profile. This phenomenon is analogous to the isomagnetic density jump observed in[9]. Such a result is natural, since the velocity of the ions behind the wave front, and consequently also their density, are determined by the electric fields, and the steepening of the density profile should be connected with the steepening of the potential profile.

These effects cannot be explained if it is assumed that the increase of the width of the jump at $M \gtrsim M_c$ is due only to resistive dissipation.

The condition $M > M_c$ is characterized by a change of the spectrum of the electromagnetic fluctuations. Figure 7 shows oscillograms of the distribution of the derivative of the magnetic field (b, d) and of the radial

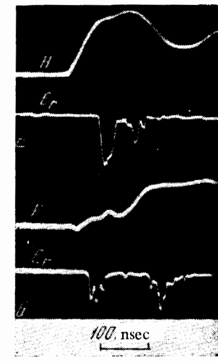

FIG. 6. Change in the lag of the electric-field profile relative to the magnetic-field profile: a—$n > n_c$, $M < M_c$; b—$n > n_c$, $M > M_c$. The electric signals were obtained with the aid of a diode pickup.

component of the electric field (a, c), plotted under different conditions: when $M < M_c$ and $M > M_c$. The profile of the magnetic field at $M > M_c$(d) has a "pedestal" elongated forward which is typical for large M, whereas when $M < M_c$ the front of the wave is relatively steep (b). At small Mach numbers (a, c) there exist inside the CSF electric-field oscillations characteristic of a dissipative front, with frequency $f \sim \Omega_0/2\pi \approx 200$ MHz at $n \sim 3 \times 10^{13}$ cm^{-3}, but at large M no fluctuations with such a frequency are observed, but slower oscillations of the electric and magnetic fields on the "pedestal" and in the front appear. It has been shown by the method described above that their wavelength is $\lambda \sim c/\omega_0$.

Measurements have shown that the quantity $2e\Delta\varphi/m_i(u_0^2 - v^2)$ (where $\Delta\varphi$ is the jump of the potential on the front and v is the velocity of the plasma behind the front in the coordinate system connected with the wave) is close to unity when $M < M_c$, in agreement with the result of[8]. However, as was observed, when $M \sim M_c$ this quantity decreases and becomes of the order of 1/2 at large M. Simultaneously, a second jump of the radial component of the electric field appears in the region of the piston (Fig. 8).

All these phenomena can be given a reasonable physical interpretation within the framework of the notion of turbulent processes in the CSF at large M. According to these notions[2], when $M > M_c$ the increasing influence of the nonlinearity leads to the so-called "overturning" of the wave front, which is accompanied by the appearance of opposing ion-ion streams. But such streams, as shown in[10] are unstable against the buildup of electromagnetic oscillations with characteristic scale c/ω_0 and with frequency of the order of the hybrid

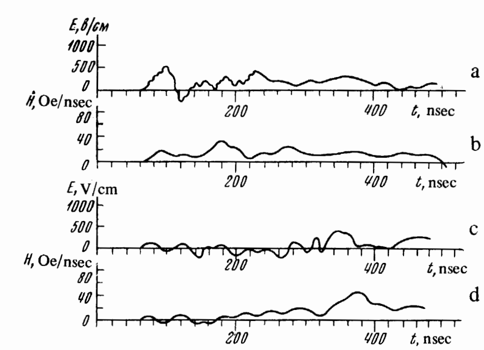

FIG. 7. Fluctuations of electric and magnetic fields in the front: a, b—$M < M_c$, c, d—$M > M_c$. Argon, $n_0 = 3 \times 10^{13}$ cm^{-3}; in cases a and b—H_0 = 1000 Oe, M = 1.5; in cases c and d—H_0 = 600 Oe, m = 3.

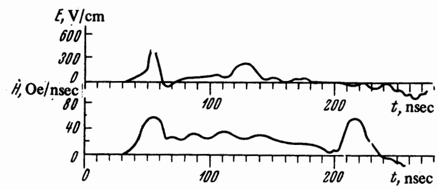

FIG. 8. Distribution of the derivative of the magnetic field and of the radial component of the electric field along a perturbed plasma layer when $M > M_c$. Successive peaks of E_r: in the front, on the piston, in the front of the reflected wave. Hydrogen, $n_0 \sim 1.5 \times 10^{14}\,cm^{-3}$; $H_0 = 400$ Oe, $M = 4$.

Larmor frequency

$$\omega_r / 2\pi = \sqrt{\omega_H \Omega_H} / 2\pi.$$

The appearance of oscillations with dimension¹⁾ c/ω_0 and frequency $M\omega_h/2\pi$ when $M > M_c$ can be interpreted as a manifestation of instability of the ion-ion streams. Excitation of oscillations leads to an effective ion viscosity in the transition region. This viscosity dissipation should thermalize the ions and lead to the increase of ion pressure behind the front. However, in the presence of ion pressure behind the front, the potential decreases by an amount $\Delta p_i/ne$, for in this case

$$-m_i n \frac{dv_i}{dt} = ne\nabla\varphi + \nabla p_i, \quad \frac{m_i}{2}(u_0^2 - v^2) = e\Delta\varphi + \frac{\Delta p_i}{n}.$$

Owing to the decrease of the slope of the front, the azimuthal velocity of the electrons decreases, and the conditions for the buildup of ion sound become worse. This possibly explains the sharp decrease of the intensity of the electric oscillations with $f \sim \Omega_0/2\pi$ when $M > M_c$ (Fig. 7c).

The appearance of the second jump of the electric field on the piston is apparently likewise connected with the thermalization of the ions. Indeed, at high ion pressure behind the front there should exist on the plasma boundary an electric field that maintains this pressure. Generally speaking, thermalization of ions behind the front may also be incomplete. But to explain the described effects it is essential, apparently, only to have a group of ions moving with different velocities. In this case "temperature" should be taken to mean a quantity of the order of $m_i\tilde{v}^2/2$, where $\tilde{v}$ is the average velocity of the relative motion of the ion streams.

Knowing the level of the electric fluctuations, we can attempt to estimate the steady-state width of the front due to the viscosity dissipation. According to[6]

$$\Delta \sim \frac{c}{\omega_0}\left(\frac{e\tilde{\varphi}}{m_i v_A^2}\right)^{-2}.$$

In an argon plasma (at $\tilde{\varphi} = 20$ V the Alfven velocity is $v_A \sim 0.3 \times 10^7$ cm/sec), the experimental values of $m_i v_A^2/e\tilde{\varphi} \approx 10-20$, giving for Δ a value close to $c/\Omega_0 = 270\, c/\omega_0$. A similar result is obtained if Δ is estimated from the amplitude of the magnetic-field fluctuations: $\Delta \sim (c/\omega_0)(H_0/\tilde{H})^2$ (assuming that $k\tilde{H} = 4\pi Ene/H_0$). In a typical case we have $H_0 \sim 300-500$ Oe and $\tilde{H} = 20-50$ Oe. In an argon plasma, however, the front did not reach the "quasistationary" phase, since under the experimental conditions we had $c/\Omega_0 \gtrsim R_{tu} = 8$ cm (R_{tu}—radius of tube).

Generally speaking, the foregoing does not exclude the ion-acoustic mechanism of viscosity, which is possible under conditions when opposing ion streams move, since the fluctuation level necessary to ensure such a front width is lower than the sensitivity of the receiving apparatus.

Generalizing all the foregoing results, we can propose the following picture of the physical processes in the CSF: at an initial plasma concentration $n > n_c$ inside the CSF, ion-acoustic waves build up, excited by an electronic current in the front. The friction of the electrons against the ion waves causes a purely resistive dissipation, which balances the nonlinear effects (at a front width $\Delta \gg c/\omega_0$), and causes effective heating of the electrons. Such a balance of the dissipative and nonlinear effects can be maintained only when $M < M_c$. When $M > M_c$, the nonlinear steepening, which is no longer halted by the dissipation, leads to a turning over of the front of the wave and to the appearance of opposing streams, a factor established by direct measurements of the energy spectrum of the ions[5]. In these streams there are excited electromagnetic oscillations which lead to the "ion viscosity." The ion pressure behind the front begins to influence the dynamics of the wave. The resistive mechanism apparently does not play a decisive role in the formation of the "steady-state" front after the overturning. An estimate of the width of the front, due to the viscosity, from the level of the electromagnetic fluctuations $\tilde{E}$ and $\tilde{H}$, gives a value close to c/Ω_0.

In conclusion, the authors are sincerely grateful to R. Z. Sagdeev for fruitful discussions and for help with the work.

¹⁾The observed frequency is determined by the Doppler effect and equals

$$\frac{u_0}{2\pi c/\omega_0} = \frac{Mv_A}{2\pi c/\omega_0} = \frac{M\omega_r}{2\pi} \sim 30 \text{ MHz}$$

when $H_0 = 600$ Oe and $M \sim 4$.

[1] R. Kh. Kurtmullaev, Yu. E. Nesterikhin, V. I. Pil'skiĭ, and R. Z. Sagdeev, 2nd Internat. Conf. on Plasma Physics, Culham, 1965, Report CN 21/218.

[2] R. Z. Sagdeev, Voprosy teorii plazmy (Problems of Plasma Theory) 4, Atomizdat, 1964, p. 20.

[3] M. Camac, A. R. Kantrowitz, M. M. Litvac, R. M. Patric, and H. E. Petshec, Salzburg Conference, 1961, Paper CN-10/132. L. I. Rudakov, Paper at Internat. Conf. on Shock-wave Physics, Novosibirsk, 1967.

[4] A. A. Galeev and R. Z. Sagdeev, Lectures on the Non-Linear Theory of Plasma, Trieste, 1966.

[5] R. Kh. Kurtumullaev, V. I. Pil'skiĭ, and V. N. Semenov, Issledovanie élektronnogo nagreva za frontom udarnoĭ volny v plazme zondovym metodom (Investigation of Electron Heating Behind the Front of a Shock Wave in a Plasma), Preprint, Novosibirsk, 1968.

[6] S. G. Alikhanov, A. I. Alinovskiĭ, G. G. Dolgov-Savel'ev, V. G. Eselevich, R. Kh. Kurtmullaev, V. K. Malinovskiĭ, Yu. E. Nesterikhin, V. I. Pil'skiĭ, R. Z. Sagdeev, and V. N. Semenov, 3rd Internat. Conf. on Plasma Physics, Novosibirsk, 1968, Report 24/A-1.

[7] V. I. Aref'ev, I. A. Kovan, and L. I. Rudakov, ZhETF Pis. Red. 7, 286 (1968) [JETP Lett. 7, 223 (1968)].

[8] J. W. M. Paul, L. S. Holmes, M. J. Parkinson, and J. Sheffield, Nature 208, 133 (1965).

[9] R. Kh. Kurtmullaev, V. L. Masalov, K. I. Mekler, and V. I. Pil'skiĭ, ZhETF Pis. Red. 7, 65 (1968) [JETP Lett. 7, 49 (1968)].
[10] B. B. Kadomtsev, Fizika plazmy i problema upravlyaemykh termoyadernykh reaktsiĭ (Plasma Physics and the Problem of Controlled Thermonuclear Reactions) 4, AN SSSR, 1958, p. 364.

Translated by J. G. Adashko
168