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INVESTIGATION OF THE ION SPECTRUM OF A PLASMA HEATED BY A SHOCK WAVE

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The energy spectra of the ions in a plasma heated by a shock wave are investigated by the passive corpuscular diagnostics technique. It is shown that at large Mach numbers ($M \gtrsim 3-4$) the single-velocity motion of the ions in the plasma current is violated up to the instant of wave cumulation on the system axis. This can be attributed to the breaking of the shock wave front under these conditions. The experimental relative width of the energy spectrum of the particles emitted in the longitudinal and transverse directions indicates a strong collisionless dissipation of energy under all conditions investigated.

ONE of the most interesting problems connected with collisionless shock waves is the mechanism of wave-energy dissipation under conditions when the pair collisions are negligible. The investigation of this problem has two aspects, namely the explanation of the structure of the shock-wave front, which is closely connected with turbulent dissipation occurring in the front, and the establishment of the relative efficiency of heating of the electron and ion components of the plasma as a function of the initial conditions and parameters of the wave.

A number of experimental investigations (see, for example,[1] performed by various direct and indirect methods have shown that the energy dissipation in the front of a wave, at Mach numbers $M = u/v_A < M_c = 3-4$ (u—wave velocity, v_A—Alfven velocity), is due principally to the turbulent resistance, and causes a predominant heating of the electrons (in agreement with the theory of[2]). However, the results obtained at $M > M_c$[3] give grounds for assuming that the heating of the ion component becomes appreciable under these conditions.

The picture of the development of the physical processes in the wave front when $M > M_c$ (the formation of an elongated pedestal and the appreciable broadening of the front[4], the change of the relative shift of the profiles of the velocity and of the magnetic and electric fields, the change of the spectrum of the electromagnetic fluctuation[5], and others) agrees with the hypothesis advanced by Sagdeev[6], concerning the breaking of the strong shock wave, the formation of interpenetrating ion streams, and the development of ion-ion instability. In the described experiments, which continue this research, we attempt to establish directly the violation of the single-stream character of the ion motion behind the wave front, the randomization of the ion velocities, and the dependence of these effects on the phase of the wave process.

Information on the energy spectrum of the ions in the plasma was obtained as a result of a study of the energy distribution of the flux of neutral charge-exchange particles with the aid of a gas stripping chamber and differential charged-particle energy analyzer (in analogy with the procedure used in[7]).

EXPERIMENTAL SETUP

Experiments were performed with the UN-4 apparatus[8], a diagram of which together with the diagnostic apparatus is shown in Fig. 1. The plasma was produced in a cylindrical glass volume of 16 cm diameter in a quasistationary magnetic field ($H_0 = 10^2-10^3$ Oe) and was compressed by a rapidly growing magnetic field ($H_\sim = 2-3$ kOe) obtained by discharging a low-inductance capacitor ($c = 0.6$ μF, $U = 40$ kV) through a surge coil. The produced cylindrical shock wave propagated towards the axis and was cumulated. Its velocity and the transformation of the shock front were determined with the aid of two magnetic probes located at different distances from the system axis.

The diagnostic apparatus consisted of a gas stripping chamber (stripping on hydrogen, $p \approx 6 \times 10^{-4}$ mm Hg) and an electrostatic charged-particle energy analyzer

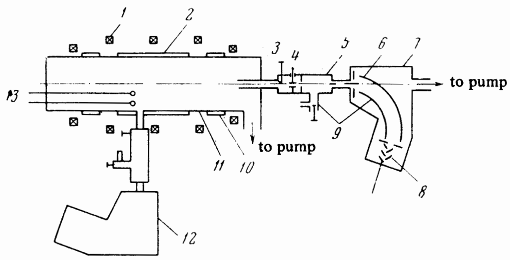

FIG. 1. Experimental setup: 1—quasistationary magnetic field coil, 2—ringing loop, 3—vacuum valve, 4—deflecting capacitor, 5—stripping chamber, 6—cylindrical capacitor, 7, 12—charged-particle energy analyzers, 8—electron multiplier, 9—leak valve, 10—preionization loop, 11—vacuum chamber, 13—magnetic probes.

based on a cylindrical capacitor[9]. The ions were registered with the aid of an open electron multiplier (EM) of the VÉU-OT-8M type. A capacitor was placed at the entrance to the stripping chamber to deflect the ions that might travel together with the neutral particles along the magnetic field and thereby greatly complicate the observed picture. The ion channel was screened against the action of the quasistationary magnetic field.

More detailed information on the construction of the diagnostic apparatus and on the results of its calibration is given in[10].

The relatively high additional gain ($\sim 10^4$) due to the small level of the signal, and the high level of the high-frequency noise from the power apparatus used to excite the shock wave, required special measures (a screened chamber, low-noise plugs and cables, etc.) to ensure complete suppression of the electromagnetic induced noise. All the main experiments were performed with the aid of two simultaneously switched analyzers. One of them, the "longitudinal" one, was connected to the surface end of the apparatus (2 cm away from the axis). The second, "transverse," analyzer was connected in diametral and chordal directions (2 cm away from the diameter) approximately in the center of the loop.

REQUIREMENTS IMPOSED ON THE DIAGNOSTICS METHOD

Investigations of fast processes in a plasma impose stringent requirements on the diagnostic methods with respect to the spatial and temporal resolutions, accuracy of time reading, and sensitivity.

The spatial resolution should correspond to the characteristic scale—the width Δ of the shock front. For relatively small Mach numbers ($M < M_c$) in a hydrogen plasma we have $\Delta \sim 10\ c/\omega_0 \approx 0.8$–$1.7$ cm at $n_0 = (1-5) \times 10^{13}$ cm^{-3} [8] (ω_0—electron Langmuir frequency). At large Mach numbers ($M > M_c$), the front width increases, reaching $\Delta \sim c/\Omega_0$[8] (Ω_0—ion Langmuir frequency), and therefore the quasistationary wave was studied at $n_0 \gtrsim 10^{14}$ cm^{-3}, when the front width $\Delta = 2-3$ cm was smaller than the radius $R = 8$ cm of the volume.

The requirement on the time resolution is determined by the parameter $\tau = \Delta/u$, where $u = Mv_A = MH_0/\sqrt{4\pi n_0 m_i}$ (m_i—ion mass). For $M = 2-4$, $H_0 = 10^2-10^3$ Oe, and $n_0 = 5 \times 10^{13}-10^{14}$ cm^{-3}, the wave velocity u lies in the range $(1-6) \times 10^7$ cm/sec. The values of τ are therefore 20–30 nsec for $M < M_c$ and 150–250 nsec for $M > M_c$. The employed apparatus satisfied these requirements. Thus, at the attained sensitivity, which ensured reliable registration of the signal, the angle aperture of the analyzer was $\sim 10^{-2}$ rad, making it possible to "examine" a section with a linear dimension not exceeding 7–8 cm on the axis of the plasma setup. The time resolution was determined mainly by the bandwidth of the electronic circuitry. The signals from the magnetic probes and from the electron multipliers were registered with the aid of DÉSO-1 oscilloscopes, which together with additional amplifiers ensured a bandwidth $\Delta f \approx 60$ MHz.

The absolute error in the determination of the time should be at least one order of magnitude smaller than the time of convergence of the wave to the axis $\Delta t = R/u = 250-400$ nsec, i.e., in our case it must not exceed 30–40 nsec. This requirement is particularly difficult to satisfy when low-energy particles are registered, since their time of flight through the analyzer amounts to several microseconds. In this case, to increase the accuracy, the signal triggering of the oscilloscope that registered the signal from the electron multiplier and the strobing pulse that started the counting were delayed with the aid of a twin-pulse generator by a time interval somewhat smaller than the time of flight. Control measurements have shown that the maximum error resulting from the instability of the generator and the recording apparatus does not exceed 30–40 nsec, at the maximum delay ($\sim$3–4 μsec). The introduced delay makes it possible to register the signal with relatively short sweeps of the oscilloscope (0.6 and 1.2 μsec), thereby ensuring the required counting accuracy.

In the determination of the particle time of flight, we took into account the delay of the signal in the electron multiplier and in the signal cables ($\sim$40 nsec).

The finite energy width of the analyzer slits (6%) also introduces an error in the time reading, but this error can be taken into account by assuming that the start of the signal is due to the arrival of the faster particles from the energy interval.

In the investigation of fast processes in the plasma it is possible (at any rate in their initial stage) to neglect the entry into the plasma of the neutral gas desorbed from the chamber walls, which in the case of slow processes[6] is the most probable charge-exchange target for the ions. In our case, the charge exchange should occur mainly with the neutral particles of the plasma. On the basis of this statement, we can estimate the order of magnitude of the diagnostic apparatus sensitivity needed to register the signal. A rough estimate shows that for a plasma with ion density $n_i \sim n^{13}-n^{14}$ cm^{-3}, degree of ionization 90%[1)], and ion temperature $\sim 10^2$ eV, the equivalent currents of the neutral particles in the solid angle subtended by the analyzer are of the order of $10^{-6}-10^{-8}$ A. Taking into account the coefficient of conversion of the neutral particles into charged ones ($\alpha = 10^{-4}-10^{-2}$) in the

[1)]This quantity is estimated from the initial gas pressure in the volume and the electron density after preliminary ionization, with allowance for the contraction of the plasma in the wave.

stripping chamber and the sensitivity of the DÉSO-1 oscilloscope ($\sim 10^{-3}$ A/cm at 75 ohm input resistance), we find that the additional current gain should be of the order of 10^9. This is produced by an electron multiplier ($\sim 10^5$) and an additional amplifier ($\sim 10^4$).

PROCEDURE FOR THE REDUCTION OF THE EXPERIMENTAL DATA

Let us examine the procedure used to obtain from the experimental data information concerning the ion energy distribution function, and concerning the ion temperature if this distribution is close to Maxwellian.

A series of oscillograms of the signals from the electron multiplier anode is usually obtained for each investigated regime; each series corresponds to the ions having the energy to which the analyzer is set (more accurately, the ion energies lie in a narrow interval that is symmetrical with respect to this setting). The stability of the plasma apparatus is continuously monitored by watching the signals from the magnetic probes.

The time correlation of the ion signals with one another and with the phases of the wave process, which is needed to obtain information on the energy spectrum of the particle, is determined, as will be shown below, by constructing space-time pictures of the wave process and of the motion of the registered particles. It should be noted here that greatest accuracy can be attained for those phases of the investigated process, to which the "smoothest" sections of the registered signals correspond.

The flux of neutral particles leaving the plasma, which determines the amplitude of the signals in the oscillograms, is proportional both to the density of the "heated" part of the ions and to the density of the neutral atoms that are contained in the plasma as a result of its incomplete ionization. From this, for example, it follows that to determine the distribution function in absolute units it is necessary, besides having the signals correspond in time with one another and with a definite phase of the wave process, also to know the time variation of the density of the neutral gas in the plasma, information which is difficult to obtain when the plasma is highly ionized. It becomes necessary therefore to confine oneself to the determination of the ion energy distribution function in relative units, which can be obtained with the aid of the following expression[10]:

$$f(E)=\frac{dn_i}{dE}=\frac{I\exp(\sigma n_i'x)^{\gamma}}{K\alpha E^{3/2}\sigma B}, \tag{1}$$

where I is the output current of the electron multiplier, K is the gain of this multiplier, α is the coefficient of conversion of neutral particles into charged ones in the stripping chamber, B is a coefficient independent of the energy, $\gamma = \exp(\sigma n_i' x)$ is the coefficient that takes into account the attenuation of the neutral beam in the transverse magnetic field on passing through the cold plasma (of thickness $n_i' x$) surrounding the emission region, and σ is the cross section for the charge exchange of a hydrogen atom with a proton.

Allowance for the coefficient γ is essential in the case of a sufficiently thick "jacket" ($n_i x > 10^{15}$ cm^{-2}) of a cold plasma surrounding the emission region. In the opposite case we have $\gamma \sim 1$. From the form of the energy dependence of the charge-exchange cross section[11] we can conclude that neglect of the attenuation of the flux of neutral particles as they pass through the plasma "jacket" leads to a certain overestimate of the ion temperature (calculation shows it to be $\sim$30% at $n_i' x \approx 10^{15}$ cm^{-2}).

Expression (1), as expected has the same functional dependence on the energy as the analogous expression used in[7] and derived on the basis of a theoretical analysis of the problem by Konstantinov and Perel'[12] for the case when the flux and neutral particles is produced as a result of the charge exchange of ions by neutral atoms entering into the plasma from the walls. Indeed, one can hardly expect any difference in the functional dependence on the energy in these expressions, if the ion charge exchange is with neutral atoms that are contained in the plasma as a result of its incomplete ionization, or come from the walls.

It is of interest to compare the obtained distribution functions with the Maxwellian function. The comparison makes it possible to see the degree of deviation from the equilibrium function, and if this deviation is small, it becomes possible to determine the ion temperature T_i. The detailed derivation, obtained in[10] assuming an isotropic Maxwellian distribution function with allowance for the influence of the small aperture angle of the ion detector on the energy spectrum in the registered particles, shows that the following relation should be satisfied:

$$\ln\frac{I\exp(\sigma n_i' x)}{K\alpha E^2\sigma}=-\frac{E}{kT_i}+\ln C, \tag{2}$$

where k is Boltzmann's constant and C is an arbitrary constant. Expression (2) is the equation of a straight line, from the slope of which it is possible to determine the ion temperature.

A similar relation obtained assuming another extreme case, namely the case of an anisotropic Maxwellian function (which, as seen from the experiment, is less realistic), gives for the ion temperature a value larger by 1.5–2 times. If the distribution function is far from Maxwellian, then the degree of randomization of the ions can be estimated from the relative width of the energy spectrum.

In our case, the measured distribution function may be distorted by the translational motion of the particles in the wave, and may therefore differ from a Maxwellian in an energy region close to the region of the translational motion of the ions in the wave. This circumstance does not make it possible to use the low-energy interval to determine the ion temperature. Therefore all the ion temperatures presented above were determined from the high-energy part of the distribution function, where the influence of the translational velocity of the particles does not come into play. As shown by the measurements, the dependence (2) is practically always approximated by a straight line, thus indicating at least a tendency towards establishment of a Maxwellian distribution.

EXPERIMENTAL RESULTS

Measurements made with the aid of an electrostatic analyzer make it possible to investigate the distribution of the ion velocities in a plasma stream and the dependence of this distribution on the Mach number. In the case of a small deviation of the distribution from equilibrium, these measurements, as already noted, make it possible to determine the ion temperature of the plasma at different phases of the wave process.

A direct proof of the violation of the single-stream motion of the ions at large Mach numbers ($M > M_C$) might have been the registration, with the aid of a "transverse" analyzer, of particles moving in the direction opposite to the direction of the motion of the front and starting their motion prior to the instant of cumulation of the wave on the axis of the system. Consequently, one of the main problems of the present investigation was to determine the location of the start of the registered particles inside the plasma and the instant of this start relative to the start of the wave process. The problem was solved with the aid of space-time pictures of the wave process and of the motion of the registered particles, which showed the time variation of the positions of the shock-wave front, of the magnetic plunger, and of the registered particles (see Fig. 2).

To construct the space-time picture of the wave process with required accuracy, it was sufficient to use two magnetic probes ($r_1 = 24$ mm and $r_2 = 38$ mm). Knowing the instants (t_1 and t_2) of the passage of the front through the coordinate (r_1 and r_2) of the probes, it was possible to plot the trajectory of front motion, by drawing a straight line through the points (t_1, r_1) and (t_2, r_2) (i.e., by assuming the velocity of the wave propagation to be constant in the region $r < r_2$). The instant of wave cumulation is determined by the intersection of this straight line with the time axis. The trajectory of motion of the magnetic plunger approximately up to the instant of wave cumulation is determined in a similar manner. The entire subsequent picture of its motion, starting with the instant of maximum compression of the plasma column, is represented qualitatively.

The space-time picture of motion of the registered particles is plotted on the basis of known data: the distances between the ion detector and the radius of the plasma volume, the time of entry of the particles into the analyzer (relative to the start of the process), and the particle energy. First one determines the position of the registered particles on the time axis at the instant when they cross the boundary of the plasma volume, and then a straight line, with a slope determined by the particle velocity, is drawn from the coordinates of the intersection points. This line, which represents the particle trajectory from the starting point, is the geometric locus of the possible start of the particles. The true locus and the instant of start are determined from the intersection of the trajectories of the particles and that part of the space-time picture on the wave process, in which the heating and charge exchange of the ions are most probable. In particular, if one makes the natural assumption that violation of the single-stream motion occurs in the front of the wave and that the particles at the instant of wave breaking begin to move backwards relative to the front propagation direction, then the location and the instant of the start are determined by the point of intersection of the particle trajectory and the front trajectory. Such space-time pictures (Fig. 2) have been constructed for the transcritical $M > M_C(a)$ and subcritical $M < M_C(b)$ regimes, and Fig. 3 shows the typical oscillograms of the signals from the magnetic probe and from the electron multiplier anode obtained under these conditions for ions of different energy. The signals from the electron multiplier are aligned with the probe signals, with account taken of the time of flight of the ions from the axis of the plasma volume to the recording system of the analyzer (i.e., in this figure, the time agreement between the signals is exact only for the instant of wave cumulation).

Let us examine a regime with large Mach numbers, $M > M_C$ ($H_0 = 300$ Oe, $h = H_\sim/H_0 \approx 4.5$). As the wave moves towards the center of the plasma volume, its amplitude increases and reaches the critical value at a distance 3—4 cm from the axis of the system, as is clearly revealed on the magnetic-probe signal by the appearance of a "pedestal" ahead of the shock jump (Fig. 3a). As seen from Fig. 2a, the starting region of the particles that move "backward" relative to the front coincides within 1—2 cm with the region where the wave-front structure changes. (The starting region of the particle, shown in Fig. 2, was obtained with allowance for the width of the front and for the energy width of the analyzer slits.)

The results offer evidence that when $M > M_C$ the

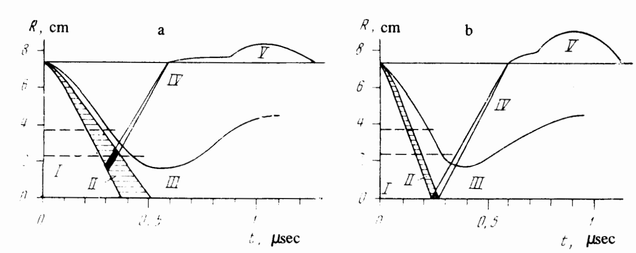

FIG. 2. Space-time picture of the process and of the motion of the registered particles, (a – $M > M_C$, b – $M < M_C$): I – region of unperturbed plasma, II – shock front, III – region of perturbed state and of the plasma, IV – trajectory of registered particles with energy 144 eV, V – profile of signal from ions of energy 144 eV. The dashed lines show the locations of the magnetic probes.

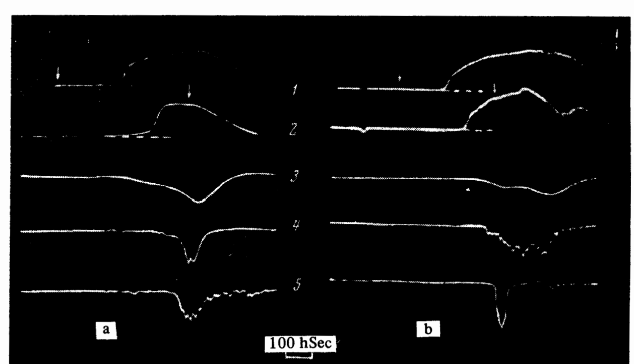

FIG. 3. Typical oscillograms of signals from the magnetic probes (1, 2) and from the anode of the electron multiplier, for ions with energies 0.15 keV (3), 1 keV (4), 1.5 keV (5), a – $M > M_C$, b – $M < M_C$). The arrows indicate the start of the process and the instant of cumulation of the wave.

plasma stream contains ions having velocities directed opposite to the stream velocity, i.e., the single-stream flow of the plasma is violated, as predicted in[6] for the "broken" front.

Starting with this instant and up to the cumulation of the shock front, the ion signal grows slowly. In the energy spectrum corresponding to this section of the signal, ions are registered with a maximum of energy up to ~500 eV, amounting to $(3-4)mu^2/2$. The maximum energies of the ions registered by a "transverse" analyzer located on the chord reached 2 keV (see Fig. 4). The ion temperature obtained by the previously described procedure amounts to 70–100 eV ($n_i \approx 3 \times 10^{14}$ cm^{-3}), which agrees with the translational ion energy in the wave. The form of the ion energy distribution function is shown in Fig. 4. The aggregate of facts obtained for $M > M_c$ indicates at least a partial randomization of the ion velocities in the region under consideration.

When the wave converges on the axis, the ion yield from the cumulation region increases, and the slow growth of the ion signal gives way to a steeper phase of the main signal (Fig. 2a). The subsequent changes are connected with the adiabatic compression of the plasma column by the growing magnetic plunger and subsequent motion of the wave towards the chamber walls after reflection from the axis.

The energy distribution of the ions that start from the cumulation region has a maximum at $E \approx 250$ eV (Fig. 4). The spectrum itself is quite broad—the maximum energy reaches $E \approx 1.6$ keV, which is approximately 10 times the translational energy of the ions in the wave. The form of the spectrum is shown in Fig. 4. The "diametral" and "chordal" measurements yield in this case practically identical results.

If it is assumed that upon cumulation the entire translational energy of the wave goes over into heat, an account is taken of the heat resulting from the adiabatic compression of the plasma column by the magnetic plunger, then the ion temperature calculated under this assumption turns out to be sufficiently close to the value of the temperature obtained from the distribution function.

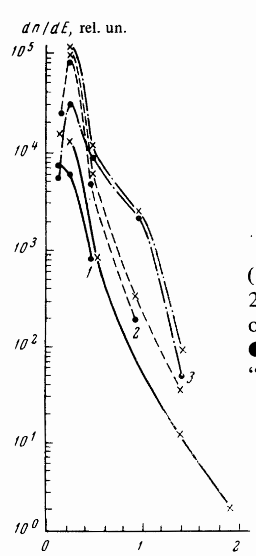

FIG. 4. Energy spectrum of the ions ($M > M_c$). Phases: 1 – breaking of the wave, 2 – cumulation of the wave, 3 – cumulation of the wave excited in the second half-cycle; ● – "diametral" measurement, × – "chordal" measurement.

The data from the longitudinal analyzer, unfortunately, cannot be used for a sufficiently accurate determination of the location and instant of the start of the particles, since the time of their motion along the surge loop exceeds the time of motion of the wave to the system axis. Therefore the results obtained with a longitudinal analyzer are used to determine the degree of isotropy of the distribution function, averaged over the time interval equal to the uncertainty in the particle production time.

Simultaneous registration of the ions traveling along and across the system demonstrates that the longitudinal and transverse temperatures $T_{i\parallel}$ and $T_{i\perp}$ are quite close to each other (see Table I).

In this experiment, the external magnetic field $H_\sim$ exciting the wave (magnetic plunger) changes sinusoidally in time. Therefore the phase of maximum compression is followed by a decrease of $H_\sim$ to zero, leading to adiabatic expansion of the plasma. The cooling of the plasma during this phase of the process is demonstrated, for example, in Fig. 3 by the slower decrease of the signals corresponding to the ions with relatively low energies. However, the *ion temperature* was not measured by us during this phase, owing to the difficulties with the time correlation on the decreasing part of the signals.

During the cumulation of the wave excited in the second half cycle of the surge-loop current, the temperature, as seen from Table I, increases insignificantly (~30%) compared with the temperature occurring when the wave cumulation takes place in the first half-cycle.

Let us consider a shock wave with $M < M_c$ ($H_0 \approx 1$ kOe, $h = H_\sim/H_0 \approx 2$). With increasing wave amplitude, the region of the start of the particles gradually shifts towards the axis of the system, and when $M < M_c$ the start of the signal from the analyzer corresponds to the instant of the wave cumulation on the axis or to later processes (reflection on the wave, etc.). Figure 2b shows the space-time picture for this case. We see that the "backward" motion of the particles relative to the front motion and prior to the start of the wave cumulation is not observed in this case. This confirms additionally the hypothesis that explains the violation of the single-stream motion in the wave at Mach numbers $M > M_c$, and the heating of the ions in the front of this wave.

It is seen from the results that when $M < M_c$ ion heating is due only to cumulative effects, since prior to the instant of cumulation there is no violation of the single-stream regime. Further growth of the ion signal, just as when $M > M_c$, is connected with the reflection of the wave from the axis and with the adiabatic compression of the plasma column by the growing magnetic plunger (Fig. 3b).

Table I

Phase of wave process	$T_{i\perp}$ eV	$T_{i\parallel}$, eV
"Breaking"	70	—
Wave cumulation	160	170
Compression of plasma column by the magnetic plunger	150	160
Cumulation of the wave excited during the second half-cycle	200	180

Table II

Phase of wave process	$T_{i\perp}$, eV	$T_{i\parallel}$, eV
Wave cumulation	210	170
Compression of plasma column by magnetic plunger	220	150
Wave cumulation excited in the second half cycle	250	160

The ion temperatures obtained for three phases of the wave process when $M < M_c$ are listed in Table II.

As seen from Table II, the transverse temperature is systematically higher than the longitudinal one by approximately 1.5–2 times. The presence in the energy spectrum of ions of rather high energy ($E \approx 3$ keV) indicates partial randomization, but smaller than in the regime with $M > M_c$.

An estimate of the ion temperature in the case of wave cumulation, connected with the assumption that the entire translational energy of the wave goes over into heat, and with allowance for the heating as a result of the adiabatic compression of the plasma column, gives a value of the same order of magnitude as the temperature determined with the aid of the analyzer.

As in the preceding regime, no appreciable temperature rise is observed as a result of wave cumulation excited in the second half-cycle of the discharge current.

In the case of small initial concentrations ($n_i \approx 0.5$–$1) \times 10^{13}$ cm^{-3}), a reduction of the results obtained for the first half-cycle of the surge-loop current is made difficult by the fact that the flux of the neutral particles emitted by the plasma is greatly weakened—a regime in which individual particles are counted sets in. Upon wave cumulation in the second half-cycle, maximum temperatures T_i = 600–1000 eV were registered (Fig. 5). The break in the line, observed in the figure, may be due either to the presence in the plasma of two regions with different ion temperatures, as expected in the second half cycle as a result of formation of a closed magnetic configuration[13], or to the distortion of the distribution function of the translational ion energy in the wave.

Practical equality of the transverse and longitudinal temperatures is observed in this case. The energy spectrum contains ions with energy exceeding $mu^2/2$ by ~10 times, thus indicating intense thermalization under conditions when the plasma was known to be "collisionless."

Investigations of shock waves with large propagation velocity are made difficult by the apparatus limit imposed on the registration of the high-energy part of the distribution (the maximum energy value is $E \approx 10$ keV) and by the appreciable attenuation of the intensity of the neutral-particle flux.

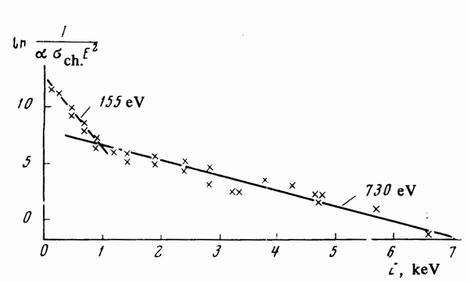

FIG. 5. Determination of the ion temperature (low concentration regime, $n_i \approx 5 \times 10^{12}$ cm^{-3}).

CONCLUSIONS

The foregoing results make it possible to draw the following conclusions:

1. When $M > M_c$, the single-velocity flow of the plasma stream is violated prior to the instant of cumulation of the wave on the system axis.
2. When $M < M_c$, the start of the registered particles and the randomization of their velocities is observed after the cumulation of the wave on the system axis.
3. The relative width of the energy spectrum of the particles, with maximum energy, exceeding by one order of magnitude the translational energy of the ions in the wave, indicates a sufficiently effective randomization of the ion velocities.
4. The breaking of the wave intensifies the randomization of the ions during the cumulation.
5. The temperature obtained from the energy spectrum of the particles agrees sufficiently well with the translational energy of the ions and waves.
6. In the low-concentration regime (when $M < M_c$), a sufficiently strong collisionless dissipation of the wave energy, and randomization of the ion velocities, is also observed upon cumulation of the wave. The temperature observed in hydrogen at $n_i \approx 0.5$–$1) \times 10^{13}$ cm^{-3} is $T_i \approx 1$ keV.

In conclusion, the authors thank R. Z. Sagdeev, at whose initiative the work was performed, V. I. Pil'skiĭ for valuable advice, and A. T. Altyntsev and A. S. Tkachuk for help with the work.

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