Physics and Contr. Nuclear Fusion Research, IAEA, Vienna, 3, 257 (1975).
[4]A. V. Arzhannikov and V. S. Koĭdan, Proc. 12-th Intern. Conf. on Phenomena in Ionized Gases, Eindhoven, 1, 1975, p. 278.
[5]V. V. Afrosimov, I. P. Gladkovskiĭ, Yu. S. Gordeev, I. F. Kalinkevich, and N. F. Fedorchenko, Zh. Eksp. Teor. Fiz. 30, 1456 (1960) [*sic*].
[6]O. V. Kozlov, A. M. Rodin, V. D. Rusanov, Yu. A. Skoblo, and A. V. Chernetskiĭ, in: Diagnostika plasmy (Plasma diagnostics), Vol. 1, Atomizdat, 1963, p. 199.
[7]V. S. Koĭdan, Candidate's Dissertation, Inst. Nucl. Phys. Siber. Div. Acad. Sci. USSR, Novosibirsk, 1971.
[8]N. A. Koshilev and O. G. Parfenov, PMTF (Prikladnaya Matematika i Teoreticheskaya Fizika ?) No. 6, 40 (1974).
[9]N. I. Alinovskiĭ, A. T. Altyntsev and N. A. Koshilev, Prik. Mat. Teor. Fiz. No. 3, 132 (1970).
[10]L. A. Sena, Stolknoveniya élektronov i ionov s atomami gaza (Collisions of electrons and ions with gas atoms), OGIZ, 1948.
[11]W. L. Fite, R. F. Stebbings, D. G. Hummer, and R. T. Brackman, Phys. Rev. 119, 663 (1960).
[12]V. S. Koĭdan and A. G. Ponomarenko, Proc. 4-th Europ. Conf. Plasma Physics and Contr. Nucl. Fusion Research, Roma, 1, 1970, p. 63.
[13]E. K. Zavoĭskiĭ, B. A. Demidov, Yu. G. Kalinin, A. G. Plakhov, L. I. Rudakov, B. D. Rusanov, V. A. Skoryupin, G. E. Smolkin, A. V Titov, S. D. Fanchenko, V. V. Shapkin, and G. V. Sholin, Plasma Phys. and Contr. Nucl. Fusion Research, IAEA, Vienna, 2, 3 (1971).
[14]C. Wharton, P. Korn, D. Prono, S. Robertson, P. Auer, and C. T. Dum, *ibid.* 2, 25 (1971).
[15]H. de Kluiver, H. W. Piekaar, W. R. Rutgers, H. Schrijver, and B. de Groot, *ibid.* 2, 67 (1971).

Translated by M. E. Mayer

Thermalization of the directed motion of plasmoids by a turbulent skin-layer discharge

L. E. Aranchuk, Yu. G. Kalinin, A. S. Kingsep, V. A. Skoryupin, and V. V. Yan'kov

I. V. Kurchatov Institute of Atomic Energy
(Submitted May 17, 1976)
Zh. Eksp. Teor. Fiz. **71**, 1849–1862 (November 1976)

Slowing down of oppositely moving plasma streams is observed experimentally when a direct skin-layer current of density $j > en(T_e/M)^{1/2}$ is passed through them. The energy of the translational motion is transformed in this case into thermal energy. The plasma column is heated along the radius from the skin layer toward the axis at the velocity of ion sound; the heating is accompanied by intense noise with a frequency on the order of ω_{pi}. A theoretical explanation of the phenomenon is proposed, based on the nonlinear instability of a two-stream plasma to finite-amplitude perturbations originating in the skin layer.

PACS numbers: 52.25.Fi

The turbulent heating of a plasma by a current is one of the most effective methods of obtaining a dense high-temperature plasma. Since the trail-blazing work by Zavoĭskiĭ and co-workers,[1–3] this problem has attracted considerable attention in plasma research to this day (see, e.g.,[4–6]). For large-scale installations with a dense plasma, the condition of turbulent heating $j > ne(T_e/M)^{1/2}$ with allowance for the actually attainable total current is easiest to realize under conditions of a skin-layer discharge, when the current flows only in a thin plasma layer. The first investigation of turbulent heating of a plasma in a large-scale installation under conditions of a skin-layer discharge was carried out in[7].

The experiments described below were performed with the same installation but under conditions when there are opposing plasma streams. It was observed in these experiments that excitation of ion-sound instability in a two-stream plasma leads to effective deceleration of the plasmoids. The energy of the translational motion goes over in this case into thermal energy. A theoretical explanation is offered for this phenomenon on the basis of nonlinear instability of a two-stream plasma to perturbations of finite amplitude, the source of which is the skin layer.

1. INSTALLATION AND DIAGNOSTICS

The TN-5[8] installation constitutes an open trap with a mirror ratio 1.85 and a magnetic field up to 7 kOe in the central part. The metal vacuum chamber of 55 cm diameter was evacuated to 10^{-8} mm Hg. A plasma column of length 3 m and diameter ~20 cm was produced in the central part of the trap by two film-hydride sources placed in the mirrors, to which capacitors up to 0.7 μF pre-charged to 20 kV were alternately switched. A 0.83-μF capacitor charged to 10–45 kV in the different experiments was connected in the direct-discharge circuit. The time variation of the plasma density and its distribution along the radius could be evaluated from the readings of electric double probes operating in the saturation regime. The results were monitored against the cutoff of a microwave signal of wavelength 4 or 8 mm. The radial distribution of the azimuthal field $H_\varphi(r)$ of the current was measured with an array of seven magnetic probes, followed by RC integration, while the total current was measured with a

Rogowski loop. In the experiments where the current distribution was not measured directly, the magnetic field H_φ was monitored at two points by magnetic probes located at radii $r_1 = 3$ cm and $r_2 = 12$ cm. Measurement of the longitudinal component field ΔH_z was carried out with a single-loop probe of diameter $d = 35$ mm at the instant of the discharge and with a 15-turn probe with $d = 40$ mm to determine the parameters of the plasmoids of the preliminary plasma. Both probes had openings and electrostatic screens.

To register the ions we used an orbital probe,[9,10] on the collector of which the charged particles could be incident with $v_\perp > \frac{1}{2}\omega_{Hi} d$ ($\omega_{Hi} = ZeH_0/Mc$ and d is the distance from the collector to the entrance diaphragm). The housing of the Larmor orbital probe was made of nonmagnetic steel 0.5 mm thick. The entrance opening of 2 mm diameter was covered with a steel grid of 50 μ mesh. The collector, in the form of a Faraday cup, was 12 mm in diameter. The probe was at a floating potential. The coupling with the oscilloscope was by means of a transformer ($f_{up} = 10^6$ Hz) or by an optronic system.

In the latter case, the signal after amplification was fed to an AlGaAs light-emitting diode having an operating speed 0.1 μsec. The variable light flux of the diode was proportional to the electric signal. This light flux was fed through a light pipe to an FÉU-83 photomultiplier, and then to an oscilloscope through an amplifier. Such an optronic high-voltage decoupling system has large interference immunity.

To register the small-scale electric noise we used a double coaxial asymmetrical electric probe (RF probe). The small arm of the probe (tungsten wire 50 μ in diameter and 0.5 mm long) received the small-scale fluctuations of the potential relative to the mean value. The latter was set by the second arm of the probe, which had a relatively large area (diameter 0.8 mm, length 3 mm). The upper frequency of the registered noise was limited by the input capacitance of the probe and amounted to 5×10^3 MHz. The signal was fed through a 75 Ω cable to a matched high-pass filter with a transmission limit $f_{min} = 250$ MHz. The indicated bandwidth of the RF probe spanned, with sufficient margin, the frequency band of the order of ω_{pi} at the plasma concentration $n = (10^{13}-10^{14})$ cm^{-3} at which the experiments were performed. The signal was subsequently detected, amplified, and fed to an oscilloscope through the optronic decoupling system described above.

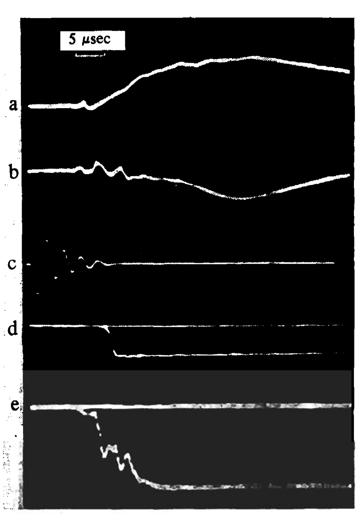

FIG. 1. Oscillograms of the readings of the double electric probe (a), of the diamagnetic probe (b), of the injector current (c), and of the cutoff of λ=8 mm (d) and λ=4 mm (e) microwave signals. The plasma is diagnosed at the center of the installation. The confining magnetic field here and below is $H_0 = 6-7$ kOe.

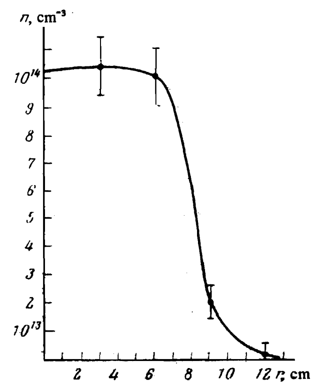

FIG. 2. Radial distribution of plasma concentration 30 μsec after the startup of the injectors. The scatter of the readings of double electric probes is indicated.

The x rays from a small volume of the plasma were registered by a photomultiplier with a plastic scintillator. The latter served as a vacuum seal, while a carbon film protecting the photomultiplier against the light from the plasma determined the lower limit of the hardness of the received x rays, $h\nu > 1$ keV. Localization of the radiation region was ensured with a collimator introduced into the plasma and with a target placed in front of the collimator.

The collimated emission of the hydrogen H_β spectral line was separated by an interference filter and registered with an FÉU-29 photomultiplier.

The microwave radiation of the plasma in the 8–2 mm band was received with horn antennas placed near the wall of the discharge chamber, and was registered with three detector heads.

2. EXPERIMENTAL RESULTS AND DISCUSSION

The filling of the central part of the trap with the plasma is illustrated by the oscillograms of Fig. 1. Figure 2 shows the averaged radial distribution of the concentration at 30 μsec after the operation of the injectors (the instant when the longitudinal-current discharge usually started). We note that the accuracy of the presented distribution $n(r)$ is limited by the assumption that the plasma temperature is constant in time and by the lack of reliable data on the radial temperature profile. The energy content of the preliminary plasma was $(2-9)\times10^{14}$ eV/cm^3.

A stable regime of the skin-layer discharge was observed at a preliminary plasma concentration on the installation axis $n_0 \gtrsim (5-9)$ cm^{-3}. Figure 3 shows typical oscillograms of the azimuthal magnetic fields $H_\varphi(r)$ of

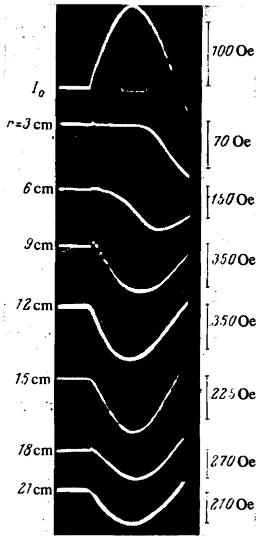

FIG. 3. Oscillograms of magnetic field $H_\varphi(r)$ of the discharge current, plotted simultaneously by means of an array of magnetic probes and a Rogowski loop (I_0). Scale time 1 μsec.

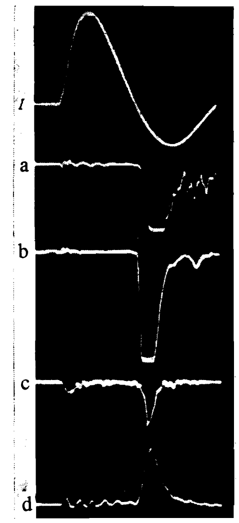

FIG. 5. Oscillograms: current I, x rays from small near-axis region of plasma (a) and powerful x radiation (b), plasma microwave radiation with λ=8 mm (c) and λ=4 mm (d).

the discharge current at $V_{\rm dir}=35$ kV, while Fig. 4 shows the averaged histograms of the current density $j(r)$. Measurements along two perpendicular diametral directions yielded quite similar results, thus indicating that the discharge had good cylindrical symmetry. The same figure shows the radial distribution of the energy content of the plasma, $nT(r)$, obtained for different instants of time from measurements of the changes in the longitudinal component $\Delta H_z(r)$ of the magnetic field.

A characteristic feature of the results is that despite the absence of an appreciable density inside the plasma column of 4 cm radius during a time 2.5–3 μsec, an increase of nT is already registered near the axis during the first microsecond, and the energy content of the plasma in this region is smaller but close in magnitude to the value of nT in the current layer.

The fact that the current is concentrated in the skin layer was verified at various points along the installation (5, 100, 150, 200 cm from the cathode). These experiments have demonstrated good longitudinal homogeneity of the discharge, and consequently the absence

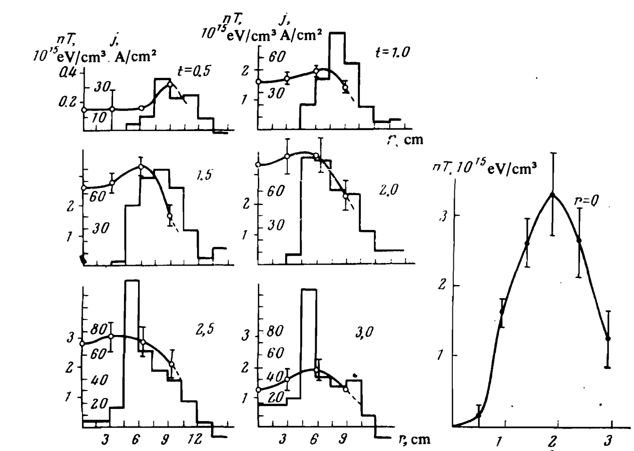

FIG. 4. Radial distributions of the current density and of the plasma energy content at different instants of time, and time variation of nT on the axis ($r=0$).

of possible local heating of the core of the plasma with subsequent propagation of the released heat along the magnetic field. It should be noted that other workers[11–13] were unable to obtain such a prolonged stable skin-effect phase. Estimates show that to heat the plasma center to the observable value of nT by Coulomb collisions the required current density is $j_{\rm Coul}>370$ A/cm² (at $T=10$ eV), and the development of ion-sound instability calls for $j>j_{\rm or}=en(T_e/M)^{1/2}=50$ A/cm². The accuracy with which the current density is measured at the center amounts to 5 A/cm², so that it can be stated with assurance that there is no plasma heating by the current at the center.

The cause of the heating of the core of the plasma column might be an electron beam. To detect the beam, we registered the local x rays from the axial region of the central part of the installation, which made it possible to observe the beam directly. We took into account also the fact that the two-stream instability should be accompanied by microwave radiation at the frequency $2\omega_{pe}$. Starting from the measured concentration profile, we registered the microwave radiation of the plasma at wavelengths 2, 4, and 8 mm. In addition, we photographed the x rays from the entire section of the plasma column. This procedure made it possible, in conjunction with the magnetic probe readings, to observe macroscopic instabilities of the plasma. The results of this entire set of measurements (Fig. 5)[1)] confirmed the absence of beams and the macroscopic stability of the plasma during at least three microseconds (the macroscopic instability that developed during the third microsecond and apparently caused the decrease of nT on the plot of Fig. 4 was investigated earlier,[14] where it was treated as current-convective instability in a plasma with anomalous resistance). At the same time, the Larmor orbital probe registered hydrogen ions with energies up to 200–250 eV near the axis (Fig. 6a) the shape of the signal turning out to be similar to the plot of the plasma energy content at the center (see Fig. 4). Measurements by two probes located at different points of the installation have demonstrated that the high-energy ions appear simultaneously over the length of the plasma column.

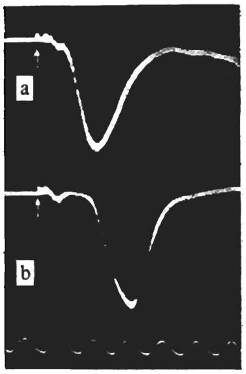

FIG. 6. Oscillograms: a—signal of orbital probe located on the axis, b—the same inside a dielectric tube mounted coaxial with the plasma column. The period of the sinusoid is 1 μsec. The arrows indicate the instant of turning on the direct discharge.

To register a stream of ions along the force lines, we placed in the control experiments a thin-wall dielectric tube 300 mm long and 80 mm in diameter coaxially with the plasma column. The signal from the orbital probe placed inside the tube turned out to be delayed by 0.6–1 sec (Fig. 6b) in comparison with the probe signal located in the same region in the absence of a tube, thus demonstrating that the peripheral current layers of the plasma column play a definite role.

One of the possible mechanisms whereby hot ions appeared near the axis may be resonant charge exchange. To verify this hypothesis, we registered the radiation of the H_β line from the plasma under ordinary conditions and with neutral hydrogen injected into the installation. The measurement has shown that the concentration of the neutral H atoms from the injected hydrogen at a pressure $p = 4\times10^{-5}$ mm Hg is comparable with the concentration of the neutral plasma particles, i.e., $n_0 \leqslant 3\times10^{12}$ cm^{-3}. For $\varepsilon_i = 50$–300 eV, the charge-exchange cross section is $\sigma_{ce} = (2.5-3)\times10^{-15}$ cm^2, yielding a charge-exchange time $t_{ce} > 8\times10^{-6}$ sec, i.e., too long for our case. In addition, the signal of the orbital probe did not change when hydrogen was admitted.

In principle, heat can be transferred from the skin layer to the center via development of drift instability with a wavelength $\lambda \sim R$ and with a characteristic frequency $\omega < \omega_{Hi}$. Transverse electric fields $E_\varphi \sim Hv/c = (300-500)$ V/cm should be produced in this case (v is the heat transfer velocity, $H = 7$ kOe). Measurement with a double electric probe revealed no fields with $E_\varphi > (50-100\text{ V})$/cm in this frequency region.

We consider next the processes connected with the development of high-frequency microinstabilities. From the obtained data (see Fig. 4) it is easy to deduce that the current velocity in the skin layer lies in an interval corresponding to excitation of ion-sound instability:

$$(T_e/M)^{1/2} < u < (T_e/m)^{1/2}, \quad u = j/ne. \tag{1}$$

It is well known that the mean free path of the ion sound in an equilibrium plasma, as a result of the Landau damping, is of the order of $\lambda_s \approx C_s/\gamma \sim \lambda_D (M/m)^{1/2}$, which amounts to several millimeters in our case. At the same time, the radius of the zero-current plasma column is ~ 5 cm. It might appear that the ion-sound noise can be regarded with good accuracy as localized in the skin layer. This, however, is not confirmed by experiment.

Figure 7 shows oscillograms of the readings of a microwave probe placed on the axis $r = 0$ (a) and at $r = 4$ cm from the axis (b). Acoustic noise as well as hot ions are registered already during the first microsecond after the start of the discharge, i.e., prior to the penetration of the skin-layer current into the central part of the installation. The observed delay of the radial signal, $\tau = (0.8-0.6)$ μsec, yields the rate of penetration of the noise into the center, $(5-7)\times10^6$ cm/sec, corresponding to the speed of sound at $T_{eff} = MC_s^2 = (25-50)$ eV. If it is assumed that the heat is transported from the skin layer by ion-sound noise, then the following relation should hold true

$$W_s \cdot 2\pi R \Delta l C_s \tau = (nT)_c \pi R^2 \Delta l, \tag{2}$$

where W_s is the noise density in the skin layer, $(nT)_c$ is the energy content of the central region of the plasma column, Δl is the column length element, R is the radius of the zero-current plasma, and τ is the time of penetration of the heat. The physical meaning of formula (2) is that the total energy content of the plasma column is equal to the total noise energy flux during the time of heating from the skin region into the central region. Consequently the degree of turbulence in the skin layer is

$$\frac{W_s}{(nT)_s} = \frac{(nT)_c}{(nT)_s} \frac{R}{2C_s\tau}, \tag{3}$$

which in our experiments of the order of unity, since the order of magnitude of the degree of turbulence in all the experiments on turbulent heating does not exceed 10^{-2}. Thus, the transport of so large an energy by noise is hardly possible.

It is natural to attempt to attribute the appearance of the heat at the center to diffusion of hot particles by the noise. Estimates show, however, that in our case $R^2/\tau \gg v_{Ti}^2/\omega_{Hi}$, i.e., the proposed diffusion coefficient exceeds (by more than one order of magnitude) the Bohm diffusion coefficient and consequently such a mechanism is unlikely.

In the investigation of the penetration of noise from the skin layer into the internal plasma layers, we succeeded in establishing that this effect takes place only when two plasma injectors operate simultaneously (Fig. 8a). On the other hand if the trap is filled through one

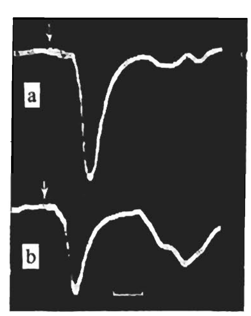

FIG. 7. Oscillograms of the signals of a microwave probe located on the axis (a) and at a distance $r = 4$ cm from the axis (b). Time scale 1 sec. The arrows indicate the instant when the direct discharge is turned on.

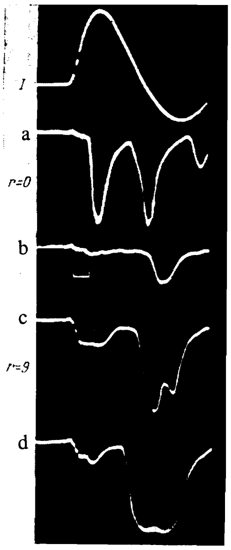

FIG. 8. Oscillograms of microwave-probe signals when the probe is located in the zero-current region ($r=0$) and in the sin layer ($r=9$ cm), in the case when the trap is filled through two injectors (a, c) and through one injector (b, d). Time scale 1 μsec.

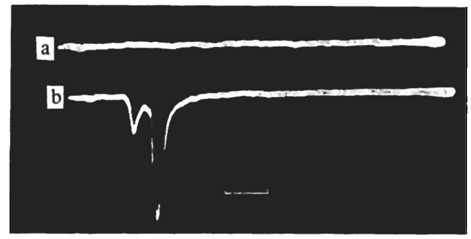

FIG. 10. Oscillograms of noise of preliminary plasma when the trap is filled with one (a) and two injectors (b). The start of the beam sweep corresponds to the instant of injector operation. The RF probe is located 150 cm from the guns. Time scale 5 μsec.

injector, the noise in the frequency range of interest to us is not registered near the axis (Fig. 8b). The readings of the RF probe in the current layer differ little in both cases (Figs. 8c, d). The method of filling manifests itself also in the readings of the orbital probe; when the trap is filled through one injector its signal at the instant of the discharge becomes smaller by a one order of magnitude.

Figure 9 shows the averaged histograms of the current density $j(r)$ and the energy content curves of the plasma at the center and at the current layer when one injector is used for the filling. Comparison with Fig. 4 shows that in this case there is no heat at the center, whereas the remaining characteristics of the discharge have changed little.

Thus, there were grounds for assuming that the observed effects of penetration of the noise into the center and the heating of the plasma column are the consequences of two-stream motion of the plasmoids and the ensuing microinstabilities. With the aid of the same RF probe we have registered noise excited when plasma streams from two injectors collide, without a longitudinal discharge. Figure 10 shows typical oscillograms of the noise in the case when the probe was located on the installation axis at a distance 150 cm from each of the guns. It is seen that when the plasmoids pass through each other the noise amplitude exceeds by more than one order of magnitude the noise background in the plasma of each plasmoid. This instability, however, does not lead in our case to a noticeable deceleration and heating of the plasmoids, and by the instant the direct discharge is turned on (30 μsec after the operation of the injectors), the intrinsic-noise level of the two-stream plasma becomes negligible. This means that in all the observed processes an essential role is played by the turbulent discharge in the skin layer.

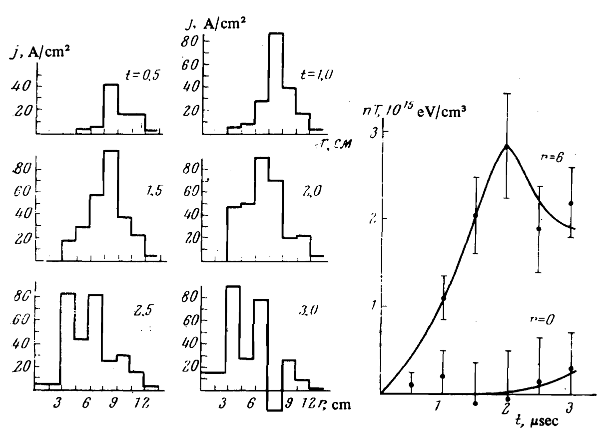

FIG. 9. Radial distribution of the current density and time dependence of the energy content of the plasma on the axis ($r=0$) and in the skin layer ($r=6$ cm) when the trap is filled with one injector.

Changing over to a regime with passage of current, we note that the total energy reserve in the moving plasmoids is in good agreement with the energy content of the plasma column. This estimate can be obtained by starting from the obvious relation

$$T_{max}=MV^2/2, \tag{4}$$

where V is the velocity of the plasmoid in the laboratory frame. The translational velocity of the ions in the plasmoids can be estimated with sufficient accuracy from the following considerations: Let the measurements be carried out at the center of the installation, and then the ions of each plasmoid have traversed a distance $L/2=150$ cm from the injector to the point of registration. The time of plasma formation can be assumed to be equal to the time of the current flow in the injector $\tau_{inj}\approx 10$ μsec (see Fig. 1), and the delay with which the discharge is turned on relative to the instant of injection is $\Delta\tau=30$ μsec. Thus, at the center of the installation we have

$$L/2(\Delta\tau-\tau_{inj})\geqslant V\geqslant L/2\Delta\tau,$$

i.e., $V=(5-7.5)\times 10^6$ cm/sec and $T_{max}\approx 12.4-28$ eV, which agrees sufficiently well with the measurements of the energy content and the propagation velocity of the ion-sound noise, determined above. The time dependence of the delay is given by the relations $V\sim\Delta\tau^{-1}$ and $T_{max}\sim\Delta\tau^{-2}$.

To verify further the assumption that the two-stream

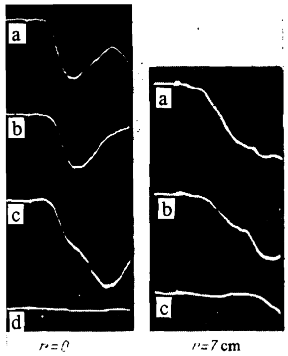

FIG. 11. Oscillograms of the readings of an orbital probe located on the axis, $r=0$, at a longitudinal discharge voltage V_{dir} equal to 35 kV (a), 25 kV (b), 12.5 kV (c), 7.5 kV (d), and in the current layer $r=7$ cm, at V_{dir} equal to 45 kV (a), 35 kV (b), and 25 kV (c). The time of the start of the discharge is determined from the marker. Beam sweep 5.5 μsec.

regime plays an important role, experiments were performed in which the delay time $\Delta\tau$ of the initiation of the direct discharge relative to the instant of operation of the guns was varied. With increasing $\Delta\tau$, the orbital-probe and RF-probe signals became weaker. It became impossible to register hot ions at $\Delta\tau \gtrsim 50$ μsec and the noise at $\Delta\tau \gtrsim 70$ μsec, in view of the extremely low signal level.

The assumption that the energy source at the center of the plasma column is the translational motion of the plasma streams was confirmed by control experiments in which the voltage V_{dir} on the capacitor of the direct discharge was measured. It is seen from the oscillograms (Fig. 11) that the signal of an orbital placed at the center (with registered ions at $\varepsilon_\perp \gtrsim 100$ eV) changes little in magnitude when V_{dir} is varied in the wide range 12.5 kV $\leqslant V_{dir} \leqslant$ 45 kV, and vanishes abruptly at V_{dir} = 7.5 kV. In this case the registration of the ions in the current layer ($r=7$ cm) ceases already at V_{dir} = 25 kV, thus indicating that the detected particles are of different type.

Measurement and comparison of the plasma pressures at the center and in the skin layer for different discharge voltages also confirmed the correction of our assumption, namely, when V_{dir} is decreased the energy content in the plasma in the zero-current column becomes higher than in the skin layer.

3. CONCLUSION AND POSSIBLE EXPLANATION OF THE RESULTS

It has thus been experimentally demonstrated that heating of the central part of the plasma column is unequivocally connected in our experiments with the method used to fill the trap with plasma, namely, heating of the central region is observed only if the two-stream filling regime is used. The measurement results allow us also to state that heating of the plasma column proceeds in a radial direction from the boundary of the skin layer towards the axis of the installation and must be accompanied by intense noise of frequency on the order of ω_{pi}. The heating wave, detected by the appearance, in the plasma, of high-energy pions produced simultaneously with the increase of nT, has a velocity that agrees with the velocity of the noise front, and is of the order of magnitude of the sound velocity C_s.

As already noted, assumptions concerning the influence of transport processes cannot explain our results satisfactorily. In a series of control experiments in which the discharge voltage was decreased, the pressure in the zero-current column of the plasma was higher than in the skin layer, thus likewise not favoring the transport processes. On the other hand, the measured energy content of the central region is in good agreement with the energy of the translational motion of the plasmoids.

The conclusion that can be drawn from the aggregate of the experimental data and from the presented estimates is the following: the heating of the central part of the plasma column is due in our experiments to the deceleration of the opposing plasma streams. The role of turbulence in the skin layer reduces to the production of an initial perturbation for the development of the instability in the two-stream plasma, which results in an anomalous collision frequency. It is important to note that the ion-sound instability proper of a two-stream plasma is incapable of ensuring the heating and deceleration of the plasmoids. The heating effect is observed only in the presence of the direct-discharge current.

An extraneous source of heating a two-stream plasma was used also in one of the earlier studies of two-stream instability.[15] In that study, however, the instability was excited only as a result of heating the plasma electrons to temperatures exceeding the energy of the translational motion, which thus did not determine the entire heating of the plasma. The instability observed earlier[15] is registered also under our conditions, but vanishes even before the discharge current is turned on.

Thus, in contrast to the previously obtained[15] and known effect of heating of a two-stream plasma, an important role in our case is played by the extraneous noise source. The noise itself, however, excited by the discharge current, cannot propagate in an equilibrium plasma over a length larger than $\lambda_D(M/m)^{1/2}$. Of course, in a two-stream plasma near the instability limit we have $\gamma=0$ and the mean free path $\lambda \sim C_s/\gamma$ may turn out in principle arbitrarily large. But if this effect were to take place in our case, the condition that the growth rate be equal to zero should be satisfied with accuracy

$$\frac{\delta\gamma}{\gamma_0} < \frac{\lambda_D}{R}\left(\frac{M}{m}\right)^{1/2} \sim (3-5)\cdot 10^{-2}, \qquad \gamma_0 \sim \omega_{pi}\left(\frac{m}{M}\right)^{1/2}. \tag{5}$$

In the opposite case we would observe in experiment a change in the amplitude of the sound signal as a function of the radius, in contradiction to the results of our measurements (see, e.g., Fig. 7).

The condition (5) must be satisfied in a plasma whose parameters depend noticeably on the radius, meaning that it should be satisfied along a sound-wave phase trajectory defined by the condition ω = const. Given the profiles $n(r)$ and $T(r)$ this is possible only if the plasma velocity profile is unique and defined with the same accuracy (5). Furthermore, this condition is violated when the plasma is heated, so that the effect of noise penetration from the skin layer into the center of the installation is quite unlikely. One might assume that as a result of the nonlinear interaction of the waves in the turbulent plasma of the skin layer the energy of ion-sound noise is transferred to some weakly-damped oscillation mode, which does indeed penetrate into the plasma: such a mode should have a frequency close to ω_{pi}, and its existence should be connected in critical fashion with the two-stream character of the plasma, i.e., $\omega \approx \pm k_z V_0$. Specifying also the conditions

$$\omega_{He} \sim 0{,}1\omega_{pe}, \quad \nabla n/n \sim 1/R, \quad V_0 \sim (2-3)C_s,$$

we have carried out a detailed analysis of the dispersion equations (see[16]), and were unable to find such a mode for the conditions cited above.

For a final choice of the model we consider first the question of the state of the plasma at the instant when the discharge is turned on. From the dispersion equation of a two-stream plasma with cold ions

$$\varepsilon = 1 + \frac{\omega_{pe}^2}{k^2 V_{Te}^2} - \frac{\omega_{pi}^2}{2(\omega - \mathbf{k}\mathbf{V}_0)^2} - \frac{\omega_{pi}^2}{2(\omega + \mathbf{k}\mathbf{V}_0)^2} = 0 \tag{6}$$

it is easy to obtain

$$\omega^2 = \frac{1}{2}\omega_s^2(k)\left[1 + \frac{2V_0^2\cos^2\vartheta}{C_s^2}\Lambda \pm \left(1 + \frac{8V_0^2\cos^2\vartheta}{C_s^2}\Lambda\right)^{1/2}\right]^{1/2},$$
$$\lambda_D = V_{Te}/\omega_{pe}, \quad \omega_s = kC_s/\Lambda^{1/2}, \quad \Lambda = 1 + k^2\lambda_D^2, \tag{7}$$

where ϑ is the angle between $\mathbf{k}$ and $\mathbf{V}$. From (7), in turn, it follows that at $V_0 > C_s$ the largest increment corresponds to oscillations with $k_\parallel/k \sim 5C_s/8V_0$, in which case $k_\parallel V_0 \sim \omega \sim \gamma \sim \omega_s$.

Let us consider the interaction of the plasmoids over the length of the installation. We recall that the discharge is turned on 30 μsec after the operation of the guns. At this instant of time the velocity of the streams at the center exceeds the sound velocity C_s, even if the latter is determined from the final plasma temperature, and in the preliminary plasma we have $C_s/V_0 \ll 1$. From the instant of the appearance of the plasma at the center of the installation (7–10 μsec after the instant of injection) one can deduce that the frontal part of the plasmoid has a velocity larger by another three or four times. This means that on the path from the electrode to the center of the installation the plasmoid region, having a velocity on the order of V_0, is penetrated by a stream of particles having velocities from V_0 to $4V_0 \gg C_s$. As a result, according to (6) and (7), sound waves should build up in the plasmoid and should propagate almost perpendicular to the system axis, $\mathbf{k} \perp \mathbf{V}_0$. The heating of the particles in this case can be approximately described by the equations of the quasi-linear theory. And since the coefficient of the quasilinear diffusion is given by

$$D_{\alpha\beta} = \frac{\pi e^2}{m^2}\int d\mathbf{k}|\varphi_\mathbf{k}|^2\delta(\omega - \mathbf{k}\mathbf{V})k_\alpha k_\beta,$$

it is easily seen that the quasilinear relaxation of the plasmoids leads to an increase of the transverse temperature of the particles.

As a result, the ion distribution function in the central part of the installation takes the form

$$f_i = \frac{1}{2}f(v_\perp)[\delta(v_\parallel + V_0) + \delta(v_\parallel - V_0)]. \tag{8}$$

Taking (8) into account, we obtain in place of (6)

$$\varepsilon = 1 + \frac{\omega_{pe}^2}{k^2 V_{Te}^2} + \frac{\omega_{pi}^2}{2k_\perp^2}(I_+ + I_-) = 0,$$
$$I_\pm = \int \frac{\mathbf{k}_\perp \partial f/\partial \mathbf{v}_\perp}{\omega \pm k_\parallel V_0 - \mathbf{k}_\perp \mathbf{v}_\perp} d\mathbf{v}_\perp. \tag{9}$$

From (9) it follows, in particular, that at $\langle v_\perp^2 \rangle \gtrsim C_s^2$ the unstable modes become stabilized. Thus, the condition of the stability of the preliminary plasma is $T_{\perp i} \sim T_e$, which does not contradict the experimental data. At the same time, for oscillations with $k_\parallel/k_\perp > C_s/V_0$, Eq. (9) reduces to (6), so that the oscillations can propagate without strong damping. Being stable in the linear approximation, such a system turns out to be unstable to perturbations of finite amplitude. The "priming" boundary condition is the ion-sound turbulence in the skin layer. Such an instability can in our case be treated as pairing instability in the interaction of waves with different signs of energy,[2)] which was predicted earlier.[17]

Let us examine this possibility in greater detail. In a two-stream plasma with $V_0 > C_s$ there exists four modes of high-frequency oscillations of two types—with negative energy and with positive energy. All of them constitute modified ion-sound oscillations. Let us analyze (6) from the point of view of the conservation laws:

$$\sum \omega_+ = \sum \omega_-, \quad \sum \mathbf{k}_+ = \sum \mathbf{k}_-, \tag{10}$$

where the subscripts ± denote waves with the corresponding sign of the energy. The condition (10) determines the possibility of nonlinear processes of the pairing type. It turns out that the two-wave process is possible with participation of two negative-energy waves traveling in opposite directions (subscripts 1 and 2) and one wave with positive energy (subscript 3). In this case $\mathbf{k}_1 \simeq -\mathbf{k}_3$. Accurate to terms $\sim C_s/V_0$ we have $k_2 \ll k_{1,3}$. The corresponding solutions of (6) in the limit $k\lambda_D < 1$ take the form

$$\omega_{1,2} = \mathbf{k}_{1,2}\mathbf{V}_0 - k_{1,2}C_s/\sqrt{2}, \quad \omega_3 = k_3 C_s/\sqrt{2} + |\mathbf{k}_3\mathbf{V}_0|. \tag{11}$$

Introducing the number of waves $n_k = W_k/\omega_k$ we have

$$\dot n_{1\mathbf{k}} = \int d\mathbf{k}' V_{\mathbf{k}\mathbf{k}'}[n_{1\mathbf{k}}n_{2\mathbf{k}'} + n_{2\mathbf{k}'}n_{3\mathbf{k}''} + n_{3\mathbf{k}''}n_{1\mathbf{k}}],$$
$$\dot n_{2\mathbf{k}} = \int d\mathbf{k}' V_{\mathbf{k}'\mathbf{k}}[n_{1\mathbf{k}'}n_{2\mathbf{k}} + n_{2\mathbf{k}}n_{3\mathbf{k}''} + n_{3\mathbf{k}''}n_{1\mathbf{k}'}],$$
$$\dot n_{3\mathbf{k}} = \int d\mathbf{k}' V_{\mathbf{k}'\mathbf{k}''}[n_{1\mathbf{k}'}n_{2\mathbf{k}''} + n_{2\mathbf{k}''}n_{3\mathbf{k}} + n_{3\mathbf{k}}n_{1\mathbf{k}'}]. \tag{12}$$

The kernel $V_{kk'}$ is calculated by standard methods.[18] The general expression for the kernel is cumbersome, but in the case when all the wave vectors are collinear and make an angle ϑ with the stream direction, this expression simplifies noticeably.[17] Calculations yield

$$V_{kk'}=32\cdot 2^{1/2}\pi^2 k_1k_2k_3\frac{C_s}{nm}\frac{1}{\cos^2\vartheta}\delta(\omega_1+\omega_2-\omega_3). \quad (13)$$

It is seen that the interaction is maximal for oblique waves, i.e., when $\cos\vartheta \sim C_s/V_0$.

Substituting the value of the matrix element in the system (12), we can obtain the characteristic time of development of the tearing instability. It turns out to be very short:

$$\tau^{-1}\sim k^2\lambda_D^2\frac{M}{m}\frac{W}{nT}\omega_{pi}. \quad (14)$$

It must be borne in mind, to be sure, that the main contribution to the matrix element (13) is made by electrons with a low velocity scatter, $|\mathbf{v}-\mathbf{V}_0|\sim C_s$, so that when the noise level is appreciable (an approximate estimate is $W/nT > m/M$) the matrix element should be renormalized.³⁾ In our case, however, the noise level is either of the order of m/M or, in any case, differs little from this value, and out of all the results of (14) the only conclusion of interest to us is that the front propagation-velocity instability and the heating rate of the plasma column should be determined exclusively by the group velocity of the sound waves.

The buildup of intense sound waves in the plasma should obviously be accompanied by heating of a small group of resonant ions with energy larger than T_e, and in view of their small number the energy of such ions can become much larger than the electron temperature. This is apparently also the reason why the heating of the core of the plasma column is always accompanied by the appearance of high-energy ions, which are registered by an orbital probe. This explanation of the observed effects seems to us most reasonable and noncontradictory.

In conclusion, we wish to emphasize the fact that the energy reserve in the capacitance of the direct discharge, needed for thermalization of the plasmoids, is much smaller than in the capacitors of the injector circuits, $2C_{\rm inj}V_{\rm inj}^2/C_{\rm dir}V_{\rm dir}^2 > 4-7$. The ratio of the specific energy content in the plasma column to the value nT in the skin layer is then approximately 4–5, and the physical efficiency of the conversion of the translational-motion energy of the plasma streams into thermal energy remains of the order of unity. This gives grounds for assuming the turbulent discharge to be an effective method of converting the kinetic energy of opposing plasma jets into thermal energy, and therefore one of the promising methods of producing a high-temperature plasma in large-scale installations.

In conclusion, the authors thank L. I. Rudakov for constant interest in the work and for valuable discussions and critical remarks.

[1)] No microwave radiation with $\lambda = 2$ mm was observed at sensitivity level higher by one order of magnitude than the one used in the measurements at $\lambda = 4$ mm.

[2)] This was pointed out to us by L. I. Rudakov.

[3)] In particular, as $W/nT \to 1$, the instability develops at the hydrodynamic time rate $\tau^{-1}\sim k^2\lambda_D^2 W\omega_{pi}/nT$.

[1] E. K. Zavoĭskiĭ, At Energ. 14, 57 (1963).
[2] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, L. I. Rudakov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. 47, 1597 (1964) [Sov. Phys. JETP 20, 1073 (1965)].
[3] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, S. L. Nedoseev, L. I. Rudakov, and V. A. Skoryupin, Second Intern. Conf. on Plasma Phys. and Control. Nucl. Fusion Res., Culham 1965, paper CN-21/154.
[4] E. K. Zavoĭskiĭ, B. A. Demidov, Yu. G. Kalinin, A. G. Plakhov, L. I. Rudakov, V. D. Rusanov, V. A. Skoryupin, G. E. Smolkin, A. V. Titov, S. D. Fanchenko, V. V. Shapkin, and G. V. Sholin, Fourth Intern. Conf. on Plasma Phys. and Control. Nucl. Fusion Res., Madison, 1971, paper IAEA-CN-28/E-1.
[5] C. Wharton, P. Korn, D. Prono, S. Robertson, P. Auer, and C. I. Dum, *ibid.*, paper IAEA-CN-28/E-2.
[6] V. A. Suprunenko, E. A. Sukhomlin, and V. T. Tolok, Plasma Phys. 15, 353 (1973).
[7] L. E. Aranchuk, E. K. Zavoĭskiĭ, D. N. Lin, and L. I. Rudakov, Pis'ma Zh. Eksp. Teor. Fiz. 15, 33 (1972) [JETP Lett. 15, 22 (1972)].
[8] L. E. Aranchuk and S. L. Nedoseev, Zh. Eksp. Teor. Fiz. 61, 1856 (1971) [Sov. Phys. JETP 34, 988 (1972)].
[9] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, L. I. Rudakov, V. A. Skoryupin, and G. V. Sholin, Zh. Eksp. Teor. Fiz. 46, 511 (1964) [Sov. Phys. JETP 19, 349 (1964)].
[10] D. J. Joughran, F. R. Scott, and H. M. Skarsgard, Can. J. Phys. 45, 3055 (1967).
[11] A. Hirose, T. Kawaibe, and H. M. Skarsgard, Phys. Rev. Lett. 29, 1432 (1972).
[12] C. B. Warton, P. Korn, and S. Robertson, Phys. Lett. 27, 499 (1971).
[13] R. D. Bengtson, K. W. Gentle, J. Jancarik, S. S. Medley, P. Nielsen, and P. Phillips, Phys. Fluida 18, 710 (1975).
[14] Yu. G. Kalinin, D. N. Lin, L. I. Rudakov, V. D. Ryutov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. 59, 1056 (1970) [Sov. Phys. JETP 32, 573 (1971)].
[15] M. V. Babykin, E. K. Zavoĭskiĭ, L. I. Rudakov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. 43, 1976 (1962) [Sov. Phys. JETP 15, 1391 (1962)].
[16] A. B. Mikhaĭlovskiĭ, Teoriya plazmennykh neustoĭchivosteĭ, (Theory of Plasma Instabilities) vol. 1, Atomizdat, 1970.
[17] V. M. Dikasov, L. I. Rudakov, and D. D. Ryutov, Zh. Eksp. Teor. Fiz. 48, 913 (1965) [Sov. Phys. JETP 21, 608 (1965)].
[18] B. B. Kadomtsev, Voprosy teorii plazmy (Problems of Plasma Theory), Atomizdat, No. 4, 188 (1964).

Translated by J. G. Adashko