ENERGY LOSSES AND EFFICIENCY OF TURBULENT HEATING IN A CURRENT-CARRYING PLASMA

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We describe an investigation of the efficiency of turbulent heating and the energy losses in a plasma in an open trap. It is shown that the heating efficiency increases with the intensity of the magnetic field in which the heating is carried out and also increases with the initial density of charged particles in the trap. The maximum heating efficiency achieved in these experiments is 25%. It is proposed that the heating is due to the development of an ion-acoustic instability in the plasma.

INTRODUCTION

A number of recently published papers[1-3] have indicated the possibility of using a current-driven instability for effective collisionless heating of a plasma. The investigation of superthermal electromagnetic radiation[4] and experiments on Raman scattering of external electromagnetic waves by turbulent fluctuations in a plasma have shown that in a current-carrying plasma the level of the high-frequency oscillations (plasma waves and ion-acoustic waves) reaches values of the order of 0.02–0.1 of nT (n is the electron density and T is the plasma temperature).[5] The existence of intense currents and strong electric fields in the plasma can lead to the development of large-scale instabilities and to a significant loss of energy from the plasma as a result of current flow. Hence, if one is interested in increasing the heating efficiency it is necessary to know the origin of the plasma energy loss. On the basis of this information it would be possible to choose judicious experimental conditions in order to reduce these energy losses.

In the experiments described below on turbulent heating we have investigated the plasma energy losses across and along the confinement field and the dependence of these losses on various parameters: the initial electron density in the trap, the voltage applied to the capacity for the direct discharge, and the magnetic field. In these experiments we have also measured the plasma diamagnetism and the x-ray bremsstrahlung (with a grounded electrode which is the anode of the direct discharge in the first half-cycle[1)]). Using the bolometer readings, the diamagnetic signal and our knowledge of the ohmic losses due to the resistance in the conducting circuits, we are able to plot curves showing the relative energy losses across the magnetic field and the total efficiency for the turbulent heating. The plasma energy losses are given by the expression

$$\eta = Q_{\perp} S \left[\frac{CV_c^2}{2} - R_c \int I^2(t)\,dt\right]^{-1}$$

where $Q_{\perp}$ is the plasma energy flux in $J \cdot cm^{-2}$ measured with a bolometer, $S = 4250$ cm^2 is the area of the side wall of the vacuum chamber, V_C is the voltage to which the capacity for the direct discharge C is charged, and R_c is the resistance of the associated circuits, including the switching gap.

The total heating efficiency is defined as

$$\xi = U_V \left[\frac{CV_c^2}{2} - R_c \int I^2(t)\,dt\right]^{-1},$$

where U_V is the energy in Joules contained in the plasma column computed from the relation $U_V = 0.8\, eHl\tau$; here, e is the signal from the diamagnetic loop in volts, H is the quasistatic magnetic field in oersteds, τ is the integration time for the integrating circuit of the diamagnetic probe in seconds, and l is the distance between the mirrors in centimeters.

EXPERIMENTAL APPARATUS AND METHOD OF MEASUREMENT

These experiments were carried out on the NPR-2 device (Fig. 1) which is an open system with a mirror ratio of 2 in which the peak magnetic field at the center is 25 kOe. A glass vacuum chamber 15 cm in diameter in the central portion of the trap and 10 cm in diameter at the mirrors is pumped to 5×10^{-7} Torr and filled with a hydrogen plasma from two hydride-layer plasma sources.[6] The injectors are located at the center of the mirrors, which are separated by a distance of 90 cm. Across these injectors, by means of a controlled switching gap, we switch in the capacity for the direct discharge C = 0.2 μF, which is charged to 16–50 kV; the discharge period for this system is 2 μsec. Additional experiments have been carried out to show that the actual diameter occupied by the current is smaller the higher the quasistatic magnetic field in which the heating occurs. However, at fields H ≥ 10 Oe this diameter remains unchanged, being equal to 8 cm. The initial den-

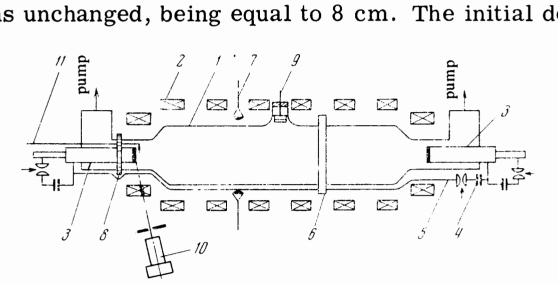

FIG. 1. Diagram of the NPR-2 device. 1) Vacuum chamber, 2) solenoid, 3) plasma injectors, 4) capacitor for the straight discharge, 5) return lead for the discharge, 6) diamagnetic probe, 7) mocrowave horns, 8) Rogowski loop, 9) bolometer, 10) scintia

[1)]Below, this electrode will simply be called the "anode" while the other electrode will be called the "cathode."

sity in the trap before and at the time at which the current is switched on is measured by the cutoff signal of a microwave system whose horns are located close to the median plane of the trap; the diamagnetic measurements are carried out by means of a single-turn coil with an integration constant $\tau = 10^{-4}$ sec. Simultaneously a Rogowski loop is used to monitor the current through the plasma; the voltage on the capacitor in the straight discharge is also monitored. The hard x-ray bremsstrahlung from the anode of the straight discharge is detected by collimated scintillation counters that use stilbene crystals.

The plasma energy losses to the sidewall of the vacuum chamber are measured with a bolometer. The bolometer is mounted in such a way that the bolometer surface that faces the plasma is flush with the inner wall of the vacuum chamber. In these experiments we have used a bismuth bolometer like that developed by Gorelik and Sinitsyn.[7] The bolometer can record the incident energy due to charged particles, neutral particles, and plasma radiation. However, our estimates indicate that the latter factor is negligibly small. The plasma energy losses along the magnetic field have been studied with molybdenum-constantin thermocouples which are located close to the grounded electrode of the direct discharge and which can be moved in the diametral plane of the vacuum chamber. The measurements with the bolometer and the thermocouples measure the total energy flux. It was not possible to follow the time behavior of the turbulent heating process with the bolometer because of the electrostatic noise.

RESULTS OF THE DIAMAGNETIC AND BOLOMETER MEASUREMENTS

The investigation of the total efficiency for the turbulent heating and the energy loss of the plasma across the confinement field were carried out at three values of the initial plasma density n_0 in the trap, 2×10^{13}, 4×10^{13}, and 7×10^{13} cm^{-3}. After the trap was filled to one of the densities indicated above a controlled switching gap was used to switch on the direct discharge and to initiate the discharge of the charged capacity. With $n_0 \leq 1.7 \times 10^{13}$ cm^{-3} the current flowing through the plasma is almost aperiodic whereas when $n_0 > 2 \times 10^{13}$ cm^{-3} the current and voltage exhibit oscillations characterized by high damping. The plasma resistance computed for these operating regimes is always very much greater (50—100 times) than the resistance computed on the basis of Coulomb collisions.

The investigation of the plasma energy loss to the walls of the vacuum chamber and of the dependence of the total efficiency of turbulent heating on the magnetic field and the longitudinal electric field were carried out at $n_0 = 2 \times 10^{13}$ cm^{-3} with an essentially uniform distribution of charged particles over the length of the device. In Fig. 2 we show oscillograms of the current through the plasma and the signals from the diamagnetic probe obtained in one experiment. In Fig. 3a and Fig. 3b we show the magnetic field dependence of the energy loss from the plasma to the side surface of the vacuum chamber at the central portion of the system and the corresponding plasma energy content following turbulent heating. These curves are plotted for different values of the initial voltage on the capacitor used for the straight discharge.

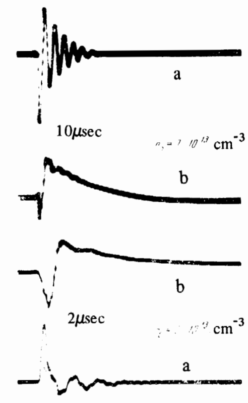

FIG.2. a) Oscillogram of the plasma current, b) diamagnetic signals. H = 15 kOe, V_C = 24 kV.

It follows from Fig. 3a that as the magnetic field increases the energy loss to the side wall of the vacuum chamber is reduced; furthermore, at magnetic fields greater than some specific value this energy loss becomes essentially fixed. At the same time, the energy content of the plasma is increased (Fig. 3b) if the heating is carried out in a strong magnetic field; however, at some definite value of the field this energy content reaches a peak and then falls off slowly. The bolometer measurements can be used to estimate the total energy loss to the entire side wall of the vacuum chamber ($S = 4250$ cm^2) if it is assumed that the energy loss per unit length of the length of the chamber is uniform. Thus, with V_C = 24 kV and H = 5 kOe the total energy loss is 8 J. It also follows from Fig. 3a that as the voltage applied to the capacitor in the straight discharge increases the plasma energy losses as measured with the bolometer increase in absolute value; however, since the energy fed into the discharge also increases in this case, the energy content of the plasma is increased (Fig. 3b).

Using the experimental curve (Fig. 3a) in Fig. 4a and Fig. 4b we have plotted the relative plasma energy loss to the side wall of the vacuum chamber and the total efficiency for the turbulent heating as functions of the magnetic field and the voltage applied to the capacitor of the discharge, taking account of the ohmic losses in the conductors and the associated circuitry. It is evident from Fig. 4a that at low magnetic fields the energy loss

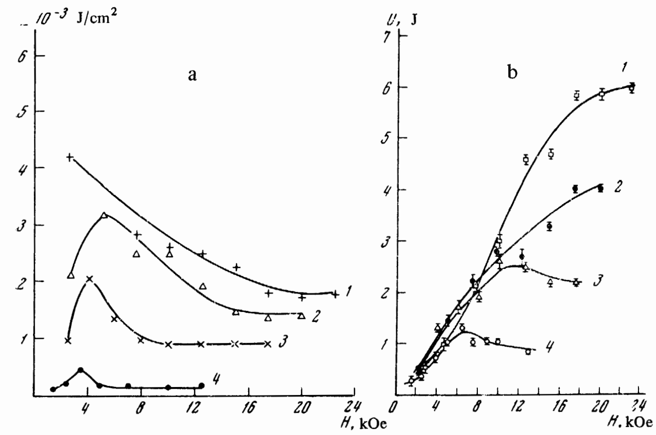

FIG. 3. a) Energy flux to the side wall of the vacuum chamber, b) energy content of the plasma. The curve 1 is obtained for V_C = 40 kV, 2) 32 kV, 3) 24 kV, 4) 16 kV. The density $n_0 = 2 \times 10^{13}$ cm^{-3}.

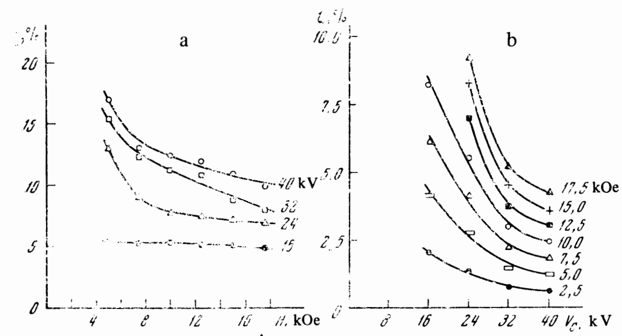

FIG. 4. a) Relative plasma energy losses to the side wall of the vacuum chamber for different values of V_c, b) total heating efficiency for different values of H.

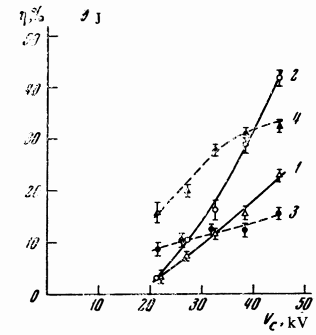

FIG. 6. Total energy losses to the side walls (curves 1 and 2) and relative energy losses (curves 3 and 4). Curves 1 and 3 obtained with $n_0 = 2 \times 10^{13}\,cm^{-3}$, curves 2 and 4 with $n_0 = 7 \times 10^{13}\,cm^{-3}$ and H = 15 kOe.

across the magnetic field reaches 15% of the energy fed into the discharge gap while the total heating efficiency increases from 2.5% to 10% as the magnetic field increases. It is interesting to note that Jensen and Scott[8] have also reported a heating efficiency of 3—4%, which is in good agreement with present results (Fig. 4b). It should be noted that the total heating efficiency measured in[8] made use of the diamagnetic signal 4 μsec after the current was switched on; however, the decay of the diamagnetic signal up to this point in time is insignificant.

As the initial density increases the energy content of the turbulently heated plasma also increases. An illustration of this feature is shown in Fig. 5, which presents the energy content of the plasma and the relative efficiency of the turbulent heating as functions of the voltage applied to the capacity used for the direct discharge. In Fig. 6 we show the plasma energy loss across the magnetic field for the following densities n_0: 2×10^{13}, 4×10^{13}, and 7×10^{13} cm^{-3}. The magnetic field was 15 kOe during the heating process. These curves indicate (Fig. 5) that the heating efficiency in a given magnetic field increases with the initial density and a reduction in the voltage applied to the capacitor for the straight discharge, reaching values of 25%. The reduction in heating efficiency associated with the higher voltage on the discharge capacitor can evidently be explained as follows: while the current flows a higher voltage applied across the discharge can evidently lead to the development of a macroscopic instability which can lead to an additional energy loss to the walls and ends of the vacuum chamber (Fig. 6). The energy loss associated with the high effective collision frequency ν^* does not explain the results obtained earlier.[3]

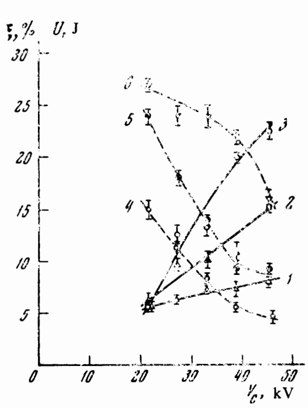

FIG. 5. The energy content of the plasma (curves 1 – 3) and the total efficiency (curves 4 – 6) as functions of the initial voltage on the capacity for the direct discharge, Curves 1 and 4 are obtained with $n_0 = 2 \times 10^{13}\,cm^{-3}$, 2 and 5 with $n_0 = 4 \times 10^{13}\,cm^{-3}$, 3 and 6 with $n_0 = 7 \times 10^{13}\,cm^{-3}$, H = 15 kOe.

INVESTIGATION OF THE ENERGY LOSS ALONG THE MAGNETIC FIELD

As indicated above, the total energy loss along the magnetic field has been measured by means of thermocouples. In Fig. 8 below, we show the distribution of the plasma energy loss over the cross-section of the vacuum chamber for different modes of operation. Figure 7a and Fig. 7b refer to measurements with an initial plasma density n_0 equal to 2×10^{13} and 4×10^{13} cm^{-3}, and a magnetic field at the center of the trap equal to 2.5 and 5 kOe; in Fig. 7c the measurements were taken with $n_0 = 7 \times 10^{13}$ cm^{-3} and H = 10 kOe. It should be noted that in various experiments the electrode close to which the measurements are carried out appears as the anode or the cathode of the straight discharge. When $2 \times 10^{13}\ cm^{-3} \le n_0 \le 4 \times 10^{13}\ cm^{-3}$ the energy loss to the cathode is 25—30 times smaller than that to the anode. When $n_0 = 7 \times 10^{13}$ cm^{-3} the polarity of the supply voltage changes the thermocouple reading by no more than a factor of two or three. The small values of the changes in the thermocouple readings in this case can be understood as follows: when $n_0 = 7 \times 10^{13}$ cm^{-3} the plasma resistance is so small that in the first half-cycle of the current all of the energy that is stored in the discharge capacitor cannot be dissipated; rather only part of it is dissipated. Hence, in the second half-cycle when the cathode of the discharge becomes the anode a significant fraction of the energy can still appear. It follows from Fig. 7 that

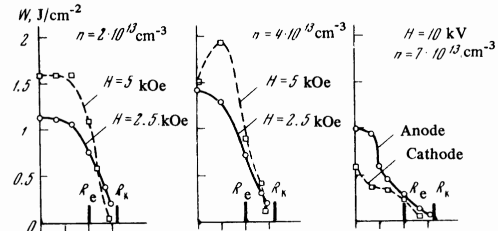

FIG. 7. Radial distribution of the energy loss along the magnetic field; R_e, electrode radius, R_{ch}, chamber radius;

the anode usually generates 60—70% of the energy stored in the capacitor; in addition 10—15% is lost in the mirrors due to streaming past the electrode of the discharge.

On the basis of these measurements, as well as the measurements of the plasma diamagnetism and the energy loss to the side walls of the vacuum chamber, we can formulate an approximate energy balance for turbulent heating. The analysis shows that under various experimental conditions the anode dissipates 60—70% of the initial energy stored in the discharge capacitor; the energy lost along the magnetic field past the anode of the direct discharge is 10—15%; the energy lost to the walls of the vacuum chamber is 5—25%. Under these conditions 2.5 to 25% of the energy fed into the discharge gap remains in the plasma.

INVESTIGATION OF THE X-RAY BREMSSTRAHLUNG

In order to obtain an understanding of the turbulent heating mechanism one must know whether or not a beam of fast electrons with energies of the order of the applied voltage arises in the plasma; this beam could contain only a small fraction of the plasma electrons but could carry the entire current and, consequently, could be responsible for the heating of the plasma. If this is the case, this beam should produce intense x-ray bremsstrahlung at the anode of the discharge. By measuring the hardness and absolute intensity of this radiation it is possible to estimate the number of fast electrons and to evaluate the contribution of these electrons to the total current. Measurements of this kind were carried out by means of a collimated scintillation counter using a stilbene crystal and an FÉU-12 photomultiplier. The hardness of the x-ray photons was estimated by means of copper absorbers. These measurements have shown that in the first half-cycle of the discharge there is a short (approximately 0.1—0.3 μsec) burst of x-rays with hardness of the order of the applied voltage (40—45 kV). The intensity of this burst is reduced by an order of magnitude as the density increases from 2×10^{13} to 7×10^{13} cm^{-3}. An estimate of the absolute intensity of the radiation for $n_0 = 2 \times 10^{13}$ cm^{-3} indicates that particles with energy of 40—50 kV can carry no more than 0.001 of the total current and that electrons with somewhat lower voltage ($\sim$20 kV) carry less than 0.01. (All of these estimates have been carried out taking account of the absorption of the x-ray radiation by the walls of the vacuum chamber.)

DISCUSSION OF EXPERIMENTAL RESULTS

Investigations of the energy balance and turbulent heating of a plasma in an open trap have shown that the basic fraction of the plasma energy is lost along the magnetic field (Fig. 7). If heating occurs in closed traps these losses would be eliminated but the losses to the side walls of the vacuum chamber would remain. Hence, it is of interest to find the origin of the energy loss across the confining magnetic field. For this purpose we now compare the results of investigations of the energy loss to the walls of the vacuum chamber under various experimental conditions.

Let us investigate the results indicated by the bolometer readings (Fig. 3a). It should be noted that when heating occurs in weak magnetic fields the energy to the bolometer is appreciably greater than the energy loss when heating occurs in a strong magnetic field. These losses cannot be explained by a high effective collision frequency ν^*. It is well known[3] that the relaxation time associated with transverse diffusion and turbulent heating is given by

$$\tau_\perp = \frac{r_0^2}{\nu^* \rho_{He}^2}, \quad \nu^* = 1.1 \cdot 10^{-12} \frac{e^2 SRn_0}{lm}.$$

Here, R is the resistance of the discharge gap containing the plasma as measured experimentally, ρ_{He} is the electron Larmor radius, r_0 is the distance from the plasma surface to the side wall of the vacuum chamber and m is the electron mass. We can estimate $\tau_\perp$ for maximum energy loss across the confined magnetic field. With $r_0 = 3$ cm, H = 4 kOe, $n_0 = 2 \times 10^{13}$ cm^{-3}, plasma column length $l = 90$ cm, S = 50 cm^2, R = 1.5—2 Ω and $T_e \sim 200$ eV the effective collision frequency $\nu^* = 4-6 \times 10^8$ sec^{-1} and $\tau_\perp \approx 10^{-4}$ sec. This time is almost two orders of magnitude larger than the heating time; consequently the energy loss of the plasma across the magnetic field due to the finite turbulent conductivity is not important.

In making these estimates we have assumed that the plasma diamagnetism is determined primarily by the electrons. But it is well known[8,12] that in turbulent plasma heating the ions also make a contribution to the plasma current. Since the ion temperature has not been measured directly in these experiments, we shall attempt to separate from the energy loss to the bolometer that part which could be associated with heated ions. For this purpose the end part of the bolometer facing the plasma was shielded by two grids with cell dimensions 0.2×0.2 mm^2. The grids were located at distance of two millimeters from each other. This shielding of the bolometer made it possible to measure the total energy flux from the neutral atoms due to charge exchange, which amounts to $\frac{1}{3} - \frac{1}{4}$ of the total energy flux to the bolometer without the shield.

Obviously one possible candidate for the plasma energy loss is the excitation of a large-scale Kruskal-Shafranov instability.[9] However, estimates show that under the present experimental conditions there is a rather wide stability margin even for the case in which the plasma is heated in a weak magnetic field (H = 2—4 kOe). In heating the amplitude of the longitudinal current in the first half-cycle in the discharge varies between 10—15 kA under different experimental conditions so that with a plasma radius r = 4—4.5 cm, $l = 90$ cm and H = 2—4 kOe the ratio H_z/H_φ exceeds the quantity $l/\pi r$ by approximately a factor of two.

It is most likely that the anomalous energy loss is associated with the excitation, in the plasma with a finite turbulent conductivity, of a current-convective instability;[10] the growth rate is given by

$$\gamma = -i\nu k^2 + i\frac{k_y E_0 c}{k_z H_z \partial j/\partial E}\frac{d\sigma_{\text{eff}}}{dx}$$

Here, we have taken account of the fact that the plasma conductivity can be a function of the electric field. In this expression the first term can be neglected since it is small compared with the second term. Assuming that

$$\frac{d\sigma_{\text{eff}}}{dx} = \frac{\sigma_{\text{eff}}}{r}, \quad \frac{\partial j}{\partial E} = \sigma_{\text{eff}}, \quad k_y = \frac{1}{r}, \quad k_z = \frac{\pi}{l},$$

we find $|\gamma| = 10^8 V_C/\pi r^2 H_Z$ where r is the plasma radius. In the range of capacity voltages 20–50 kV with $H = 2$–20 kOe the quantity $|\gamma| = 2 \times 10^7 - 5 \times 10^6\ \text{sec}^{-1}$.

It is then evident that under the present experimental conditions a significant fraction of the plasma energy loss across the magnetic field is explained by the excitation of a current-convective instability in the plasma, which has a finite conductivity.

CONCLUSION

In these experiments we have established the following:

1. The energy content of the plasma and the total efficiency for the turbulent heating both increase with initial density. The maximum value of nT in these experiments is $4 \times 10^{16}\ \text{eV} \cdot \text{cm}^{-3}$ and the maximum heating efficiency is 25%.

2. It is proposed that the plasma energy loss to the walls of the vacuum chamber during the turbulent heating process is made up of the energy loss associated with charge-exchange neutrals and the loss due to the excitation of a current convective instability in the finite-conductivity plasma.

3. It can be stated that the observed plasma heating is due to the interaction with the plasma of a beam of fast electrons with energies of the order of the applied voltage; the number of such electrons does not exceed 10^{-3}–10^{-4} of the total number of electrons in the plasma.

In the case in which an ion-acoustic instability develops in the current-carrying plasma[11] the instability limit is determined by the ion-acoustic velocity $c_s = \sqrt{T_e/M}$; for the two-stream instability the condition $u_T = \sqrt{T_e/m}$ must be satisfied where u_T is the mean velocity associated with the current. Hence, in order to evaluate the kind of instability that is excited by the current we have analyzed the experimental results as described below. Using the reading of the diamagnetic probe at the time the current goes through zero in the first half-cycle we have determined the plasma temperature and have used this to compute the ion-acoustic velocity. The mean current velocity is determined from the known density, the cross section of the current column, and the maximum value of the current. The error in the calculation of the ion-acoustic velocity in this analysis is no worse than 15–30% since the introduction of the plasma paramagnetism carried out for certain experiments has shown that the plasma temperature at this time does not fall by more than 30–50% of the value at peak current.

The ratio u_T/c_s for 100 experiments is shown in Fig. 8 for different modes of operation in turbulent heating—different initial densities, electric fields and magnetic fields. It will be evident from Fig. 8 that the majority of the points fall close to the line $u_T/c_s = 1$. There are essentially no points below the line $w_T/c_s = 1$.

In regimes in which the energy content of the plasma is small, corresponding to the lower values of the initial plasma density in the trap, the accumulation of points can be understood, but even here there are no points that lie below 10.[2)] From this feature in the location of

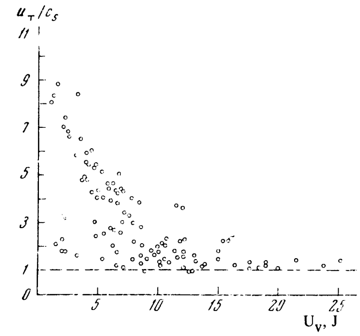

FIG. 8. The ratio u_t/c_s as a function of the energy content of the plasma.

the points we can draw the conclusion that the ion-acoustic instability is excited in the current-carrying plasma under the present experimental conditions.

In conclusion, the authors are highly indebted to E. K. Zavoĭskiĭ and L. I. Rudakov for their continued interest and for valuable discussions of the experimental results. The authors also thank L. L. Gorelik and V. V. Sinitsyn for providing us with the bolometers which were necessary for carrying out these experiments.

2) It should be noted that in this region the electron plasma frequency is 2.5 – 3 times lower than the electron cyclotron frequency.

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