Energy Balance of Ions in Turbulent Discharges in a Longitudinal Magnetic Field

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The efficiency of ion heating in turbulent z-discharges with anomalous conductivity due to the excitation of ion-acoustic instabilities in the plasma is investigated experimentally. Approximate formulas are derived for calculation of the electron and ion temperature in the current peak of pulsed z-discharges in experiments on turbulent plasma heating. The results of the calculations are compared with the experimental data. Satisfactory agreement is obtained between the calculated ion temperatures and those measured experimentally.

EXTENSIVE information has been accumulated up to the present time on phenomena accompanying plasma heating in high-current z-discharges.[1] However, it has not been possible up to the present time in experiments of this type to learn the general regularities which determine the efficiency of ion heating in z-discharge plasmas with anomalous conductivity. Development of models for ion heating in a plasma with anomalous conductivity is hindered principally by the fact that in most of the experimental studies which have been published up to the present time there are no data on the dependence of the experimentally measured ion temperatures on the parameters of the discharge.

The present work is the continuation of a series of investigations[2-8] devoted to study of the interaction of rapidly varying electromagnetic fields of large amplitude with a dense high-temperature plasma. In the present work we analyze the efficiency of turbulent ion-heating processes in high-current z-discharges. We discuss the particular case in which the depth of penetration of the pulsed fields into the plasma due to excitation of ion-acoustic microinstabilities[7] is clearly greater than the radius of the plasma column and we can expect that under experimental conditions the current distribution over the cross section of the discharge is not too far from uniform.

The analysis of experimental data in this work is supplemented by a phenomenological model describing the heating of electrons and ions in z-discharges with anomalous conductivity. On the basis of the assumptions used, it is possible to construct a rather simple and clear model which leads to results qualitatively suitable for practical application. The regularities found in the present work are compared with the results of similar studies published previously.[9-14]

DESCRIPTION OF EXPERIMENTS

The experiments were carried out in a series of YaNUS installations. The characteristic design features common to all the installations and the plasma diagnostic methods used in the experiments have been described in our earlier articles.[2-8] A block diagram of the apparatus, which was the same for all experiments, is given in [4]. Preliminary ionization of the gas in the chamber was accomplished by means of a pulsed Penning discharge. For simplicity of interpretation of the results obtained, we did not use the corkscrew configuration of longitudinal magnetic field in the series of experiments described. For discharge current amplitudes $I \lesssim 50$ kA we used chambers of length $L = 1$ and 0.4 m, and for currents $I \approx 0.3$ MA we used $L = 0.15$ m.

Aluminum electrodes were used. Tubes of quartz or high-frequency ceramic were used as vacuum chambers. The current generator in all experiments was a high-voltage pulse generator with low characteristic impedance, operating under conditions close to critical. The gas was hydrogen.

Discharges were studied in the plasma density range 10^{13}–10^{15} cm^{-3}. The transverse dimensions of the current column were limited by dielectric diaphragms. Discharges with plasma column radii from 1 to 4 cm were studied in various experiments. In all experiments the pulse had a characteristic rise time from zero to maximum $t_0 \approx 2\times10^{-7}$–$1\times10^{-6}$ sec. The electrical parameters of the pulse-generator circuit were chosen so that t_0 was less than the flight time of thermal ions in the discharge gap in the direction along the axis of the system. Only in the experiments with a chamber length $L = 0.15$ m could this condition not be satisfied.

In accordance with [7], on fulfillment of the condition $B_z/B_\varphi > 1$, $(L/a)^2 \gg 1$, the heat losses due to electronic conduction along the system axis and in the direction perpendicular to it under turbulent discharge conditions could be considered rather small for the experimental conditions. B_z and B_φ above are the longitudinal field and the field of the discharge current.

The experimental values of electron and ion temperatures in the experiments were determined from simultaneous measurements of the diamagnetic effect in the plasma, averaged over the cross section of the column, and of the energy distribution function of the ions. The diamagnetism of the plasma was measured by ordinary methods[1-14] by means of magnetic probes and loops surrounding the discharge. Study of the energy spectrum of the ions in the experiments was carried out by the well known method of analysis of neutral hydrogen atoms in the range from 100 eV to several kilovolts.[5,9-14] A more detailed description of the features of the apparatus used and of the measurement technique is contained in [5].

The distribution of the ions in energy was determined for two directions of emission of charge-exchange atoms from the plasma—along the magnetic field B_z and perpendicular to it. In experiments with a dense plasma ($n > 10^{14}$ cm^{-3}) for the charge-exchange atom energy region lying below the sensitivity threshold of the apparatus $\mathscr{E} \lesssim 100$ eV, the particle spectrum was determined by means of direct measurements by an electrostatic analyzer of the Hughes-Rojansky type for ions emitted along the axis of the system. Under all experimental conditions the ion spectrum obtained was close to isotropic.

The plasma density in the experiments was determined by means of microwave diagnostics, laser interferometry, spectroscopy in the visible region, and corpuscular diagnostics.

The diameter of the current column in the experiments was assumed equal to the internal diameter of the diaphragms, in accordance with the data of magnetic measurements in [7].

EXPERIMENTAL RESULTS

The discharge characteristics found in the experiments turned out to be in many respects the same as in most studies of turbulent heating of plasma under similar conditions.[1,9-14] Thus, the measurements made showed that over a wide range of discharge parameters the plasma in the experiments is characterized by an anomalously low value of conductivity, which is unexplainable in terms of the Coulomb collision mechanism. Plasma conductivity values obtained from the volt-ampere characteristics of the discharge show that the resistance of the interelectrode gap has its greatest value during the rise of the current from zero to the maximum. In agreement with this the heating of the plasma is mainly completed at the moment $t \approx t_0$ of the current maximum in the pulse, and the energy contribution to the discharge in the subsequent stages of plasma heating is small. Just as in [1,9-14], the plasma conductivity in the region of most efficient heating is several orders of magnitude below the Spitzer value, if in analysis of the experimental results we neglect the potential drop adjacent to the electrodes. High-temperature ions in the discharge appeared near the point of passage through zero of the voltage applied to the discharge gap. The x rays observed in the initial stages of the discharge were, as a rule, cut off at the moment of appearance of heated ions in the plasma.

We note one feature of the discharges studied. Special measurements with magnetic probes showed that when heating pulses longer than 3–4 μsec were used, large-scale MHD perturbations of large amplitude were observed under experimental conditions. Appearance of this form of instability in the experiments led to a rapid cooling of the plasma, accompanied by separation of a large quantity of impurities in the discharge gap. For the current pulse duration selected in the experiments, $t_0 \approx 10^{-6}$ sec, large-scale perturbations of the current column were not, as a rule, observed if the plasma density exceeded a critical value 10^{13} cm^{-3}.

In order to determine the efficiency of particle heating in z-discharges with anomalous plasma conductivity, we obtained experimentally the maximum value during the pulse of the gas-kinetic pressure $p = \langle nT \rangle = n(T_e + T_i)$ as a function of the amplitude of the current magnetic field B_φ. Here T_e and T_i are respectively the electron and ion temperatures in the discharge. The experimental data are given in Fig. 1. In accordance with the experimental results it is evident that the discharge chamber designs and plasma heating method used in the experiments are characterized by the simple empirical relation

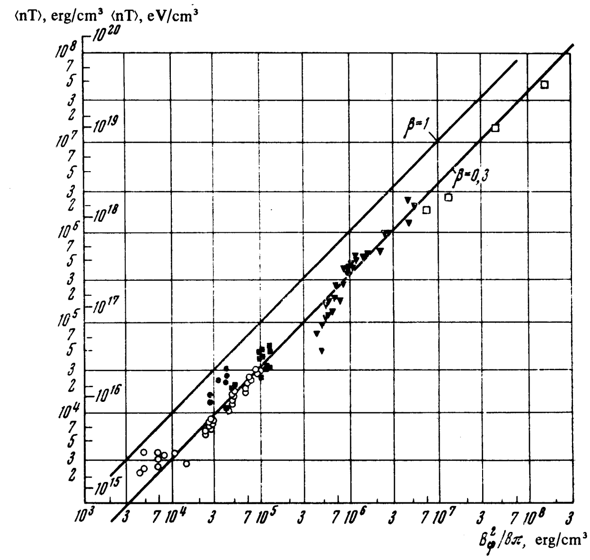

FIG. 1. Gas-kinetic pressure of the plasma $p = \langle nt \rangle = n(T_e + T_i)$ as a function of the current magnetic field B_φ under various experimental conditions in apparatus of the YaNUS series: ○, □, ○–B_z = 1.5–3 kOe, L = 1 m, a = 3.5 cm, n ≈ 3 × 10^{13} cm^{-3}; ∇–B_z = 4–6 kOe, L = 0.4 m, a ≈ 2–2.5 cm, n ≈ (2–4) × 10^{14} cm^{-3}; □–B_z = 2–8 kOe, L = 15 cm, a ≈ 1.2–1.4 cm, n ≈ 4 × 10^{15} cm^{-3}.

$$\langle nT \rangle = \beta B_\varphi^2 / 8\pi \quad (1)$$

with an average value $\beta = 0.3 \approx$ const for a wide range of discharge parameters. The value of β obtained is close to the data of [9-15].

We recall that under the experimental conditions the theoretical value of the turbulent skin-layer thickness δ_S [7] is always larger than the radius of the plasma column. Therefore the plasma-temperature dependence on the current field obtained in the experiments is a somewhat unexpected fact, since in accordance with the analysis made in [7] Eq. (1) should, strictly speaking, be observed only in "skinned" discharges.

Comparison of the results of measurements in different experiments, carried out in [8], indicates the extremely general nature of Eq. (1).

Let us turn to discussion of the results which describe the ion heating process in z-discharges with anomalous conductivity. Systematic measurements of the energy spectrum of ions in the present experiments have been made for installations characterized by a value $\langle nT \rangle \approx 10^{16}$–$10^{17}$ eV-cm^{-3}. In contrast to similar studies such as [9-14], the measurements carried out by us permit determination, although rather crudely, of the dependence, unknown up to this time, of ion temperature on plasma concentration and on discharge-current amplitude.

As illustrative material we have shown in Fig. 2 on a semilogarithmic scale typical ion spectra obtained in experiments for two values of plasma density. For both curves the current field is $B_\varphi \approx 1.6$ kOe, the longitudinal magnetic field B_z = 3 kOe, the plasma column radius a = 3.5 cm, $\langle nT \rangle \approx 2 \times 10^{16}$ eV-cm^{-3}. The slope of the different portions of the curves indicates exis-

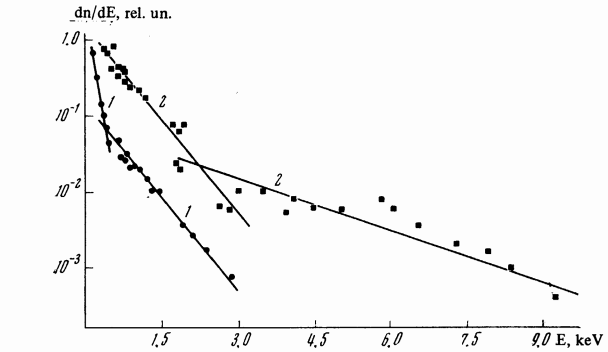

FIG. 2. Ion energy spectrum obtained in the experiments. Curve 1—$n = 3 \times 10^{13}$ cm^{-3}, $\langle nT\rangle = 2 \times 10^{16}$ eV/cm^3, $T_{i1} = 100$ eV, $T_{i2} = 470$ eV. Curve 2—$n = 1 \times 10^{13}$cm^{-3}, $\langle nT\rangle = 2 \times 10^{16}$ eV/cm^3, $T_{i1} = 470$ eV, $T_{i2} = 1700$ eV, a = 3.5 cm, L = 1 m.

tence of two values of ion temperature in the discharge in each of the regimes. It is natural to assume that the more numerous ion group corresponding to the low temperature value $T_i = T_{i1}$ is the main group. An estimate of the maximum quantity of hot protons with $T_i = T_{i2} > T_{i1}$, made on the assumption that the spectrum obtained is formed by superposition of two Maxwellian distributions, shows that the fraction of ions with $T_i = T_{i2}$ is no more than 1% of the number of ions with $T_i = T_{i1}$.

From comparison of curves 1 and 2 of Fig. 2 it is evident that with increasing plasma density the ion temperature falls both for the group with $T_i = T_{i1}$ and for the group with $T_i = T_{i2}$. It was established in the experiments that the experimentally measured ion spectra depend weakly on the longitudinal magnetic field intensity. In the energy region studied the ion distribution function depends weakly on the discharge current pulse duration. As experiments showed, for a given plasma concentration the values of T_{i1} for each installation are determined for the most part only by the amplitude of the field B_φ. The relations $T_e/T_{i1} > 3$, $T_e/T_{i2} \approx 1$ were always satisfied under the experimental conditions.

Estimates made show that under the conditions of most experiments the main contribution to the energy balance of the discharge is from ions with $T_i = T_{i1}$. The ion group with $T_i = T_{i2}$, which satisfies the condition $T_{i2} \approx T_e$, can play an appreciable role only in the dynamics of establishing the level of plasma turbulence.[1]

The relation (1) found above, together with the inequality $T_e/T_{i1} > 1$, permits finding the ratio, often used in the theory of plasma instabilities, of the directional electron velocity $u_{\|} = j/en$ to the ion-acoustic velocity $u_s = (T_e/M)^{1/2}$ at the moment of the peak discharge current:

(2)

Here j is the current density, M is the ion mass, $\delta_s \approx c/\omega_{0i}\beta^{1/2}$ is the thickness of the turbulent skin-layer.[7] Terms of order T_{i1}/T_e were dropped in derivation of Eq. (2). ω_{0i} is the plasma ion frequency.

From the experimentally known values of n, β, $\langle nT\rangle = n(T_e + T_i)$, T_{i1}, T_{i2}, and a in the experiment we calculated the quantities

$$\frac{T_e}{T_{i1}} = \frac{\langle nT\rangle}{T_{i1}} - 1, \quad \frac{T_e}{T_{i2}} = \frac{\langle nT\rangle}{T_{i2}} - 1, \quad \alpha.$$

The data obtained in the experiment for the case $\langle nT\rangle = 2 \times 10^{16}$ eV-cm^{-3} and three plasma density values $n = 3 \times 10^{13}$ cm^{-3}, 1×10^{13} cm^{-3}, and 10^{14} cm^{-3} are plotted in Fig. 3 by the points with respective numbers 1, 2, and 3. For comparison with the theory of ion-acoustic microturbulence, we have chosen a coordinate system in Fig. 3 in which the limit of excitation of ion sound is described by curve 1.[16]

The accuracy with which T_e/T_i and α are determined, which was estimated from the spread in the measurements, is no better than 30%. It is evident from Fig. 3 that within the experimental errors all of the ratios T_e/T_{i1} found in the experiments are close to the position of the limit of ion-acoustic instability. As has already been noted, the values of T_e/T_{i2} are always grouped in the region $T_e/T_{i2} \approx 1$.

To confirm the general nature of the result obtained, together with the data of the present work we have plotted in Fig. 3 the results of similar measurements in [10–12], where the energy distribution of the ions in experiments on turbulent heating of plasma had a clearly expressed two-temperature nature. It is evident that, in spite of the substantial difference in the design of the apparatus and in the values of n, a, β, and L, these data also are in good agreement with the regularity found: the values of T_e/T_{i1} are close to the limiting values, $T_{i2} \approx T_e > T_{i1}$.

We note a series of experimental studies[9, 13, 14] (Fig. 3, points 7, 8, and 9) in which the ion energy spectrum is described by only one temperature value $T_i = T_i^*$. In this case, according to the data of Fig. 3 always $T_i^* \approx T_e$ and either the ion group with $T_{i1} < T_e$ was not observed in the experiments as the result of insufficient sensitivity of the measuring equipment in the region $\mathscr{E} < 500$ eV, or not ion-acoustic micro-oscillations but some other mechanism of energy transfer from electrons to ions is responsible for heating the ions. In fact, for $T_i \approx T_e$ the ion-acoustic instability excitation criterion is clearly not satisfied and excitation of ion sound under such conditions is impossible.

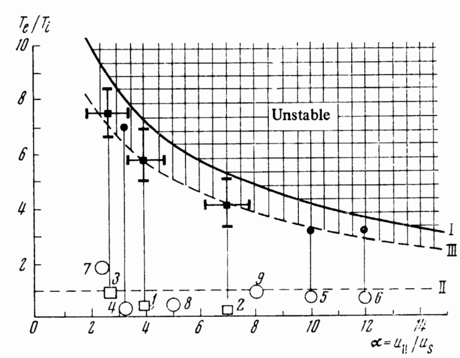

FIG. 3. The dependence obtained experimentally for the ratio T_e/T_i on the parameter α. Points 1, 2, and 3 were obtained in the present work for $n = 3 \times 10^{13}$ cm^{-3}, $n = 10^{13}$ cm^{-3}, and $n = 10^{14}$ cm^{-3} for conditions corresponding the data of Fig. 2. Point 4 is taken from ref. 12, 5 from ref. 10, 6 from ref. 11, 7 from ref. 9, 8 from ref. 14, 9 from ref. 13. Curve I is the theoretical location of the boundary of ion-acoustic microinstability, II—$T_e/T_i = 1$, III—experiment.

DISCUSSION OF RESULTS OBTAINED

Turning to analysis of the experimental results obtained in study of the regularities of electron and ion heating in high-current z-discharges with anomalous plasma conductivity, we note that the diagnostic methods used by us, which are the usual methods for most similar work, permit measurement of only the integrated characteristics of the plasma column in the experiments. Therefore, in interpretation below of the results obtained, it is necessary in most cases to work with quantities averaged over the cross section and length of the plasma column.

In establishment of the regularities necessary to explain the properties of z-discharges of the type discussed, we will limit ourselves to the following model representations. We will assume that the appearance of anomalous conductivity in high-current z-discharges is due to excitation in the plasma of ion-acoustic instability. The process of momentum transfer from electrons to ions in a plasma with a steady background of ion-acoustic microinstability is analyzed in a number of articles, for example, in [1,17,18]. In accordance with the theoretical results given in these articles we can expect that the Joule heat dissipated in the anomalous resistance is transferred initially to the electrons, and then through the microfield directly to the ions.

We will assume that in the case discussed the interaction of particles in a turbulent plasma is equivalent in the last analysis to ordinary binary collisions with an effective collision frequency ν_S due to the presence of the microfield of the ion-acoustic instability in the plasma. Here, as experiment shows, under the conditions of most experiments with high-current z-discharges the contribution of Coulomb collisions to the particle heating process is negligible. As a result of this fact, in construction of the model it is assumed that the role of binary collisions in discharges with anomalous conductivity is unimportant.

We note also that the optimal prospects which can be associated with the transition to turbulent methods of electron and ion heating in z-discharges are given by the calculation of plasma heating by a current on the assumption of the complete absence of energy loss. Therefore, as the simplest variant, we have discussed below only the case in which during the heating of the plasma the energy loss from the discharge is small and does not need to be considered.

In a case where the assumptions made are valid, the equations which describe the energy balance in turbulent z-discharges with current heating of plasma retain their usual form:

$$\frac{d}{dt}\frac{3}{2}[n(T_e+T_i)]=\mathbf{Ej},\quad \frac{d}{dt}T_i=\delta\nu_s(T_e-T_i). \tag{3}$$

Here ν_S is the effective collision frequency, n is the plasma density, T_e and T_i are the temperatures of the principal, most numerous group of electrons and ions, respectively, δ is the fraction of energy lost by an electron in a time $\tau_S = \nu_S^{-1}$. We assume that the anomalous conductivity σ_S is related to ν_S by the usual relation: $\sigma_S = ne^2/m\nu_S$.[7]

As is well known, in collision of a light particle with a particle at rest, the latter can receive an energy transfer of the order of the mass ratio $\delta \approx 2m/M$. In our case this quantity is unknown. To estimate it we will use the following reasoning. Under extremely general assumptions[19] it can be shown that in the case of a steady current-flow process in the discharge, when all of the energy acquired by an electron between collisions is transferred to ions, the following equality is satisfied:

$$\delta=(u_\parallel/u_{Te})^2=\alpha^2 m/M. \tag{4}$$

In the case discussed the system is nonstationary and we can state only that $2m/M < \delta \lesssim \alpha^2 m/M$. At the same time, in the current peak when $u_\parallel \approx$ const, we can evidently assume that the relation $\delta = \alpha^2 m/M$ is valid.

We note that in most experiments with high-current z-discharges, as a rule, the inequality $(u_\parallel/u_{Te})^2 \ll 1$ or the equivalent inequality $(M/m)^{1/2} > \alpha \gtrsim 1$ is satisfied.

We will limit ourselves to discussion of the special case of pulsed z-discharges. Let us consider the plasma heating process only during the phase corresponding to the rise of the discharge current I(t) from its zero value to the maximum $I(t_0)$. In the interval $0 \le t \le t_0$ we can approximate the shape of the current pulse by the relation $I(t) = I(t_0)\sin\omega t$. Note that for this choice of I(t), $t_0 = \pi/2\omega$ and $B_\varphi = 2I(t_0)/ca$.

Let us take into account the threshold nature of the ion-acoustic instability. For this purpose we will write the effective frequency of collision of electrons with ions in the form

$$\nu_s=\begin{cases}\nu_0(1-\alpha_c/\alpha) & \text{for } \alpha>\alpha_c,\\ 0 & \text{for } \alpha<\alpha_c,\end{cases} \tag{5}$$

where the function $\alpha_c(T_e/T_i)$ corresponds to the critical value of α, beginning with which instability arises for a given ratio T_e/T_i. The relation between T_e/T_i and α_c, which was taken from [16], is shown in Fig. 3, curve I. The analytical form of the function $\alpha_c(T_e/T_i)$ is rather cumbersome,[1,16] and therefore in practical calculations it is convenient to use an approximation of α_c in the form

$$\alpha_c\approx 75(T_i/T_e)^{3/2}. \tag{6}$$

We can convince ourselves by direct numerical verification that Eq. (6) differs from the exact relation[1,16] by no more than 5% in the range $2 \le \alpha \le 15$. In Eq. (5) ν_0 is a still undetermined constant which can be obtained either on the basis of exact calculations of the dynamics of development of the ion-acoustic instability under experimental conditions, or can be evaluated on the basis of the experimental data.

In accordance with the data of Fig. 1, in what follows we will assume that under the experimental conditions the relations $\alpha \gtrsim \alpha_c(T_e/T_i)$, $T_e/T_i \gg 1$, which are necessary for excitation of the ion-acoustic microinstability, are always satisfied.

We will add one more assumption. We will assume that the principal fraction of the thermal energy released in the plasma up to the moment when the peak current value is reached is associated only with the change of energy of the conducting medium on penetration of the current magnetic field into it. In this case the heating stops at the moment when $\partial B_\varphi/\partial t$ in the discharge goes to zero.

We will consider the results of a general analysis of processes of this type,[20] from which after integration of Eq. (3) we find the average value of thermal energy density in the discharge at the moment $t \approx t_0$:

$$\langle nT\rangle = \frac{1}{4\pi V}\int B_\varphi \delta B_\varphi dV \approx \frac{B_\varphi^2}{8\pi}. \quad (7)$$

In Eq. (7) δB_φ is the increase in B_φ during the rise of the discharge current from zero to its maximum, and the integral is taken over the entire volume of the plasma cylinder $V = \pi a^2 L$.

As we see, the theoretical dependence (7) obtained in our model representations correctly reflects the regularity (1) found in the experiments and differs from the experimental behavior only by a correction factor $\beta \approx$ const ≈ 0.3.

Taking into account Eqs. (1), (5), and (7) and the assumptions made, we will rewrite the system of Eqs. (3) in the form

$$nT_e = \beta B_\varphi^2/8\pi \quad \text{for } t \approx t_0; \quad (3a)$$

$$dT_i/dt \approx T_e \nu_0 \delta (1 - \alpha_c/\alpha) \quad \text{for } 0 \leqslant t \leqslant t_0. \quad (4a)$$

Let us estimate the value of $\nu_0\delta$ expected from the theory of ion-acoustic instability. We will use the estimate for ν_0 given in one of the most recent publications:[18]

$$\nu_0 \approx 2m\omega_{0e}/M. \quad (8)$$

It is easy to be convinced that for the case in which ν_0 corresponds to Eq. (8), even in the most unfavorable conditions of z-discharges with record-breaking small current-pulse durations $t_0 \approx 10^{-6}$ sec and for the usual values $a \approx 5$ cm, $\beta \approx 0.5$, and $n \gtrsim 10^{13}$ cm^{-3}, in accordance with the theory[18] we should have:

$$\nu_0\delta > \omega. \quad (9)$$

We will assume that the inequality (9) obtained from the calculations is satisfied in the experimental conditions with z-discharges. Then, for the case of an incompressible plasma column the validity of the relation (1) obtained in the experiments, and of Eq. (2) which follows from it, follows directly from (3a). Further, using inequality (9), we obtain from (3b) the asymptotic approximation

$$\lim (1 - \alpha_c/\alpha) = 0 \quad \text{for} \quad \omega/\nu_0\delta \to 0, \quad (10)$$

where at the moment $t = t_0$ the quantity α satisfies equality (2), and α_c is found from Eq. (6). Since according to Eq. (5) the condition $1 - \alpha_c/\alpha = 0$ determines the location of the boundary of ion-acoustic instability (Fig. 1), in the case when Eq. (10) is valid we should expect that in the approximation adopted the experimental values of $T_e/T_{i1} = f(\alpha)$ should be grouped in the region of transition of the system from an unstable state to a stable one. It is not hard to convince ourselves that the result obtained has a quite general nature and does not depend on the specific form assumed in Eq. (5) of the functional relation $\nu_s(\alpha_c, \alpha)$, if ν_s increases sufficiently rapidly with distance from the boundary of instability (Fig. 1).

The relations obtained permit determination of the efficiency of heating electrons and ions in z-discharges with anomalous conductivity, if at the moment $t = t_0$ the plasma column radius a, discharge current $I(t_0)$, the quantity β, and the plasma density n are known. We recall that the system of Eqs. (3) is applicable, strictly speaking, only to discharges in which the particle interaction is described by binary collision theory. The attempt set forth above to use Eqs. (3) formally to describe processes in discharges with anomalous conductivity naturally can be justified only as the result of a systematic comparison of the results of the calculations with experiment.

In terms of the assumptions which have been made, Eqs. (1), (2), (6), and (10) determine the energy balance in the plasma of z-discharges with ion-acoustic microinstability. We recall that the data of the experiment are satisfactorily described by the model representations developed above only for cases in which experiments on plasma heating revealed a two-temperature distribution of ions in energy under conditions of an anomalously low plasma conductivity measured in the discharge.

The agreement obtained between the experimental results and the model calculations indicates the correctness of the assumptions which we have made as to the nature of the electron and ion heating processes in pulsed z-discharges with ion-acoustic microinstability.

Unfortunately, in the current stage of the investigations the level of the diagnostic technique and the accuracy of the quantities measured with it are still far from sufficient to determine the causes of the systematic deviation observed in the experiments of the measured T_e/T_{i1} and calculated T_e/T_i (Fig. 3). Therefore it is difficult to say whether the observed systematic difference is associated with the experimental error, with the inaccuracy in calculation of $\alpha_c(T_e/T_i)$, or with the hysteresis phenomena which are normal for instabilities of a threshold nature. Independently of further improvement in the theoretical results and measurements, it is already apparent that the model which we have presented for evaluation of T_e and T_{i1} allows prediction of the parameters of discharges with an accuracy sufficient for practical purposes.

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