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TURBULENT HEATING OF IONS IN A SKIN-EFFECT HIGH FREQUENCY DISCHARGE

L. V. DUBOVOĬ, B. A. IVANOV, and V. I. CHERNOBROVIN

D. V. Efremov Research Institute for Electrophysical Apparatus

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The ion energy spectrum in a high-frequency discharge with a skin current is measured by corpuscular-diagnostics techniques. The shape of the spectrum indicates the existence of two groups of ions in the experiments. The main group has a temperature $T \sim 50$ eV and a smaller group possesses a temperature $T \sim 700$ eV, the mean electron temperature in the plasma being $\sim$100 eV. Both ion groups can be described by a Maxwellian energy distribution function. An analysis of the results shows that the plasma during the initial stage is collisionless and the heating of electrons as well as ions is of a turbulent nature. The results of the experiments are in satisfactory agreement with the theory that predicts plasma heating due to excitation of ion-acoustic microinstability in the skin-layer region.

OHMIC heating of a plasma, using the Coulomb mechanism of collisions of charged particles, is one of the most convenient methods of obtaining electron and ion temperatures on the order of several hundred electron volts. In the region of higher temperatures, however, the method becomes little effective, particularly for heating of ions. The decrease of the resistivity of the plasma, which accompanies the increase of the temperature, calls for inadmissibly large values of currents to ensure a sufficiently high level of power input to the plasma.

When the experimental conditions are suitably chosen, the use of time-varying currents can lead to a concentration of the heating fields in the skin, thereby increasing, as can be readily shown, the impedance of the plasma load by a factor $a/2\delta > 1$ times, if the skin-layer thickness δ is smaller than the radius a of the current column.

Heating of a plasma in a skin-effect high-frequency (HF) discharge in experiments on dynamic stabilization of a plasma was investigated in[1], but, quite unexpectedly, the heating efficiency turned out to be here much higher than expected for the case of pure Coulomb conductivity.

To explain this effect, the following hypothesis was advanced in[1]: just as in experiments with powerful pulsed discharges[2], a small-scale ion-acoustic instability can develop in the region of the skin layer, and this leads to an additional growth of the resistivity of the plasma, to a corresponding increase of the absorbed HF field energy, and to a more effective heating of the plasma. Favoring this hypothesis was, in particular, the threshold character of the heating process, which was in satisfactory agreement with the criterion for the occurrence of ion sound in a plasma in the region of the skin layer.

The present investigation, which is a continuation of[1], is devoted to the study of the energy spectrum of ions in a HF discharge with anomalous resistance, since one can expect, on the basis of the theory of ion-acoustic instability[2,3] and of experiments on turbulent heating of a plasma in pulsed discharges, that the electron heating observed in[1] will be accompanied by ion heating under the conditions of a skin-effect discharge. At the same time, the energy spectrum of the ions can yield additional information concerning the mechanism of plasma heating in a HF discharge[3].

We use the following notation: $\omega_0^2 = 4\pi ne^2/m_e$ and $\omega_{0i}^2 = \omega_0^2 m_e/m_i$—electron and ion plasma frequencies, respectively, $\omega_{ce} = eB/m_e c$ and $\omega_{ce} m_e/m_i$—electron and ion cyclotron frequencies, $B_\varphi = 2I_0/ca$—magnetic field of the current, $\omega_{c\varphi} = eB_\varphi/m_e c$, ν—collision frequency of the electrons in the plasma, $\sigma = \omega_0^2/4\pi\nu$—conductivity of the plasma, and $\beta = 8\pi nT/B_\varphi^2$—plasma pressure referred to the magnetic field of the current.

A block diagram of the setup is shown in Fig. 1. We used a quartz discharge chamber of 10 cm diameter and length $L = 100$ cm; the plasma-column diameter was $2a = 4$ cm, and was bounded by two glass diaphragms placed in the region of the discharge electrodes. The spatially-homogeneous quasi-stationary magnetic field B_z could be varied in the experiments from 500 to 3000 Oe, the discharge current $I = I_0 \sin \times (\omega t)$ had a frequency $\omega = 1 \times 10^7$ sec^{-1}; in the experiments, $I_0 = 1$ kA, the current pulse duration was 250 μsec, the amplitude of the voltage applied to the discharge gap was $\sim$1.5 kV, the active component of the discharge resistance was 0.6 ohm, the power absorbed in the plasma $W = 0.3 \pm 0.1$ MW, the initial gas pressure $P = 2 \times 10^{-3}$ Torr, and the gas was hydrogen. The running energy density in the discharge, $\langle nT \rangle \approx 1 \times 10^{17}$ eV/cm, was determined from the diamagnetic effect; the electron temperature previously measured by the double-probe method was $T_e \approx 100$ eV. The skin-layer thickness was measured with magnetic probe and amounted to $\delta = 0.5$ cm. The energy lifetime of the

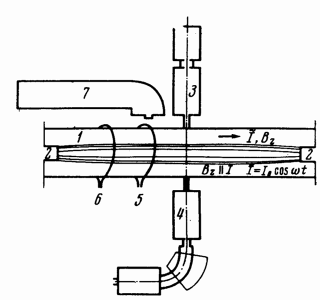

FIG. 1. Block diagram of setup. 1 – Plasma column, 2 – discharge electrons, 3 – source of beam of probing atoms, 4 – atom analyzer, 5 – diamagnetic probe, 6 – Rogowski belt, 7 – spectrograph.

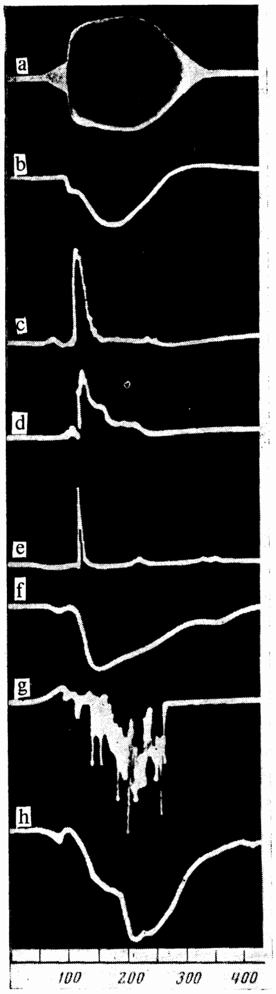

FIG. 2. Oscillograms: a – HF current; b – diamagnetic signal; c – flux of hydrogen atoms E = 100 eV; d – flux of hydrogen atoms, e = 700 eV; e – flux of hydrogen atoms, E = 12 keV; f – emission intensity of H_β line; g – flux of carbon atoms C_0; h – emission intensity of C_{II} in discharge.

plasma was $\tau = \langle nT \rangle LW^{-1} \approx 10^{-5}$ sec. The results depended little on the value of the longitudinal magnetic field B_Z, in spite of the fact that the experiments were performed under conditions when $\omega \gtrless \omega_{ci}$.

As shown in[1], the radial distribution of the plasma has a sharp boundary in the region $r \sim a = 2$ cm, determined by the internal diameter of the diaphragms, and a flat top. To estimate the plasma density we used in the present experiments the procedure of absorption of a beam of hydrogen atoms[4] passing through the discharge. The measured plasma density $n \approx 1 \times 10^{14}$ cm^{-3} corresponds to no less than 75% ionization of the gas in the entire volume of the discharge.

The hydrogen ion energy distribution function f(E) in the discharge was determined from the energy spectrum of the charge-exchange atoms H_0 emitted from the plasma in a direction perpendicular to B_Z. This has made it possible to reduce to a minimum the contribution of the current velocities of the ions to f(E). An atomic-particle analyzer was used in the experiments, with a lower energy sensitivity limit E_k equal to 100 eV for hydrogen and 500 eV for carbon[5].

Figure 2 shows the following experimental oscillograms: of the HF current I; the diamagnetic signal $\Delta\Phi \sim \langle nT \rangle$; of the quantity S proportional to the flux of hydrogen atoms incident on the discharge, for the most characteristic values of the atom energy E = 0.1, 0.7, and 12 keV; of the emission intensity of the H_β and C_{II} lines in the region between the boundary of the plasma and the chamber wall; and of the flux of neutral atoms of the impurity carbon C_0 with energy 1 keV. An important feature of the obtained oscillograms is the typical jumplike growth of the diamagnetic signal $\Delta\Phi$ and of the yield of the charge-exchange atom flux S at the initial stage of the discharge; this growth is typical of all operating conditions. Since it was shown earlier that the appearance of a diamagnetic signal in the experiments is always connected with the instant of formation of the skin layer in the discharge, it can be assumed that the production of fast charge-exchange atoms is also due to the process of plasma heating in the region of the skin layer. It is seen from the oscillograms that the time of establishment of the flux of neutral atoms, and consequently also the time of heating of the ions in the discharge, does not exceed $(3-5) \times 10^{-6}$ sec.

An estimate of the energy carried away from the plasma by the charge-exchange atoms during the initial stage of the discharge shows that the corpusular stream incident on the walls of the chamber can lead to the occurrence of an intense liberation of gas from the walls. This is confirmed by the time variation of the emission of the H_β and C_{II} lines in the region of the gas chamber next to the wall. Thus, the maximum emission of the H_β line corresponds to the arrival of the bulk of the hydrogen at the boundary of the plasma, shifted by a time $t \approx 40$ μsec from the start of the discharge; as expected, by virtue of the large mass of carbon, the large yield of the neutral C_0 atoms and the maximum emission of the C_{II} line correspond to $t \sim 120$ μsec.

The lack of complete information concerning the space-time characteristics of the gas flow from the walls makes it difficult to interpret quantitatively the process of plasma cooling in the region of the skin layer by the impurities. We shall therefore pay principal attention to the process of plasma heating only during the initial stage of the existence of the discharge.

The dynamics of the behavior of the ion component of the plasma during this stage is characterized by the energy spectrum of the hydrogen ions f(E), shown in Fig. 3, and obtained for instants of time t equal to 0, 50, and 100 μsec. As seen from the curves of Fig. 3, the ion spectrum f(E) for $t \approx 0$ is satisfactorily described by two segments of straight lines corresponding to the state of the plasma with two groups of ions, each of which characterized by its own Maxwellian

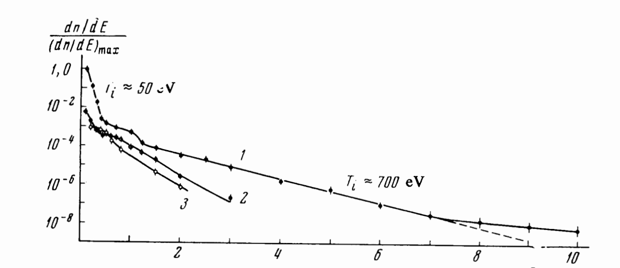

FIG. 3. Energy distribution function of hydrogen ions. 1 – t = 0, 2 – t = 50 μsec, 3 – t = 100 μsec. The curves are normalized to the value of $(dn/dE)_{max}$ corresponding to dn/dE at t = 0 and E = 100 eV.

energy distribution function $f_1(E, T1)$ and $f_2(E, T_2)$. From the slopes of the curves we have $T_1 = 50$ eV for the low-temperature ion group, and $T_2 = 700$ eV for the high temperature group.

For the succeeding stages of the existence of the discharge, the low-temperature part $f(E)$ vanishes. The reason for this phenomenon will be discussed below.

The experimentally obtained function $f(E, T)$ for $t \sim 0$ makes it possible to find the ratio of the density n_1 of the ions with $T = T_1 = 50$ eV to the density n_2 of the ions with $T = T_2 = 700$ eV. This can be carried out most simply under the assumption that, just as for $E \gg 100$ eV, $f_1(E)$ and $f_2(E)$ in the region $E < E_k = 100$ eV that is inaccessible to measurement are described by a Maxwellian distribution function with corresponding ion temperatures T_1 and T_2. The quantity determined in this manner is

$$\frac{n_1}{n_2} = \int_0^\infty f_1(E)\,dE \Big/ \int_0^\infty f_2(E)\,dE \sim 10^2$$

and the ion group with $T_1 = 50$ eV can be regarded as the main group, while $T = 50$ eV can be regarded as the average temperature of the ions in the discharge. The obtained values $T_1 = 50$ eV are in good agreement with control estimates of the ion temperature from measurements of the Doppler broadening of the line H_β in the discharge. Thus, in accordance with the optical measurements at $t \approx 0$, the quantity T_i will be of the order of 70 eV.

Starting from the experimentally obtained Maxwellian character of the function $f(E, T) \propto T^{-1/2} \exp(-E/T)$, we can calculate from the oscillograms of the charge-exchange atom flux $S(t) \sim f(E)$ (Fig. 2) the functions $T_{1,2}(t)$. Figure 4 shows plots of $\langle nT \rangle = \varphi(t)$, $n(t)$, and $T_{1,2}(t)$, averaged over several discharges and obtained as a result of suitable reduction of the experimental data. In the calculations of $T_{1,2}$ it can be assumed that the decrease of the flux of the registered charge-exchange atoms $S(t)$ is connected principally with cooling of the ions, and is determined mainly by the factor with the exponential dependence on $T_{1,2}$ in $f(E, T)$, being weakly dependent on the change of the plasma density and of the charge-exchange center concentration.

A comparison of the data of Figs. 2–4 shows that the time interval $0 \le t \le 20$ μsec, which is characterized by the minimal contamination of the plasma by the gas-release products from the walls, corresponds to the largest value of the ion temperatures $T_{1,2}$. It is also seen that with increasing concentration n, which is proportional to the rate of entrance of the impurities in the plasma, $T_{1,2}$ decreases by an approximate factor of 2 during 15 μsec from the instant of the start of the discharge. Attention is called to the fact that the group of ions with $T = 50$ eV which is all resolved by the apparatus at $t \sim 0$ (Fig. 3), falls in the case of $t > 50$ μsec in the region $E < E_k = 100$ eV and is no longer registered in the experiments. The qualitative course of the obtained curves remains unchanged in the entire range of the values $B_z = 0.5$–3 kOe and $n = 5 \times 10^{13}$–5×10^{14} cm^{-3} used in the experiments.

It is convenient to start the analysis of the processes responsible for the experimentally observed heating of

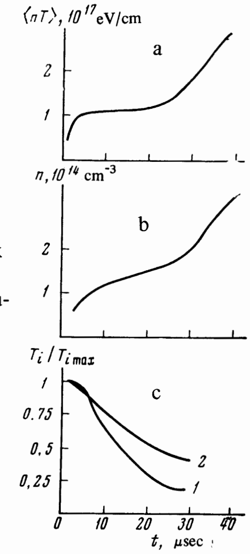

FIG. 4. Quantities calculated for the initial stage of the discharge: a – running energy density in the discharge ⟨nT⟩, b – plasma concentration n(t), c – $T_1(t)/T_{1max}$ (curve 1) and $T_2(t)/T_{2max}$ (curve 2). The time dependence of $T_{1,2}(t)/T_{1,2max}$ is calculated from the oscillograms of the flux of atoms with energies 100 eV and 4.5 keV, respectively.

the electrons and ions at $t < 30$ μsec with a comparison of the role of the most probable mechanisms, under the experimental conditions, for the absorption of the energy of the HF fields by the plasma. It is assumed in the subsequent analysis that the magnetic field is strong enough and that the transport phenomena in a direction perpendicular to the magnetic field are appreciably attenuated for the electronic plasma component. This is true if the Larmor radius ρ of the particle is small compared with the thickness of the skin layer. In our case $\rho \le 0.04$ cm $< \delta$, and the electrons are magnetized if $\omega_{ce}/\nu \gg 1$. As will be shown below, even under the most unfavorable conditions in the skin layer we have $\omega_{ce}/\nu > 10$ and the conditions for the magnetization of the electrons are always satisfied. For ions we have $\rho_i \approx 1$ cm $\sim a$ and the ions are not magnetized. In the plasma column the ions are contained by the space charge of the electrons frozen in the magnetic field.

Let us examine now the processes that exert the strongest influence on the magnitude of the skin layer in the experiments. We shall use the well known formula for the skin-layer depth δ governed by the pair collisions of the particles, $\delta = (c/\omega_0)(2\nu/\omega)^{1/2}$, and substitute for ν the effective frequency ν_{eff}. In the general case $\nu_{eff} = \Sigma\nu_\alpha$, where the index α corresponds to one of the concrete mechanisms of the interaction of the conduction electrons either with the particles (the so-called pair collisions) or with the fields produced by the turbulent state of the plasma (collective interactions). For the case of a plasma with a Coulomb mechanism of collisions between the particles $\nu_{eff} = \nu_1 + \nu_2 = \nu_{1,2}$, where ν_1 is the frequency of the Coulomb collisions, $\nu_2 = \pi U_{Te}/L$ is the frequency of collisions between the electrons and the end electrodes in the discharge[6], and U_{Te} is the thermal velocity of the electrons.

If a current I with an amplitude exceeding a definite critical value flows in the plasma, the state of the plasma may become unstable. During the course of development of the instability, some of the energy of the translational motion of the electrons produced by the current I goes over into the energy of the nonequilibrium plasma oscillations excited in this system. If at the same time the translational velocity of the electrons $U_{\parallel} = I/2\pi a e n \delta(\nu_{1,2})$ acquired by the electrons in the region of the skin layer determined by the pair collisions and by the collisions with the electrodes exceed a threshold value $U_C \sim U_S = (T_e/m_i)^{1/2}$, then ion-acoustic oscillations can arise in the plasma[2,3]; if $U_C \gtrsim U_{Te} \approx (T_e/m_e)^{1/2}$, then instability on electron Langmuir oscillations can arise in the plasma[7,8]. The cause of the instability is the current in the plasma. The external field producing the current performs work, excites collective oscillations, and can cause collisionless heating of both the electrons and ions[1-3,7,8].

Let us proceed to analyze the processes determining the skin effect of the electromagnetic field, produced by the turbulent plasma. It should be noted that in spite of the absence of a complete theory of these processes, we can obtain even now, on the basis of the analysis presented in[2,3], sufficiently reliable estimates for the quantities that characterize most fully the main features of the process of flow of current through a plasma in the turbulent state. It is necessary, of course, to emphasize immediately that the estimating formulas given by the theory for ν_{eff} in the turbulent plasma are approximate, and the accuracy of the experimental data on the density and temperature of the plasma is relatively low. Therefore a comparison of the results of the calculation and of the experiment is presently possible only in order of magnitude.

Following[2,9], let us stop to discuss in greatest detail on the case of penetration into a plasma of fields produced by a HF current, if $U_{\parallel}(\nu_{1,2}) \gtrsim U_S$. As shown by an appropriate analysis, in this case, the induced Cerenkov effect causes ion-acoustic oscillations to become excited in the plasma. With increasing oscillation, as a result of the interaction with the microscopic fields, the electrons will lose the momentum that they acquire in the accelerating electric field, i.e., they will be acted upon by an effective friction force. Such an interaction is equivalent to a definite degree to electron-ion collisions, since the plasma ions take part in the ion-acoustic oscillations. With increasing oscillation energy, the friction force increases until it balances the action of the electric field. The current velocity U then decreases, until it becomes comparable with a quantity close to $U_C \approx U_S$. The current velocity cannot fall below U_S, for then the oscillations will attenuate and the friction force will decrease.

In connection with the foregoing, we can use for the estimate of $\nu_{eff} \approx \nu_3$ the general relation $e\mathscr{E} = m_e U_{\parallel} \nu$[2], which is valid for the steady state, replacing in it $U_{\parallel}$ by U_S. To determine the thickness of the skin layer, we shall use the approximate equalities

$$\frac{B_\varphi}{\delta} \approx \nabla x B_\varphi = \frac{4\pi}{c}\sigma \quad , \quad j = \sigma\mathscr{E} = enU_{\parallel} \approx enU_s.$$

By simple manipulations we determine from the foregoing relations

$$\delta_3 = \frac{c}{\omega_0}\frac{c}{U_s}\frac{\omega_{c\varphi}}{\omega_0} \equiv \frac{c}{\omega_{0j}}\left(\frac{2}{\beta}\right)^{1/2}, \qquad \nu_3 = \frac{\omega}{2}\frac{c^2}{U_s^2}\frac{\omega_{c\varphi}^2}{\omega_0^2}.$$

The expression obtained for δ_3 coincides fully with the result of more rigorous calculations in[9]. In accordance with[2], the approximate equality $U_{\parallel} \sim U_S$ is valid only for relatively weak plasma electric field intensities satisfying the condition

$$\mathscr{E} < \mathscr{E}_{\text{кs}} = (m_e/m_i)(8\pi n T_e)^{1/2}.$$

For $\mathscr{E} > \mathscr{E}_{CS}$ we have $U_{\parallel} \gg U_S$ and in accord with[10] we get

$$\nu_{3s} \approx 10^{-2}\omega_{0i}(U_{\parallel}/U_s)(T_e/T_i).$$

The collision process in this case is due to the nonlinear Landau damping of the turbulence waves by the ions. The frequency ν_{3S} is always larger than ν_3. Both expressions for $\nu_{3,3S}$ were verified experimentally in experiments on turbulent heating of a plasma in straight discharges and in experiments on collisionless shock waves. It was established that both relations are in satisfactory agreement with the experimental data.

In spite of the fact that the inequality $E < E_{CS}$ is always satisfied under our experimental conditions, where it is necessary to use ν_3 in place of ν_{eff}, when the values ν_3 and ν_{3S} are formally used they yield nearly equal numerical results.

Since in experiments on the interaction between the high frequency fields and the plasma one measures as a rule either the thickness of the skin layer δ or the resistance R of the discharge gap, or else the power absorbed in the plasma W, it is convenient to write out certain relations that connect them with each other. For the case of greatest interest, when $\nu_{eff} \gg \omega$, $c/\omega \gg L$, and $a \gg \delta$[10] we have

$$W = 0{,}5 I_0^2 R_1 = \frac{c}{16\pi}\left(\frac{\omega}{2\pi\sigma}\right)^{1/2} 2\pi a L B_\varphi^2$$

(I_0—amplitude of the alternating current).

For the case $a < \delta$, it is more convenient to use the relation

$$W = 0{,}5 I_0^2 R_2 = 0{,}5 I_0^2\left(\frac{L}{2\pi a^2 \sigma}\right).$$

The values of ν_α, δ_α, W_α, and $U_{\parallel}/U_S$ calculated for each of the electron-collision processes analyzed above are compared with the obtained experimental data in the table. We calculated the cases of absorption of HF energy in a plasma cylinder of length L = 100 cm with allowance for only the Coulomb mechanism of collision ($\nu_{eff} = \nu_1$), with allowance for collisions of the electrons with the ends of the discharge gap ($\nu_{eff} = \nu_2$), and also for the case of ion-acoustic instability in the region of the skin layer ($\nu_{eff} = \nu_3$).

It was assumed in the calculations that I_0 = 1 kA, $n = 10^4\ \text{cm}^{-2}$, and a = 2 cm; ν, δ, and W are given in sec^{-1}, cm, and MW, respectively.

In analyzing the data of the table it is necessary to note, first, that the state of the plasma with the collision frequency described by the collisions $\nu_{eff} = \nu_1 + \nu_2$ is unstable against excitation of ion-acoustic oscillations in the region of the skin layer ($U_{\parallel} > U_S$). On the other hand, for the experimentally observed value $\delta \simeq 0.5$, the excitation of a strong two-stream instabil-

	ν_α	C	W	$U_{\parallel}/U_s$
Experiment	$4\cdot10^8$	0.5	0.3	~1
Coulomb collisions	$2\cdot10^6$	0.05	—	8
Collisions with electrodes	$2\cdot10^7$	0.1	0.02	4
Ion-acoustic instability	$2{,}5\cdot10^8$	0.4	0.1	1

ity with $U_{\parallel} > U_c = (T_e/m_e)^{1/2}$ is impossible, since U $(T_e/m_e)^{1/2}$ always. At the same time, the experimentally measured thickness of the skin layer agrees well with the calculated value for the case of ion-acoustic instability in a plasma, and the translational velocity determined from the discharge current and from the thickness of the skin layer is close in the experiment to U_s. We see that the foregoing facts favor the assumption that the most probable type of current instability under the experimental conditions is ion-acoustic instability.

It should also be noted that by virtue of the inequality $\nu_2 > \nu_1$ at $T_e \gtrsim T_i \approx 10^2$ eV the Coulomb collision mechanism is incapable of explaining the process of transfer of the HF energy of the fields to the electrons and ions, for in this case the plasma is collisionless and the entire energy of the HF heating generator absorbed in the system should be released directly on the electrodes. The Coulomb collisions cannot explain likewise the heating of the ions as a result of collisions with the electrons, for even if we assume formally the possible existence in the discharge of electrons with $T_e = 10^2$ eV, the time during which they transfer the energy to the ions should be $\tau_{ei} \approx 0.3 \times 10^{-3}$ sec, which is much higher than the observed heating time $\tau \lesssim 5 \times 10^{-6}$ sec. Thus, the Coulomb collision mechanism cannot explain either the experimentally obtained values of τ_{eff}, δ, W, nor the very fact of heating of particles, and this seems to be the most weighty evidence in favor of the turbulent nature of the processes in the region of the skin layer in the given experiments.

One more proof in favor of the turbulent state of the plasma in the investigated system is that there is no resonance of the absorption of the high frequency energy in the region of the ion cyclotron frequency ω_{cj}, thus contradicting the experiments of[11], where this resonance did occur under analogous conditions, but at lower power levels. The effect can be explained by assuming that the inequality $\omega/\nu_i < 1$, at which resonance is impossible, is satisfied in the plasma in the turbulent state. If this assumption is valid, $\nu_i \gtrsim 10^7$ sec^{-1}, the mean free path of the ion is $\lambda_i \sim U_{Ti}/\nu_i \sim 1$ cm $\ll$ L, and the presence of high-temperature ion in the system can be easily explained.

Before we proceed to compare the results of the experiment with further conclusions of a theory that takes into account the interaction and heating of charged particles in a discharge with microscopic pulsations of the fields of the plasma in the turbulent state, we must stop briefly to discuss the applicability of the expression employed for ν_3 to the experimental conditions. Such an analysis is essential, for strictly speaking the expression for ν_3 has been derived for an unbounded plasma, a stationary current, and in the absence of an external magnetic field B.

As shown by calculation[2], the growth increment of the ion-acoustic instability $\gamma \approx \nu_3 \gg \omega$, and this makes it possible to regard the problem as a stationary one, with repetition of the process of excitation of the instability during each half cycle of the high frequency current, In this case the alternating current can be regarded as an independent sequence of pulses ensuring heating of the plasma when averaged over the time.

Further, since the wavelength λ_s of the instability assumes in the region of maximum growth increment values close to the Debye wavelength $\lambda_D \sim U_{Te}/\omega_0 \sim 10^{-3}$ cm $\ll \delta$, it follows that for the region of the skin layer the problem can be considered the same way as in the case of unbounded space.

Finally, in accordance with[2,3], when the inequality $\omega_0 > \omega_{ce}$ is satisfied in the experiments, the longitudinal magnetic field should not exert a strong influence on the process of development of the ion-acoustic instability. Thus, as seen, the use of the results of the theory[2,9,12], in spite of the idealization used during the formulation of the problem, can be regarded as perfectly valid.

Let us recall one of the features of the model under consideration, namely that in the central part of the discharge, satisfying the inequality $r < a - \delta$, $U_{\parallel} \sim 0 \ll U_s$, there should be no turbulence and the plasma is always collision free, if $T_{e,i} > 10$ eV. This means that when $T_{e,i} > 10$ eV the particles, while moving freely along the magnetic-field force lines, collide only with the electrodes, and consequently should lose their energy rapidly. On the basis of the foregoing it must be assumed that the high-temperature particles produced as a result of interaction with the high frequency field should in this case be concentrated predominantly in the region of the skin layer. Estimates show also that in the absence of turbulence in the central part of the discharge, it is impossible to maintain in the latter a temperature higher than 10 eV, either as a result of the diffusion of the particles from the region of the skin layer, or as a result of thermal conductivity. Nor can high-temperature ions fall into this part from the skin-layer region, since this would violate the condition of quasineutrality of the plasma.

On the basis of the foregoing, it is natural to assume that the central part of the discharge can be filled only with plasma with $T_{e,i} < 10$ eV, and the contribution of this part to the measured quantity $\langle nT \rangle$ is small.

The validity of the foregoing qualitative arguments is confirmed by the fact that the experimentally obtained quantity $T_e + T_i \approx 150$ eV agrees best with the results of the measurement of the diamagnetism of the plasma, corresponding to $\langle nT \rangle = 10^{17}$ eV/cm, if it is assumed that the high temperature part of the plasma is concentrated mainly in the region of the skin layer.

Proceeding to a discussion of the details of the mechanism of the anomalous ion heating observed in the experiments, it should be noted that the recently published numerous calculations of the process of ion heating upon excitation of ion-acoustic instability in a plasma by a current[2,3,12] are unfortunately even more approximate in character than the calculations of ν_{eff}. A comparison of the experimental results with this part of the calculations is presently practically impossible, owing to the lack of sufficiently perfect procedures for determining the dispersion characteristics of the turbulence on ion-acoustic oscillations. Nonetheless, in spite of the foregoing, there is no doubt that the main qualitative predictions of the theory in this region are valid. Thus, in accordance with[3,2], in a turbulent plasma with a developed ion-acoustic instability, the ions should be intensely heated because they scatter the oscillations excited by the translational electron streams. For the bulk of the ions, the calculated value of T_i can reach 0.1–0.3 of T_e, which, as is readily seen, is in qualitative agreement with the experimental results. The theory also makes it possible to explain the presence of the experimentally observed group of ions with $T_2 \gg T_e$ and $n_2 \ll n$. Their occurrence may be connected with phase resonance of a small group of ions, the velocities of which lie in an interval close to U_s.

Thus, the theory of ion-acoustic instability in a plasma with a skin-layer current makes it possible in final analysis to explain at least qualitatively, both the presence of high-energy electrons and ions and the two-temperature character of the ion energy distribution function. The proposed scheme for calculating the values of ν_{eff}, δ, and W, together with the assumptions concerning the most probable concrete mechanisms of energy lost from the plasma, makes it possible to estimate in a number of cases beforehand the order of magnitude of the experimentally expected values of $\langle nT \rangle$, W, and R.

In conclusion, it should be noted that, independently of the type of instability, the turbulent mechanism of heating ions and electrons in a collisionless plasma, observed in experiments with skin-effect high-frequency discharge, is of great practical interest because of its simplicity. The employed scheme can be used as a basis for developing new nonresonant methods of high-frequency heating of particles in straight and toroidal magnetic traps for thermonuclear research.

One can expect effects similar to those observed to be encountered also at relatively low rates of change of the current in such installations as the "Tokamak" and the stellarator, provided an electron temperature on the order of 1 keV and higher is reached in them. The presence of dissipative processes in the region of the turbulent skin layer in installations using a high frequency field for the stabilization or containment of a plasma, can lead to an appreciable broadening of the stability zones as a result of the losses introduced thereby in the system. The inverse process is also possible, in which in installations in which high frequency fields of large amplitudes are used, the unfavorable role of the resistive and superheating instabilities increases in the region of the skin layer.

It should be noted that an obvious shortcoming of the here-considered method of plasma heating is due to the fact that the release of the energy of the high frequency field is localized in the surface layer of the plasma column. In this connection, undisputed interest attaches to experiments aimed at the study of transport phenomena in processes of turbulent heating of plasma in discharges with large current densities in the region of the skin layer.

The authors are grateful to D. D. Ryutov, who kindly called their attention to the following important circumstance. In accordance with the results of a theoretical analysis, for example, in[7,8], it can be assumed that in the general case of arbitrary values of T_e and T_i the approximate equality $U_\parallel \approx U_s$, which was used above, should be replaced by the more accurate $U_\parallel = \theta U_s$, where θ is a numerical factor that depends strongly on the ratio T_e/T_i. Only if $T_e/T_i \gg 1$ do we have $\theta = 1$, $U_\parallel \approx U_s$, and $\delta \approx \delta_s$. If $T_e/T_i \approx 1$, then the ion-acoustic oscillations should attenuate strongly, the noise level should fall, and the plasma conductivity and θ should increase. Since the measured value $\delta \approx \delta_s$ is in good agreement with the assumption that $U_\parallel \approx U_s$, this might indicate that under the experimental conditions $T_e/T_i \gg 1$. At the same time, at the experimentally obtained ratio $T_e/T_i \approx 2$ the calculated value of θ should be large (of the order of $(m_i/m_e)^{1/2}$), $U_\parallel \sim U_{Te} \gg U_s$, and $\delta \ll \delta_s$, but this does not agree with the measured value of $\delta \approx \delta_s$. Therefore, if we assume that calculations of the type in[7,8] are applicable to the experimental conditions, it must be allowed that the bulk of the ions in the region of the skin layer has a temperature much lower than $T_e \gtrsim T_i$ 50 eV (apparently 5–10 eV), and ions with $T_i = 50$ eV constitute a small fraction of the total number of particles. In this case it is precisely the ions with temperature of the order of 50 eV that should be regarded as "hot."

In the analysis of the foregoing contradiction it is necessary to note, first of all, that it is necessary to exercise a certain degree of caution in a quantitative comparison of the results of the quasilinear-approximation calculations with real experimental conditions. By way of illustration, it is useful to note the results of a recent calculation[13], where the case of excitation of ion-acoustic instability in a plasma was analyzed in the presence of a weak background of turbulent Langmuir pulsations in the plasma, with an energy density level w small compared with the density of the thermal energy nT of the particles. The solution obtained in[13] for $w \neq 0$ points to a possible existence in an isothermal plasma of ion sound, which, as noted above, is strongly attenuated as a result of the Landau absorption by ions if it is assumed that $w = 0$[7,8]. The occurrence of isothermal sound has a threshold character and is possible only when $w \gg w_c$, where $w_c/nT \approx m_e/m_i \approx 10^{-3}$.

Although the criterion for the occurrence of Langmuir instability, $U_\parallel > U_{Te}$, is as a rule not satisfied under the conditions of experiments on turbulent heating of a plasma by a current via the mechanism of ion-acoustic instability, in the experiments of this series, just as in our experiments, a weak background of oscillations, corresponding to ion sound, is always observed at frequencies close to the electron plasma frequency. Usually $w/nT \gtrsim 10^{-2}$[2], and therefore $w \gg w_c$ always, in accordance with[13], even for a weakly non-isothermal plasma, characterized by the ratio $T_e/T_i \approx 2$ in our experiments, the process of damping of the ion sound as a result of the Landau effect can be neglected. It is natural to expect here that when an attempt is made to compare qualitatively the results of the experiment with the theory in the region $T_e/T_i \sim 1$, the calculations of[7,8] should be refined.

On the other hand, an analysis of the presently published experimental results on turbulent heating of plasma under conditions when the most probable type of current instability is assumed to be ion sound, shows that as a rule $T_e/T_i \approx 1$[14-16] and not $T_e/T_i \gg 1$. Kalinin et al. observed[16] under conditions close to those described by Zavoiskiĭ et al.[15], where the measured ratio T_e/T_i did not exceed 2–3, that at the highest efficiency of the process of turbulent heating of the plasma the relation $U_\parallel \approx U_s$ is satisfied. Comparing the results of our experiments with the data of[2,14-16], it is to be expected that the more probable situation in experiments with plasma in a strongly turbulent state is one in which under real conditions the relations $T_e/T_i \gtrsim 1$ and $U_{\parallel} \sim U_s$ are satisfied and not $T_e/T_i \gg 1$ and $U_{\parallel} \approx U_s$.

If the foregoing experimentally-supported assumption is correct, then it is necessary to give preference in estimating the minimum value of the ion temperature under our conditions to the interpretation variant described in the present paper for our results, where it is assumed that $T_i = 50$ eV. Favoring the validity of just this hypothesis are also control experiments performed by us on the determination of the temperature of the ions in a plasma by measuring the Doppler line width of the glow of the discharge in the skin-layer region. As already mentioned, this has established that for the main group of the ions the average temperature of the hydrogen atoms is of the order of 50—70 eV.

In connection with the timely character of the question touched upon here, the authors plan to develop in the nearest future a special procedure for determining the ion energy distribution function in the ion energy region $10 \leq E \leq 10^2$ eV.

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