SKIN EFFECT IN TURBULENT Z DISCHARGES

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We analyze the results of experiments with pulsed z discharges characterized by an anomalous value of the plasma conductivity in the region of the skin layer. It is shown that the singularities in the behavior of powerful linear discharges, particularly self-compressed z pinches, agree with the hypothesis of the probable excitation of ion-acoustic microinstability in their current layer.

THE use of pulsed and high-frequency electromagnetic fields to contain, heat, and stabilize high-temperature plasma is closely connected with the processes that determine the behavior of the alternating currents of large amplitude in the region of the skin layer. The theory can predict relatively rigorously the singularities of the process of penetration of rapidly alternating fields into a plasma in the case when the collisions of the charged particles are described by Coulomb interaction forces[1]. However, as shown by numerous experiments[2-4], the real value of the plasma conductivity in the region of the skin layer of powerful pulsed z-discharges turns out to be much lower than the value determined by the Coulomb collisions.

The anomalous behavior of the plasma conductivity in the region of the current layer was observed already in the earliest experiments with z-pinches stabilized with longitudinal magnetic fields. Thus, for example, magnetic-probe measurements[3,4] have shown that during the initial stage of the discharge, with a duration $t_a \approx a/V_a \approx 3-4\ \mu$sec, currents flow through a well pronounced surface layer, the plasma is macroscopically stable, and the current outside the skin layer is small (here a is the plasma-column radius and V_a is the Alfven velocity). In spite of the obvious absence of the usual manifestations of the turbulent state of the discharge in the form of a noticeable fluctuation level in the magnetic-probe signals, an anomalously low value of the plasma conductivity, accompanied by an inexplicably high value of the gas-kinetic pressure in the skin-layer region, was observed. It was established from probe measurements of the azimuthal field $B_\varphi(r)$, the axial field $B_z(r)$, and the gas-kinetic pressure p(r) that the Suydam criterion is not satisfied for the plasma in the skin layer during this stage of the discharge, and it was therefore to be expected that the obtained current configuration would be unstable with respect to excitation of large-scale magnetohydrodynamic perturbations. Actually, the skin effect disappeared completely starting with an instant of time $t \gtrsim t_a$, and the probes began to register strong low-frequency magnetic-field fluctuations with a frequency close to $\omega_a \approx V_a/a$. Although the plasma conductivity had, as before, an anomalously low value during this stage, the transition of the plasma to a new, macroscopically unstable state led immediately to an abrupt decrease of the gas-kinetic pressure.

The behavior of the plasma in a state characterized by large-scale fluctuations and by the absence of the skin effect was subsequently satisfactorily explained within the framework of the theory of magnetohydrodynamic stability of z-discharges[5]. In connection with the low value of the temperature of the bulk of the electrons and ions, which is typical of discharges in the MHD unstable state, this stage of existence of the discharge is always highly undesirable. At the same time, there is undisputed interest in the above-described first phase of the z-pinch discharges, characterized by the presence of a well-formed skin layer, by the absence of macroscopic field and density perturbations, by an anomalously low conductivity and by a strong heating of the plasma.

The first attempts to explain the foregoing singularities of powerful discharges did not lead to any positive results. Although the correct assumption that there is probably a connection between the anomalous conductivity at the start of the discharge and the possible excitation of two-stream microscopic instability in the region of the skin layer[1,2,4] was advanced in a number of the papers of that period, no due attention was paid to the results. Since no heating of the plasma in z-discharges, which would mean adiabatic compression of the current column as a result of the pinch effect, was obtained owing to the rapid deterioration of the skin layer during the macroscopically-unstable stage, further experiments with this type of discharge were discontinued, and the experimental results were subsequently entirely forgotten.

Interest in z-discharges was recently very actively revived in connection with E. K. Zavoĭskiĭ's suggestion of using the anomalous resistance of a plasma with a high level of microscopic fluctuations for the purpose of developing a method of turbulent plasma heating in linear discharges. A review of the results of the investigations of different modifications of the turbulent-heating method at plasma densities $n < 10^{14}$ cm^{-3} is contained in the monograph of Zavoĭskiĭ and Rudakov[6].

In this paper, which is a continuation of[7,8] we attempt to generalize the phenomenological model of a quasi-stationary HF discharge with a turbulent state of the plasma in the region of the current layer[7] to include the case of powerful pulsed z-discharges with a stable skin layer and with an anomalous plasma conductivity in the current-flow region. Unless otherwise stipulated, the term "turbulent" will refer only to such a state. As will be shown later, the conditions for the skin effect to appear in discharges characterized by microturbulent instability corresponds to a plasma density $n > 5\times 10^{13}-10^{24}$ cm^{-3} at current-column transverse dimensions on the order of 5–10 cm.

We consider systems in which the electric field $\mathscr{E}$ of the current I is parallel to the external magnetic field E. It is assumed that the discharge has cylindrical symmetry, the maximum value of the current is determined only by the parameters of the external circuit, and the skin effect is due to purely dissipative processes.

It is assumed in the particular case considered here that the anomalous behavior of the plasma conductivity in the skin layer is due to the occurrence of ion-acoustic microscopic instability in the current-flow region[6-8].

Experiment has shown that the most characteristic property of discharges of this type in the turbulent state is the fact that as a rule the electron drift velocity u_I in the current layer satisfies the condition $u_I = \alpha u_s$, where $u_s = (T_e/M)^{1/2}$ is the velocity of the ion sound. Here T_e is the electron temperature and M the ion mass. On the basis of the previously obtained data[7-9] one should expect $\alpha \approx 1$ for the case of powerful pulse discharges and for sufficiently high values of the plasma density, $n > 10^{14}$ cm^{-3}.

The conditions necessary for the occurrence of a turbulent state of a plasma of the proposed type in the skin-layer region ($u_I \gtrsim u_s$, $T_e > T_i$) were analyzed in detail in[7,8,10]. In accordance with[10], the expression for the thickness δ_s of the turbulent skin layer, following excitation of ion sound, is

$$\delta_s = cB_\varphi(a)/4\pi neau_s, \tag{1}$$

where $B_\varphi(a)$ is the field of the current I at the boundary of the plasma r = a. The electron temperature that determines the value of δ_s can be obtained (see[7,8], by equating the energy W_s absorbed by a unit surface of the plasma column

$$W_s = \frac{B_\varphi^2(a)}{16\pi}\delta_s\omega \tag{2}$$

to the energy flux density $q_\perp$ carried away as a result of the transverse electronic thermal conductivity

$$q_\perp = 2\chi_\perp dT/dr \approx 2\chi_\perp T\delta_T^{-1}. \tag{3}$$

Expression (3) is valid if it is assumed that the entire thermal energy of the discharge is contained in the main in the region of the thermal skin layer δ_T. The following notation is used: $\omega = 2\pi/t_h$, t_h is the characteristic time scale of the variation of I(t); $\chi_\perp = (nT\nu_s)(m\omega_c^2)^{-1}$ is the thermal-conductivity coefficient of the magnetized plasma[11]; $\omega_0 = (4\pi ne^2/m)^{1/2}$, $\omega_{0i} = (m/M)^{1/2}\omega_0$, and $\omega_c = eB_\perp/mc$ are respectively the plasma-electron, plasma-ion, and electron-cyclotron frequencies; $B_\perp = (B_\varphi^2 + B_z^2)^{1/2}$; ν_s is the effective collision frequency of the electrons in the turbulent plasma; $\Theta = \delta_s/\delta_T$; α and Θ are assumed to be unknown constants.

From the equality $W_s = q_\perp$ we obtain an expression for the gas-kinetic pressure in the region of the skin layer under conditions of quasi-stationary heating:

$$p_s = \frac{B_\varphi(a)B_\perp(a)}{8\pi\Theta^{1/2}}.$$

Recognizing that $p_s = n(T_e + T_i) \approx nT_e$, we can obtain T_e from (4), since n is known. To simplify the subsequent operations, $B_{z,\varphi}(r, t)$ will henceforth stand only for the magnetic-field components measured directly in the experiment.

For the plasma-heating regime under consideration, the true value of p(r) at the maximum, $p = p_m$, may differ from p_s by a certain numerical coefficient, the value of which can be obtained either by sufficiently exact calculation or from the experiment. Taking into account also the possible inaccuracies of our analysis, we introduce a correction factor R for (4):

$$p_m = Rp_s. \tag{5}$$

Let us estimate the value of δ_s expected in the approximation of our model. From (1) and (5) we get

$$\delta_s = \frac{1}{\alpha R^{1/2}\Theta^{1/4}}\frac{c}{\omega_{0i}}\left(\frac{2B_\varphi(a)}{B_\perp(a)}\right)^{1/2}. \tag{6}$$

We list the assumptions made in the derivation of the expression for p_s:

$$a \gg \delta_s,\quad \omega_c/\nu_s \gg 1,\quad \nu_s/\omega \gg 1,\quad \omega_0 \gg \omega_c,$$

$8\pi p_s/B_\perp^2 < 1$, the value of ν_s is isotropic in all directions, it is assumed that $T = T_e + T_i \approx T_e$ by virtue of the inequality $T_e > T_i$, which is necessary in order for ion-acoustic instability to be excited. We use the relation $\delta_s = (c/\omega_0)(2\nu_s/\omega)$.

The validity of the foregoing assumptions was discussed earlier in[7]. Under conditions typical of most installations with pulsed and HF discharges, these assumptions, with the exception of the quasi-stationarity conditions, are as a rule well satisfied.

Let us find the conditions that ensure a stationary character of the heating process. The energy lifetime τ_ϵ of a plasma in the skin layer can be determined for the case in question from the relation $W_s\tau_\epsilon = nT\delta_T$[8]. Using (4), we get

$$\tau_\epsilon = \frac{2R}{\omega\Theta^{3/2}}\frac{B_\perp(a)}{B_\varphi(a)}. \tag{7}$$

For single current pulses having a time dependence $I(t) = I_0\sin(\omega t)$, the maximum of p(t) corresponds to the heating time t_h defined by the relation $\omega t_h \approx \pi/2$. The stationary nature of the problem is characterized by the ratio t_h/τ_ϵ:

$$\frac{t_h}{\tau_\epsilon} = \frac{\pi\Theta^{3/2}}{4R}\frac{B_\varphi(a)}{B_\perp(a)}. \tag{8}$$

For quasi-stationary HF discharges, the condition $t_h/\tau_\epsilon \gtrsim 1$, which corresponds to a steady-state value $p = p_s$, is reached immediately, within several oscillation periods, amounting to $N > B_\perp/B_\varphi$. In self-compressed z-pinches, where $B_\varphi(a) \sim B_\perp(a)$[2-4], we have $t_h/\tau_\epsilon \approx 1$ and the quasi-stationary condition is also satisfied in practice. In experiments with plasma heating by a single current pulse in a strong longitudinal magnetic field $B_z \gg B_\varphi$, where $\tau_\epsilon \gg t_h$, it is necessary to use for the determination of p, instead of (4) and (5), the relation

$$p_m = Rp_s(1 - e^{-t_h/\tau_\epsilon}). \tag{9}$$

For the sake of brevity, we introduce the function $\psi = [1 - \exp(-t_h/\tau_\epsilon)]$. Then expression (9) takes the form $p_m = Rp_s\psi$. Taking (4)–(6) and (9) into account, we obtain for the thickness of the skin layer in the general case when $B_\perp > B_\varphi$

$$\delta = \delta_s \psi^{-1/2}. \tag{10}$$

It should be noted that in the assumed model, when $B_\perp \gg B_\varphi$, the loss due to turbulent thermal conductivity becomes negligible in pulsed-heating processes, and p_m is determined only by the power input to the plasma W_s, so that the discharge current is most effectively utilized. In this limiting case we have

$$p_m = \frac{\Theta}{32} B_\varphi^2(a), \tag{9a}$$

$$\delta = \left(\frac{8}{\pi}\right)^{1/2} \frac{1}{\alpha\Theta} \frac{c}{\omega_{0i}}. \tag{10a}$$

It follows from (8) and (9) that in order to obtain maximum heating efficiency at a given I, it is not advantageous to use fields $B_z > 3B_\varphi$. It is therefore more economical to resort to the use of self-contracted z-pinches to attain maximum p_m in turbulent plasma heating, for in this case the cost of the power supply needed to produce B_z is greatly reduced, whereas the cost due to the turbulent-thermal conductivity loss is relatively low. This still leaves open, of course, the question of the limits of applicability of the HF stabilization method used in the present experiments.

In the case of self-contracted discharges with a trapped field[3,4], it is necessary to make in (9) the substitution $B_\perp(a) \approx B_\varphi(a)$, $\psi = 1$

$$p_m = \frac{RB_\varphi^2(a)}{8\pi\Theta^{1/2}} \tag{9b}$$

$$\delta_s \approx \frac{2^{1/2}}{\alpha R^{1/2}\Theta^{1/4}} \frac{c}{\omega_{0i}}. \tag{10b}$$

It is interesting to note that in the derivation of (9), by virtue of the specific nature of the model in question, the quantities ν_s and ω have dropped out from the expression for p_m. It can therefore be assumed that, subject to the limitations stipulated above, relation (9) is to some degree universal and suitable for any particle-collision mechanism.

We note that in (9) and (10) the value $p \approx nT_e$ in the skin layer is determined by the maximum values of $B_{z,\varphi}(a, t)$, which in turn depend only on the value of the discharge current I and the magnetic field intensity B_z at the plasma boundary.

Let us proceed to the results of the verification of the calculated data. It had been found experimentally[7,8] for the case of a quasi-stationary HF discharge with anomalous conductivity in the skin-layer region that $\alpha \approx 1$. Indirect considerations led in the same references to the expected estimate $\Theta \approx 1.5$.

For the general case of pulsed currents with arbitrary variation of I(t), the parameters Θ, R, and α remain undetermined. To find them or at least to obtain a rough estimate it is possible in principle, to use magnetic-measurement data for each concrete type of discharge.

To determine experimentally the values of Θ, R, and α in the present investigation, we measured the functions $B_{z,\varphi}(r, t)$ in a quasi-stationary HF discharge (the Omega installation[7,8]) and in a pulsed linear z-discharge (the Janus-2 installation[12]. To simplify the interpretation of the measurement results, we used no magnetic mirrors in the experiments. The components $B_z(r, t)$ and $B_\varphi(r, t)$ were determined with movable magnetic probes. The current density $j_z(r)$ and the gas-kinetic pressure p(r) were obtained by standard reduction[2,4] of the experimental plots of $B_{z,\varphi}(r)$. In integrating the pressure-balance equation, we used zero boundary conditions at the chamber walls.

In both cases, the discharge current varied like $I(t) = I_0 \sin(\omega t)$. For the HF discharge, $\omega_1 = 10^7$ sec^{-1} and $I_0 = 1$ kA. For the installation with the pulsed heating, $\omega_2 = 2.4 \times 10^6$ sec^{-1} and $I_0 = 30$ kA; the measurements were performed during the first half-period of the current generated by a high-voltage surge circuit. The gas used was hydrogen. The discharge-gap length in both cases was L = 1 m. A description of the installations, of the elements of their electric circuitry and of the diagnostics methods employed is contained in[7,8,12]. One should expect that in accordance with (10) the condition $a > \delta_s$ should be satisfied in the experiments at $n > 10^{14}$ cm^{-3}, if $\alpha \approx 1$. A summary of the most important parameters of the installations is given in the table.

To suppress the large-scale magnetohydrodynamic instabilities, a method previously developed by us[13] for HF plasma stabilization was used in both systems. To this end, the frequencies of the discharge currents $\omega_{1,2}$ were chosen to satisfy the condition that the growth increment of the most dangerous types of MHD perturbations always be much smaller than ω under the concrete conditions of the experiment[13]. As expected, no macroscopic instabilities with noticeable amplitude were observed under the employed experimental conditions. This is evidenced, in particular, by the presence of a skin effect, by the regular character of the probe oscillograms, and by the good reproducibility of the measured plots of $B_{z,\varphi}(r)$ from point to point and from discharge to discharge. Since the growth increment of the ion-acoustic perturbations is $\gamma \approx \omega_{0i} \gg \omega_{1,2}$, the condition for the excitation of microscopic instabilities was not violated at the chosen values of ω.

By way of example, Fig. 1 shows typical measured values of $B_\varphi(r, t)$ corresponding to the phase angles of the first half-period $\omega_2 t = \pi/6$, $\omega_2 t = \pi/2$, $3\pi/2$, and π for the case of a pulsed discharge. Figure 2 shows a plot of $B_{z,\varphi}(r)$ for $\omega_2 t = 3\pi/2$ and the radial

Name of installation	a, cm	L, m	$n \cdot 10^{-15}$, cm^{-3}	$B_\varphi(a)$, kOe	$B_\perp(a)$, kOe	δ, cm	Θ	$p_m \cdot 10^{-6}$, dyne·cm^{-2}	R	α
a. Omega	1.5	1	0.1—0.2	0.15	2.4	0.5	1.5—2	0.014	1.4	1
b. Janus-2	4.5	1	0.3	1.5	2.6	1.5	1.5—2	0.05	0.5	1.2
c. Tarantula [14]	18	1	1	2.7	2.7	1	1	0.15	0.6	1.3
d. Columbus-4 [3]	2	0.61	5—10	8.6	9.2	1	1.5—2	2.6	1.3	0.5

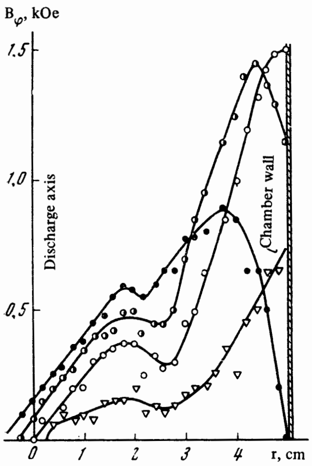

FIG. 1. Azimuthal component of the current field against the radius in the first half-period of the pulsed discharge of the Janus-2 installation. $B_z(a) \approx 2$ kOe, $I_0 = 30$ kA. ∇—$\omega_2 t = \pi/6$, O—$\omega_2 t = \pi/2$, ◑—$\omega_2 t = {}^3/_2\pi$, ●—$\omega_2 t = \pi$.

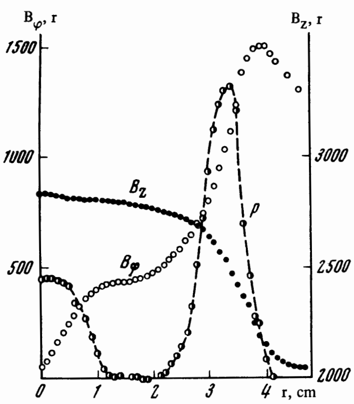

FIG. 2. Plots of $B_z(r)$, $B_\varphi(r)$, and p(r) in a pulsed discharge of the Janus-2 installation for $\omega_2 t \approx 3\pi/2$. The p(r) scale in the diagram is in arbitrary units. The value of p(r) at the maximum is $p_m \approx 5 \times 10^4$ dyne/cm^2.

distribution p(r) calculated from it. The value of p(r) at the maximum is $p_m \approx 5 \times 10^4$ dyne/cm^2, and the plasma density is $n = 3 \times 10^{14}$ cm^{-3}.

A characteristic feature of the obtained curves is the relatively free penetration of the field B_φ in the near-axis part of the discharge at $\omega_2 t < \pi/4$, when the plasma temperature is relatively low, and the subsequent capture of the current in the region $r \lesssim a/2$ at $\omega_2 t > \pi/2$, accompanied by the appearance of a current in the opposite direction in a thin surface layer $a - \delta < r < a$. The most clearly pronounced effect of the captured currents is seen at $\omega_2 t = \pi$, when the total current is $I(t) = (ca/2)B_\varphi(a) = 0$ (Fig. 1), and an appreciable current flows in the initial direction through the plasma cylinder near the axis, whereas an equal and opposite current flows in the skin layer. Since, in accord with the present theoretical notions, the configuration of $B_{z,\varphi}(r)$ with currents flowing in the opposite direction near the axis and on the periphery can have a larger stability margin with respect to certain types of MHD perturbations[1,2,5], this effect should contribute, together with the HF stabilization principle employed by us, to the stable state of the skin layer observed in the present experiments in discharges at $\omega t > \pi/2$.

To complete the picture, the data obtained in the

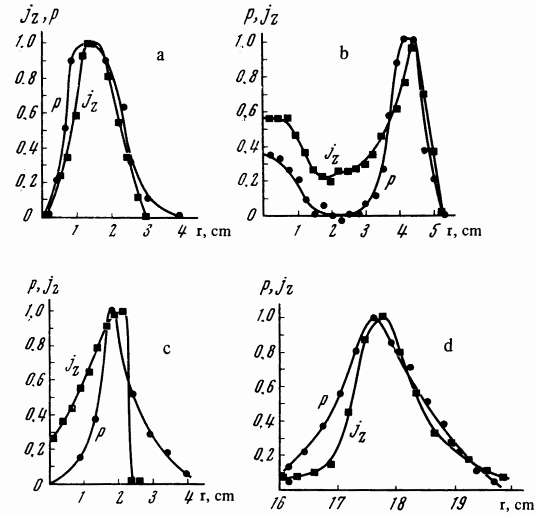

FIG. 3. Current density $j_z(r)$ and gas-kinetic pressure p(r), in fractions of the values of j_m and p_m at the maximum, in the region of the skin layer: a—Omega, b—janus-2, c—Columbus-4, d—tarantula.

present paper were supplemented with typical measurement results for the case of z-pinches with discharge currents $I \gtrsim 10^5$ A. To this end, we show in Fig. 3 the plots for the current density $j_z(r)$ and the pressure p(r), obtained by measurements on the installations Omega (Fig. 3a), Janus-2 (Fig. 3b), the z-pinch of the Tarantula installation in the region of the magnetic current plunger[14], and the self-compressed z-pinch of Columbus-4[3] (the parameters of the installations are listed in the table). For convenience in comparison, the plots of j_z and p shown in Fig. 3 are normalized to their values at the maximum, namely, $j_z = j_z(r)/j_m$ and $p = p(r)/p_m$.

From Figs. 2 and 3 we see that under the experimental conditions, both for a quasi-stationary HF discharge and for pulsed heating at $\omega_2 t \gtrsim \pi/2$, the discharge is concentrated in a skin layer and the gas-kinetic pressure of the plasma is concentrated mainly in a narrow layer near the plasma-vacuum boundary.

From the data of Fig. 3 we see that the quantity Θ, defined as the ratio $\Theta = \delta_S/\delta_T$, lies in the range $1 < \Theta < 2$ for all four installations. Taking into account the symmetrical character of the peaks of the p(r) curves, one should expect the heat outflow to be approximately equal on both sides of the point where $p = p_m$, corresponding to the coefficient 2 in Eq. (2) for $q_\perp$, which was introduced in the present paper in contrast to[8]. A complete comparison of the measured skin-layer thickness δ, the pressure p_m, and Θ with the values of α and R calculated from (9) and (10) is given in the table. From a comparison of the tabulated data we see that in the intervals 10^{14} cm$^{-2} \lesssim n \lesssim 10^{16}$ cm^{-3}, 10^4 dyne/cm$^2 \lesssim p \lesssim 3 \times 10^6$ dyne/cm^2, 10^2 Oe $\lesssim B_\varphi \lesssim 10^4$ Oe, 1 kA $\lesssim I_0 \lesssim 2.5 \times 10^5$ A, $2 \lesssim a \lesssim 20$, and 1 kOe $\lesssim B_z \lesssim 10$ kOe, the value α lies in the range 0.5—1.3, $R \approx 0.5$—1.3, $\Theta \approx 1.7$, and the calculated values of $p_S\psi$ and $\delta_S\psi^{-1/2}$ are sufficiently close to the experimentally measured p_m and δ.

It should be noted, of course, that the seemingly large scatter of the values obtained for R and α, which reaches 30—40% in some cases, actually fits satisfactorily into the expected range of errors of the determination of $B_{z,\varphi}$ and p_m. In particular, errors of the same order of magnitude can result merely from the error connected with neglecting the inertial term in the pressure-balance equation[2,3]. Taking the foregoing into account, for tentative estimates we can put in (4)—(10), with sufficient degree of reliability R, $\alpha \approx 1$ and $\Theta \approx 1.5-2$.

We note that the approximate equality of $u_I/u_s = \alpha \approx$ const which we obtained above is valid only for the considered range of z-discharge parameters. Thus, for example, if the plasma density is $n < 10^{14}$ cm^{-3}, the value of α begins to depend strongly on the concrete experimental conditions[8,9]. Unfortunately, there is at present no rigorous quantitative theory of this complicated phenomenon, and the determination of p_m and δ in the case when $\alpha \neq$ const calls for the use of more artificial means of solving the problem. By way of an example, we note that in[8] we used a semi-empirical dependence of α on the discharge parameters, and this enabled us to obtain satisfactory agreement between the experimental data at $\alpha \neq$ const and the results of model calculations, in spite of the approximation $\psi = 1$ used for the case $B_z/B_\varphi \gtrsim 1$.

It can easily be verified by direct calculation that in all the cases considered in the present paper the ratio of the measured skin-layer thickness to that calculated for the case of pure Coulomb collisions is never smaller than 10—20. This is direct evidence of the turbulent state of the plasma in the skin-layer region.

The satisfactory agreement between the experimental results and the present calculations for $\alpha \approx 1$ favors the assumption that the most probable cause of the anomalous plasma resistance in the skin-layer region of strong z-discharges is ion-acoustic instability.

It is of interest to ascertain in greater detail the connection between the $B_\varphi(r)$ dependence shown in Fig. 1 for $\omega_2 t > \pi/2$, when currents flow in opposite directions in the central part of the plasma column and at its boundary, and the condition for MHD stability of skin-layer discharges. The urgency of this question is due primarily to the fact that it is precisely at $\omega t \gtrsim \pi/2$ that a minimum level of large-scale fluctuations is observed in the Tokamak T-3 and Zeta installations and the conditions for most effective heating and containment of the particles are satisfied[15,16].

In the case when the extrapolation of the relations obtained above is valid up to discharge-current amplitudes $I_0 \approx 1$ MA, $B_z \approx 10^2$ kOe at $n \approx 10^{16}$ cm^{-3}, the scheme for heating the plasma with short pulses of longitudinal current in thin columns with the transverse dimensions on the order of several thicknesses of the ion-acoustic skin layer $\delta_s\ c/\omega_{0i}$ may become capable of competing with the method of particle heating by adiabatic compression of the plasma in Θ-pinch installations.

It must be emphasized, of course, that the effectiveness of using turbulent plasma heating in z-discharges is strongly limited by the inevitable skin-effect concentration of the heat in the region of the current layer. To eliminate this shortcoming of the method it will be necessary apparently to use more complicated combined heating schemes in investigations with large-scale thermonuclear traps. In particular, it is possible to use for this purpose the scheme of turbulent heating of the plasma in z-discharges with simultaneous generation of a radially-converging collision-free shock wave with the aid of a collapsing current layer[14].

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