EFFICIENCY OF CURRENT HEATING IN A DENSE PLASMA OF A STRONG CURRENT GAS DISCHARGE

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The physical efficiency of current heating of a dense plasma in a strong-current gas discharge stabilized by a strong magnetic field is considered. The heating efficiency is of the order of 60%. Current heating is the result of successive development of a number of stream instabilities and takes place so long as the current flows in the active region of the discharge. The previously obtained value of the plasma thermal energy density ($nkT = 3 \times 10^{18}$ eV/cm^3) is confirmed.

1. INTRODUCTION

THE question of efficiency is of great significance in the study of heating by current as a promising method of obtaining thermonuclear plasma in a reactor with positive yield.

The relatively high efficiency of current heating, in final analysis, is determined by the anomalously large value of the active resistance of the plasma, which, unlike the case of classic ohmic heating, does not decrease with increasing plasma temperature.

The theoretical premises for the use of stream instabilities for plasma heating were developed in[1-5].

The anomalously large high resistance of a strong-current gas-discharge plasma was first observed experimentally in[6]. Subsequently this fact was observed in a large number of experiments[7-17]. In experiments with the "Grom-3" setup it was shown that if the applied electric field is sufficiently strong, a stream instability develops in the discharge, and leads to effective heating of the electron[12] and ion[13] components of the plasma. The observed plasma heating is the result of successive development in the discharge of a whole series of stream instabilities of various types.

In the initial stage of the investigated discharge, the plasma was sufficiently isothermal and the excitation of the stream instability relative to the ion-acoustic oscillations was impossible. Therefore as soon as the electrons in the electric field of the discharge acquired a translational velocity exceeding the initial thermal velocity, an electron-ion instability of the Budker-Buneman type was excited, and led to heating of the plasma electrons. With further heating of the electrons, the critical value of the current density ($j_{cr} \geq neV_{Te}$) increases appreciably and heating stops, since the discharge current is usually limited by the parameters of the supply source. In this experiment the electrons were heated at this stage to a temperature on the order of 50 eV, whereas the ion temperature remained at the initial level, of the order of 5–10 eV. In this case conditions were created in the discharge favoring the excitation of stream instability relative to ion-acoustic oscillations, which indeed determined the further heating of the plasma to temperatures on the order of several keV. The maximum attainable electron and ion temperatures of the plasma are determined in this case by the violation of the conditions for the excitation of this instability ($T_e \gg T_i$, $j_{cr} > neV_{Te}\sqrt{m_e/M_i}$). Depending on the initial plasma parameters and on the type of gas, other successions of stream instabilities are possible and can lead to effective heating.

We have investigated the physical efficiency of current heating of a dense plasma of a strong-current gas discharge in the regime when ion-acoustic instability was excited.

2. EXPERIMENTAL SETUP AND DIAGNOSTIC TECHNIQUE

The experiments were performed with the "Grom-3" apparatus, which is a strong-current gas discharge in hydrogen, stabilized by a strong magnetic field. The inside diameter of the cylindrical discharge chamber is 10 cm, and the distance between electrodes is 25 cm.

The maximum intensity of the external magnetic field is 16 kOe, the total discharge current reached 300 kA and had a period of 9 μsec, while the range of working-gas pressures was 1×10^{-2}–5×10^{-4} mm Hg. The construction and the parameters of the setup are described in detail in[15]. In the experiment we measured the density of the current flowing through the central part of the discharge, the electric field, and the density of the kinetic energy in the plasma.

The distribution of the current density in the plasma was investigated with the aid of a system of magnetic probes disposed along the radius of the plasma column in the central plane of the discharge. Figure 1 shows the radial current-density distribution measured in this manner at the instant of excitation of stream instability in the plasma. It is seen from the figure that the highest current density, at which the condition for the excitation of stream instability is satisfied, is in the region next to the axis, with an approximate diameter of 2 cm. On the other hand, an appreciable fraction of the current flows in the region next to the wall, where the conditions for current heating are not satisfied. It should be noted that since the outside dimension of the system of magnetic probes (diameter 6 mm) turned out to be comparable with the dimensions of the active region of the discharge, measurements of the current density on the

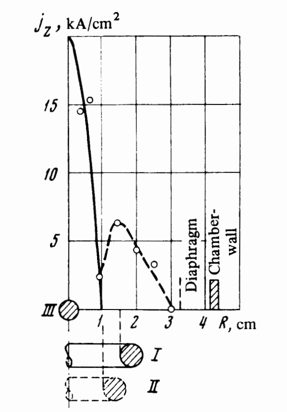

FIG. 1.

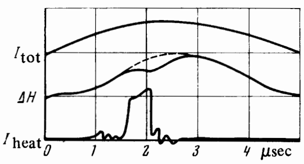

FIG. 2

FIG. 1. Radial distribution of the density of the longitudinal current j_z, obtained by measuring with a system of local magnetic probes (H_0 = kG, $P_0 = 1.5 \times 10^{-2}$ mm Hg). The figure shows the dimensions of the discharge chamber and of the diagram, and also of the local magnetic probes III and "combined" probes I and II.

FIG. 2. Oscillograms of total discharge current (upper trace), of the diamagnetic-loop signal and of the internal current flowing in the active region of the discharge. The dashed line shows the value of the paramagnetic signal due to the total discharge current.

discharge axis yield a result that is somewhat too low.

Thus, in the present experiment, to determine the real efficiency of the current heating, it was necessary to investigate processes that occur in the region of the discharge next to the axis.

To this end, a combined probe was constructed, consisting of a Rogowski belt and a multiturn diamagnetic loop, enclosing the active region of the discharge. The probe was placed in a quartz torus with minor outside diameter 6 mm and major inside diameter 20 mm. The diamagnetic loop had 50 turns of wire having a diameter 0.25 mm. The Rogowski belt consisted of 300 turns of wire of 0.15 mm diameter. In view of the fact that the torus was inside the hot plasma, it withstood a limited number of discharges, which nevertheless was sufficient for the measurements.

Figure 2 shows the temporal oscillograms of signals from the internal Rogowski loop and the diamagnetic loop, and of the total discharge current. We see that during the time when the internal current grows, the plasma is heated and a diamagnetic effect appears. This is manifest in the oscillogram of the magnetic flux as an appreciable decrease of the paramagnetic signal due to the total discharge current.

This method makes it possible to measure simultaneously the density of the thermal energy of the plasma particles as well as the density of the current, both averaged over the cross section of the probe. The values of these parameters on the discharge axis could be obtained by using their radial distributions measured by local magnetic probes (see Fig. 1). In this experiment these distributions were approximated by parabolas in the form

$$j(r) = j_0(1 - r^2/a^2).$$

These measurements, supplemented with measurements of the electric field in the discharge, make it possible to estimate the conductivity of the plasma and the plasma-oscillation energy density[8]. The electric field was estimated from measurements of the difference of the potentials in the discharge gap, assuming a uniform distribution along the system.

Using the experimental data obtained by the described methods, it is possible to estimate the physical efficiency of the current heating of the plasma in a strong-current gas discharge.

3. ANALYSIS OF ENERGY BALANCE IN THE DISCHARGE IN THE CASE OF CURRENT HEATING

Assuming total ionization of the working gas, the equation of the energy balance can be written in the form

$$dW/dt = \eta\sigma E^2 - W/\tau_{\text{loss}}, \tag{1}$$

where τ_{loss} is the time constant of the departure of energy from the magnetic trap (the energy containment time) without current heating, σ is the effective electric conductivity of the plasma in the case of current heating, E is the intensity of the electric field in the plasma, η is the physical efficiency of the current heating, and $W = (3/2)nk(T_i + T_e)$ is the density of the thermal energy in the plasma.

It was shown in earlier experiments[12,13] that as the result of heating, the relation $T_e \approx 2T_i$ is established between the electron and ion temperatures. In this case $W = 2.25\ nkT_e$.

The coefficient η is a reflection of the existence of increased energy loss from the trap, due to different instabilities during the period of flow of the strong discharge current that heats the plasma. The efficiency and the time constant of the additional loss τ is connected by the simple relation

$$\frac{1}{\tau} = \frac{\sigma E^2}{W}(1-\eta). \tag{2}$$

The introduction of the dimensionless coefficient η in this analysis is more convenient. Solving Eq. (1) under the assumption that τ_{loss}, E, and σ are quantities that vary slowly in time (as is well satisfied under the conditions of our experiment), we obtain

$$W(t) = \eta\sigma E^2\tau_{\text{loss}}[1 - \exp(-\tau_{\text{heat}}/\tau_{\text{loss}})]. \tag{3}$$

Here τ_{heat} is the duration of the pulse of the heating current. If the energy loss from the system is sufficiently high, then the maximum attained thermal energy density in the plasma is given by

$$W_{max} = \eta\sigma E^2\tau_{\text{loss}} \tag{4}$$

and is practically independent of the heating-current pulse duration.

In the case when the loss is small ($\tau_{\text{heat}} \ll \tau_{\text{loss}}$), then

$$W_{max} = \eta\sigma E^2\tau_{\text{heat}} \tag{5}$$

and the density of the thermal energy in the plasma is proportional to the duration of the heating-current pulse. If τ_{heat} is sufficiently large, then the heating will continue until the condition for excitation of the instability responsible for the heating is violated. For example, if the current heating is due to ion-acoustic instability, then the heating conditions can be written in the form

$$U_0 \geqslant \gamma V_s = \gamma \sqrt{\frac{m_e}{M}}\, V_{Te}, \tag{6}$$

where m_e and M_i are the masses of the electrons and ions, and U_0 is the current-drift velocity.

The value of the coefficient γ should depend strongly on the relation between the electron and ion temperatures of the plasma during the last stage of heating[4]. The experimentally determined value of this coefficient is $\gamma \approx 2.5$. This result is in good agreement with a number of other measurements[18].

The value of the maximum attainable thermal energy in this case, obtained from the condition (6), is given by the expression

$$W_{max} = \frac{4.5\pi\sigma^2 E^2}{\gamma^2 \omega_{0e}^2} \frac{M_i}{m}. \tag{7}$$

Neglecting the loss in the trap, we can write the minimum value of the heating time in the form

$$\tau_{\min} = \frac{4.5\pi\sigma}{\eta\gamma^2\omega_{0e}^2} \frac{M}{m_e} \tag{8}$$

Here ω_{0e} is the electron plasma frequency.

The values of τ_{heat}, τ_{loss}, and W can be obtained from the form of the diamagnetic-signal pulse, and the values of σ and E can be measured directly. Thus, the obtained relations enable us to estimate, on the basis of the experimental data, the value of η and to trace the variation in different discharge regimes.

4. DISCUSSION OF EXPERIMENTAL RESULTS

Figure 3 shows the dependence of the thermal energy of the plasma and the value of the coefficient η as functions of the electric field in the plasma. We see that η depends little on the electric field, and we therefore use in subsequent investigations its mean value $\eta = 0.6$.

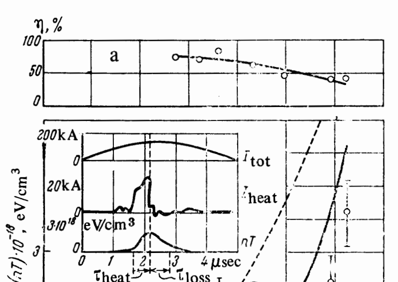

FIG. 3. The solid curves show the dependence of the physical efficiency η of the current heating (a) and of the density of the thermal energy of the plasma, calculated from formula (3) (b). (The mean value is $\eta = 60\%$). The points represent the values of the density of the thermal energy of the plasma, obtained from direct measurements of the diamagnetic effect by means of an internal probe. The dashed line represents the thermal energy of the plasma calculated by formula (7). $E_D \approx 10^{-12}\, n/T_e$ is the critical Dreicer field. The insert shows an oscillogram of the total discharge current I_{tot} (upper trace), of the current in the active region of the discharge I_{heat}, and a plot of "pure" diamagnetic signal nT obtained from the oscillogram of the magnetic flux (see Fig. 2). τ_{heat} – heating time, τ_{loss} – energy loss time.

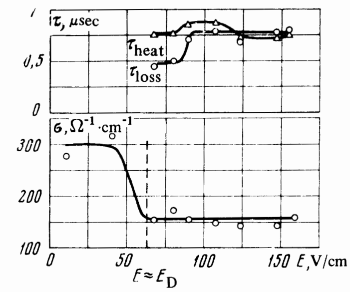

FIG. 4. Plasma conductivity σ, heating time τ_{heat}, and loss time τ_{loss}, obtained from an analysis of the diamagnetic signal, vs. the electric field.

The solid curve in Fig. 3 shows the dependence of the density of the thermal energy on the electric field, obtained by calculation from formula (3). The values needed for the calculation of the physical quantities were obtained from measurements, the results of which are shown in Fig. 4. The points denote the values of this quantity, obtained by independent measurements with the aid of a diamagnetic loop. The plateau observed in this investigation near the threshold value of the electric field (see Fig. 3) can be obtained from the equation of the energy balance in the discharge.

The oscillogram shown in Fig. 3 demonstrates the time variation of the "pure" diamagnetic signal, obtained as a result of a reduction of the oscillogram of the magnetic flux in the near-axis region of the discharge (see Fig. 2). For clarity, we show also oscillograms of the total discharge current and of the current flowing in the active zone of the discharge. Attention is called to the fact that the plasma heating occurs only during the time of flow of the heating current, and stops after the current stops. This agrees well with the picture of the development of current heating. It must be noted that in this case more than half of the energy supplied to the plasma is lost during the heating time as a result of the poor containment properties of the trap. The dashed curve of Fig. 3 shows the value of the thermal energy of the plasma calculated from formula (7). The discrepancy between experiment and calculations observed at certain values of the electric field, can be attributed to the fact that in this case the development of ion-acoustic instability is limited by the heating of the ions, leading to equalization of the ion and electron temperatures and to an increase of γ. It should be noted here that whereas in the former case the plasma heating is determined practically only by the electric field in plasma and by its density, in the latter case an important role is played by the balance between the energy loss and energy supply, as already noted above.

5. CONCLUSIONS

Thus, we have investigated the physical efficiency of current heating of a dense plasma. The efficiency of heating turned out to be higher than obtained in earlier investigations by the authors, where the efficiency was determined principally by the loss in the external circuits without allowance for the loss in the magnetic trap itself in the absence of current heating.

It is shown that the current heating of the plasma occurs during the time of current flow in the active region of the discharge, and after the end of the heating approximately 60% of the supplied energy remains in the form of thermal plasma energy.

It is shown that the density of the thermal energy of the plasma increases approximately like E^2, and that the mechanism limiting the development of the ion-acoustic instability in the case of strong electric fields is probably ion heating.

The previously obtained high value of the density of the thermal energy of the plasma in the current-heating regime ($nkT \approx 3 \times 10^{18}$ eV/cm^3) has been confirmed by different independent methods.

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[1] Ya. B. Faĭnberg, Atomnaya énergiya 11, 313 (1961).

[2] O. Buneman, Phys. Rev. 115, 503 (1959).

[3] V. D. Shapiro, Zh. Tekh. Fiz. 31, 522 (1961) [Sov. Phys.-Tech. Phys. 6, 376 (1961)]; Zh. Eksp. Teor. Fiz. 44, 613 (1963) [Sov. Phys.-JETP 17, 416 (1963)].

[4] L. I. Rudakov and L. V. Korablev, Zh. Eksp. Teor. Fiz. 50, 220 (1966) [Sov. Phys.-JETP 23, 145 (1966)].

[5] V. L. Sizonenko and K. N. Stepanov, ZhETF Pis. Red. 9, 468 (1969) [JETP Lett. 9, 282 (1969)].

[6] V. A. Suprunenko, E. D. Volkov, E. A. Sukhomlin, and N. I. Rudnev, Zh. Tekh. Fiz. 31, 1057 (1961) [Sov. Phys.-Tech. Phys. 6, 771 (1961)].

[7] B. A. Demidov, N. I. Elagin, D. D. Ryutov, and S. D. Fanchenko, Zh. Eksp. Teor. Fiz. 48, 454 (1965) [Sov. Phys.-JETP 21, 302 (1965)].

[8] M. A. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, S. P. Nedoseev, L. I. Rudakov, and V. A. Skoryupin, Third International Conference on Plasma Physics, Culham, England, Paper CN-21/154, 1965.

[9] S. M. Haberger and M. Friedman, Phys. Rev. Lett. 21, 674 (1968).

[10] I. G. Brown, D. L. Dimock, E. Mazzucato, M. A. Rothman, R. M. Sinclair, and K. M. Young, Third Conference on Research of Plasma Physics and Controlled Thermonuclear Reactions, Novosibirsk, 1968. Paper CN-24/O-3.

[11] L. A. Artsimovich, G. A. Bobrovskiĭ, E. P. Gorbunov, D. P. Ivanov, V. D. Kirillov, E. I. Kuznetsov, S. V. Mirnov, K. A. Razumova, V. S. Strelkov, and D. A. Shcheglov, ibid, Paper CN-24/B-1.

[12] E. A. Sukhomlin, V. A. Suprunenko, N. I. Reva, and V. T. Tolok, ZhETF Pis. Red. 1, No. 2, 45 (1965) [JETP Lett. 1, 68 (1965)].

[13] E. A. Sukhomlin, V. A. Suprunenko, L. I. Krupnik, P. A. Demchenko, V. I. Tyupa, N. I. Reva, and A. A. Sakharov, Ukr. fiz. zh. 12, 507 (1967).

[14] P. Ya. Burchenko, B. T. Vasilenko, E. D. Volkov, R. M. Nikolaev, V. A. Potapenko, and V. T. Tolok, ZhETF Pis. Red. 3, 243 (1966) [JETP Lett. 3, 156 (1966)].

[15] V. A. Suprunenko, Ya. B. Fainber, V. T. Tolok, E. A. Sukhomlin, N. I. Reva, P. Ya. Burchenko, N. I. Rudnev, and E. D. Volkov, Atomnaya énergiya 14, 349 (1963).

[16] T. H. Jensen and F. R. Soctt, Phys. Fluids 11, 1809 (1968).

[17] V. S. Koidan, A. N. Papyrin, A. G. Ponomarenko, and B. A. Yablochkov, ZhETF Pis. Red. 8, 389 (1968) [JETP Lett. 8, 241 (1968)].

[18] Yu. G. Kalinin, D. N. Lin, V. D. Ryutov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. 56, 462 (1969) [Sov. Phys.-JETP 29, 252 (1969)].

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66