SOVIET PHYSICS

JETP

A translation of the Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki

Vol. 26, No. 1, pp. 1-277 (Russ. Orig. Vol. 53, No. 1, pp. 3-416) January 1968

INVESTIGATION OF PLASMA HEATING UNDER CONDITIONS OF TWO STREAM INSTABILITY IN A LINEAR DISCHARGE

A. P. BABICHEV, A. I. KARCHEVSKIĬ, Yu. A. MUROMKIN, and E. M. BURYAK

Submitted to JETP editor December 7, 1966

Zh. Eksp. Teor. Fiz. **53**, 3–15 (July, 1967)

Heating of a plasma produced by passing a longitudinal current through a magnetic mirror trap (mirror ratio 2) is investigated. The quasistationary magnetic field in the middle part of the trap changed from 250 to 2000 Oe. It is shown that in the initial pre-breakdown stage of discharge beam heating of the plasma occurs; this results in the appearance of hot electrons with a temperature ~ 50 keV and density $\sim 4 \times 10^{10}$ cm^{-3} in the cold plasma ($n_e \approx 2 \times 10^{12}$ cm^{-3}). The confinement time of the plasma with hot electrons in the magnetic trap was anomalously small (50–70 μsec), and decay of the hot plasma does not occur in a monotonic manner. Thus oscillograms of the diamagnetic signal exhibit sharp kinks accompanied by x ray flashes. The heating efficiency of the plasma depends on the configuration of the magnetic field: fast electron production increases when the discharge is excited in an inhomogeneous magnetic field. It is shown that a dense ($n > 2 \times 10^{14}$ cm^{-3}), relatively cold ($T_e + t_i < 10$ eV) plasma is formed when attempts are made to heat the plasma by excitation of a heavy-current oscillatory discharge ($J \approx 15$ kA, $f \approx 70$ kHz). In addition the objections are considered, raised by Babykin et al.[13] against our previous papers;[1,2] it is shown that these objections are unfounded.

1. INTRODUCTION

In earlier investigations,[1,2] performed with the "Aspa" installation, we studied the efficiency of turbulent heating of plasma electrons by current of a direct discharge described first by Babykin et al.[3] It was shown in [1,2] that when current is made to flow through a plasma situated in a magnetic mirror trap, a small fraction of the electrons (up to 1%) of the plasma electrons is heated to high temperatures (the energy of this group of hot electrons exceeds 3–5 keV). Generation of a group of high-energy electrons in a cold plasma was attributed in [1,2] to the fact that in the initial state of development of the direct discharge there exists a beam of accelerated (starting) electrons, the interaction of which with the cold plasma causes part of the accelerated electrons to be captured in the trap, or a group of fast electrons to be generated in the cold plasma.[4,5]

Simonov and co-workers[6] have shown that heating of the electronic component of the plasma by excitation with a direct discharge is due to the interaction between the beam of the accelerated electrons with the injected plasma, and that under certain conditions a relatively large fraction of the plasma electrons (up to 10%) is heated to energies comparable with the potential initially applied to the plasma (to 15–60 keV).

Inasmuch as heating of even the electronic component of the plasma is of great practical and scientific interest, we have set up a number of additional

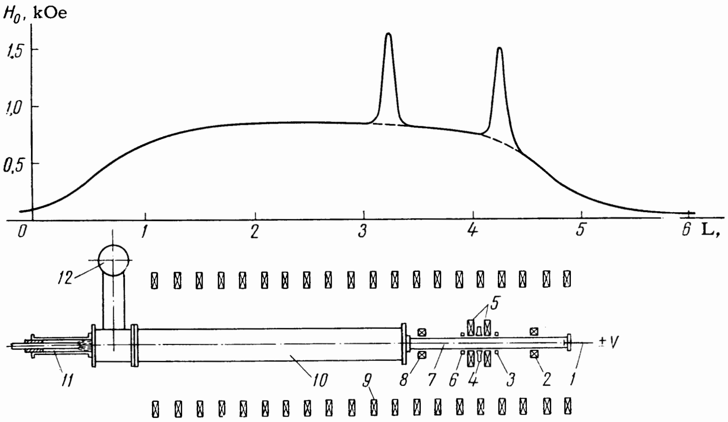

FIG. 1. Experimental setup. 1 – High-voltage metallic electrode, 2,8 – coils No. 1 and No. 2 of the quasistationary mirror trap, 3 – Rogowski loop, 4 – radio interferometer horns, 5 – pulsed magnetic field coils, 6 – diamagnetic loop, 7 – glass chamber, 9 – solenoid of leading magnetic field, 10 – metallic vacuum chamber, 11 – coaxial plasma injector, 12 – diffusion vacuum pump. On the top is indicated the distribution of the intensity of the leading magnetic field along the axis of the installation (U = 1000 V, C = 1.5 × 10^4 μF).

experiments, described below, aimed at investigating the mechanism of plasma heating in a direct discharge.

2. EXPERIMENTAL SETUP

The experimental investigation of the mechanism of plasma heating by a longitudinal current was performed with the "Aspa" installation, a diagram of which is shown in Fig. 1. The vacuum chamber of the installation is a sectionalized cylindrical tube. The first chamber section, 10, of 250 mm diameter and 3 m length, was made of stainless steel 2 mm thick. The second section, 7, is a glass tube with inside diameter 100 mm and length 1.5 m. To decrease the interaction between the plasmoid and the walls, we used in some experiments a diaphragm of stainless steel, 0.2 mm thick and with opening diameter 6 cm, placed at the entrance to the glass chamber. Inasmuch as the results of all our investigations were independent of the presence or absence of a diaphragm at the entrance to the glass tube, we shall henceforth not identify the experiments in which no diaphragm was used. Windows for plasma diagnostics were placed in the metallic and in the glass parts of the setup. The chamber was evacuated to 2×10^{-6} mm Hg by two oil-vapor diffusion pumps 12 with traps cooled by liquid nitrogen.

The vacuum chamber was located along the axis of a large solenoid 9 of 1 m diameter and 4.5 m length, consisting of 20 series-connected individual sections. Discharge of a capacitor bank of 0.02 F charged to 3 kV through the solenoid 9 (Fig. 1) produces a quasistationary longitudinal leading magnetic field H_0 with maximum intensity of 3 kOe on the solenoid axis and with half-period of about 0.1 sec. The switching device was an I-1-200/1.5 ignitron. On both ends of the glass tube were located additional coils, 2 and 8, connected in series with the main solenoid. As a result, a quasistationary field of mirror configuration was produced inside the glass chamber, with a distance 1.3 m between mirrors and a mirror ratio 2.

In individual experiments we also carried out adiabatic compression of the plasma with the aid of two dynamic coils 5 located in the central part of the glass tube and producing a pulsed magnetic field of mirror configuration with a growth time of 40 μsec and a decay time of 350 μsec. The distance between the coils was 20 cm, the mirror ratio was 2.5, and the maximum magnetic field in the mirrors was 25 kOe. The pulsed magnetic field was produced by discharging into each coil a capacitor bank of 300 μF charged to 6 kV. The switching devices were vacuum discharge gaps.

A coaxial plasma injector, 11, was placed at one end of the metallic chamber. The source capacitor-bank rating was 12 μF and the voltage 10 kV. An electrodynamic valve was used to admit into the source 0.5–1 cm^3 of working gas (hydrogen, argon, xenon) at atmospheric pressure. At the end of the glass chamber opposite to the source end was located a metallic electrode, 1, to which it was possible to apply with the aid of a discharge gap (Fig. 2) a high voltage pulse $\pm V_{\text{dir}}$ from a capacitor C_{dir}, the rating of which was either 0.1 or 2 μF, depending on the experimental conditions. When the high voltage V_{dir} was applied, a current was excited along the magnetic field in the plasma jet and heated the plasma.

As in the earlier investigations,[1,2] we measured in the experiments the plasma density with the aid of a radio interferometer operating at 2 mm wavelength, and the magnetic field in the plasma with the aid of coils surrounding the glass tube of the setup; we also measured the voltage and current of the direct discharge. In addition, we registered in the experiments the hard (W > 5 keV) x rays with collimated NaI crystals coupled to photomultipliers. The crystals were located outside the vacuum chamber, and the radiation was extracted from the

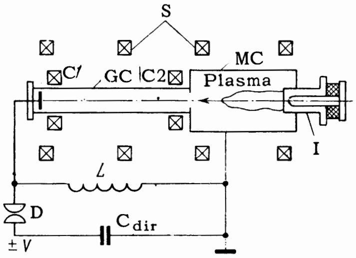

FIG. 2. Switching diagram of direct discharge. GC – glass chamber, $l = 1750$, diameter 110; MC – metal chamber, $l = 3000$, diameter 250; S – solenoid; C_1,C_2 – supplementary coils No. 1 and No. 2; I – injector; D – air discharge gap.

chambers through tubes covered with lavson polyester film 20 μ thick.

3. EXPERIMENTAL RESULTS

The experiment was performed in the following fashion: Voltage from the capacitor $C_{dir} = 2\ \mu F$ (Fig. 2) was applied to the end electrode in the glass tube in synchronism with the operation of the Marshall source. In this case, the electrode voltage followed the plasma jet entering the glass chamber. Figure 3 shows oscillograms of the current and of the magnetic field ΔH in the plasma, obtained for such an excitation of the longitudinal current in the trap with mirror-magnetic field configuration. The entire current flow can be roughly subdivided into two stages. First the current increases slowly (initial stage of the discharge, approximately 60 μsec, see Fig. 3), after which it goes over into the ordinary oscillatory mode.

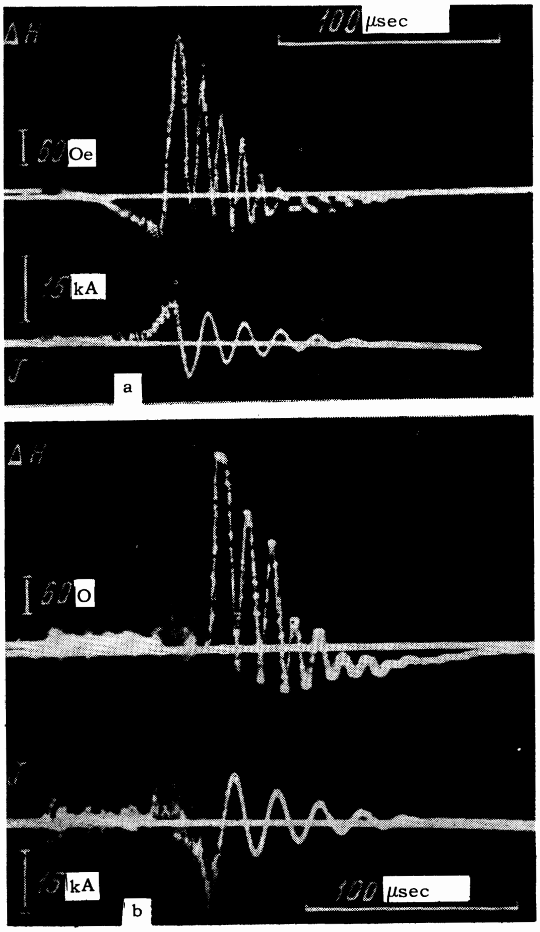

FIG. 3. Oscillograms of current and magnetic field in a plasma when the discharge is excited in the mirror trap: a – $V_{dir} = -20$ kV, $C_{dir} = 2\ \mu F$, $H_0 = 900$ Oe; b – $V_{dir} = +20$ kV, $C_{dir} = 2\ \mu F$, $H_0 = 900$ Oe.

The oscillograms of the magnetic field forced out by the plasma show that diamagnetic signals are observed during the initial discharge stage (see, for example, Fig. 3a) and can be associated with plasma heating. These diamagnetic signals are missing from the initial (pre-breakdown) stage of the discharge, if a voltage of positive polarity is initially applied to the electrode (Fig. 3b), although the character of the current flow during the initial discharge stage remains practically the same.

After the discharge goes over into the oscillatory mode, the oscillograms of the magnetic field in the plasma (Fig. 3) reveal paramagnetic oscillations connected with the passage of an oscillating current, with amplitude on the order of 10 kA through the plasma. The paramagnetic oscillations are observed at double the current frequency, and agree well in magnitude with estimates based on the quasistationary force-free discharge model. After the end of the current flow, "residual" diamagnetic signals are observed, which are clearly seen in Fig. 3 and whose duration is usually approximately 50–100 μsec, and whose magnitude corresponds to a plasma pressure $nT \approx 2 \times 10^{15}$ eV/cm³. These diamagnetic signals and their possible connection with plasma heating will be discussed in part B of the present section.

A. Investigation of the Plasma Heating Mechanism During the Initial Stage of the Discharge

Let us consider the main characteristics of the plasma discharge during the initial stage. The absence of plasma heating when the end electrode has positive polarity cannot be attributed, for example, to the trivial asymmetry of the system and to the construction of the direct-discharge electrodes. The simple assumption that there is no heating in the case of positive potential on the electrode, owing to the fact that one of the electrodes at the entrance to the glass chamber is annular and the end electrode is solid, is refuted by the following control experiment: The end electrode was replaced by a titanium plasma source, which injected plasma in the direction of the entrance diaphragm, and the coaxial injector was not turned on. In this case plasma heating was observed during the initial stage of the discharge only when the titanium injector was at positive potential relative to the potential of the annular electrode at the entrance to the glass chamber, and was not observed at all when the polarity was reversed. The dependence of the plasma heating on the polarity of the direct discharge at fixed parameters of the injected plasma jet indicates that the heating observed during the initial stage of the discharge must not be connected with heating by current.[3]

In order to avoid consideration of processes occurring during the oscillatory stage of the discharge, the direct-discharge capacitance was decreased to 0.1 μF, and the direct discharge was excited several dozen microseconds after turning on the Marshall injector. Thus, (by decreasing the discharge capacitance C_{dir} and by choosing the delay time between the connection of the direct discharge and the operation of the Marshall source) it is easy to attain conditions under which the capacitance C_{dir} is completely discharged into the plasma jet after 10–15 μsec, without the discharge becoming oscillatory. The general picture of the current flow and of the behavior of the magnetic field in the plasma under such discharge parameters ($C_{dir} = 0.1$ μF, $V_{dir} = 10-40$ kV) is similar to that observed during the initial stage of the discharge when a large capacitance is used ($C_{dir} = 2$ μF). In this case, too, plasma heating could be observed only when the electrode polarity was negative (Fig. 4a).

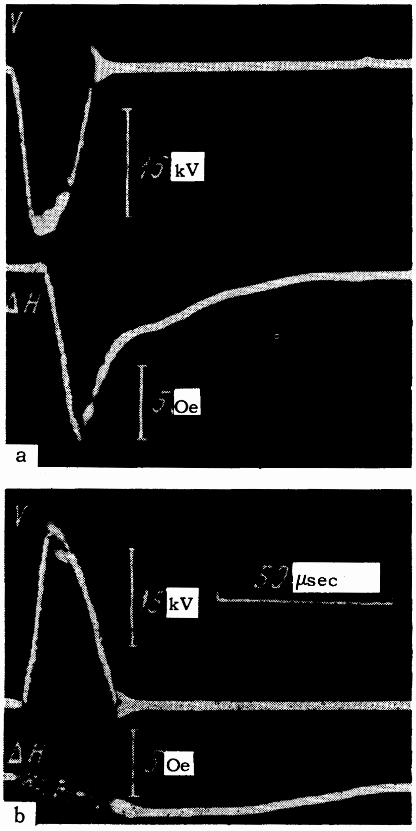

FIG. 4. Voltage of direct discharge and signal of diamagnetic loop: a – $V_{dir} = -30$ kV, $C_{dir} = 0.1$ μF, $H_0 = 1000$ Oe; b – $V_{dir} = +30$ kV, $C_{dir} = 0.1$ μF, $H_0 = 1000$ Oe.

From the decay time of the magnetic-probe signal we can determine the time of containment of the heated plasma in the magnetic trap. Figure 4 shows oscillograms of the direct-discharge voltage and of the diamagnetic plasma signal for two polarities of the direct-discharge voltage. It is clearly seen (Fig. 4a) that when a high voltage (of negative polarity) is applied the diamagnetic signal increases, and the plasma containment time amounts to approximately 50 μsec.

A characteristic feature is that the time of emission of x rays from the magnetic and the time of decay of the diamagnetic signal are in good correlation with each other (Fig. 5). Such a strong temporal correlation gives grounds for assuming that the plasma pressure as revealed by the diamagnetic signals is determined by the hot electrons revealed by the bremsstrahlung x rays. The hardness of the x rays was estimated from the absorption in the filters. At an electrode voltage $V_{dir} = -30$ kV, the x-ray energy was 50 keV. Since the plasma pressure measured with the aid of the diamagnetic signals is $nT \approx 2 \times 10^{15}$ eV/cm^3, it can be stated that the x rays with $W = 50$ keV are due to the electrons whose density is $n = 4 \times 10^{10}$ cm^{-3}, whereas the total plasma density measured with the aid of the radio interferometer is $\sim 2 \times 10^{12}$ cm^{-3}.

The experimental results fit within the framework of the two-stream mechanism of plasma heat-

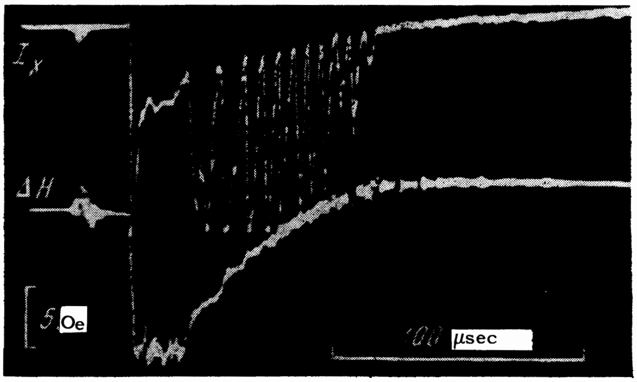

FIG. 5. Oscillograms of diamagnetic-loop signal and of x rays emitted from the trap (arbitrary units); $V_{dir} = -40$ kV, $C_{dir} = 0.1$ μF, $H_0 = 250$ Oe.

ing. To register the beam of accelerated electrons outside the magnetic trap, a thermal probe, which could be moved radially without breaking the vacuum in the system, was placed in the metallic vacuum chamber on the side opposite that of the electrode. The plane of the probe was perpendicular to the longitudinal leading magnetic field, and the probe was screened on the side of the incoming plasmoid. The thermal probe was made of a copper plate 5 mm in diameter and 0.2 mm thick, and the heating of the probe was registered with the aid of a thermocouple. The measurements have shown that approximately 60% of the energy stored in the capacitor C_{dir} is carried by the beam of accelerated electrons. It is noteworthy that the accelerated electrons are uniformly distributed over the entire cross section of the glass chamber; even when the diameter of the metallic end electrode was specially reduced to 1 cm, the current of the accelerated electrons was registered in a cross section of 7 cm diameter. In these measurements, no metallic diaphragm was used at the entrance to the glass chamber. The thermal probe made it possible to estimate also the current of the accelerated electrons, from the known values of the electron energy in the beam (equal to the applied potential) and from the current passage time. These estimates show that the current of the accelerated electrons is practically equal to the total current of the discharge, and its order is 300–500 A over the entire cross section of the glass chamber.

We note that when the end electrode is negative the accelerated-electron beam penetrates through the entire plasma-jet column, passes through the magnetic mirrors, and is registered along the entire length of the setup. On the other hand, when a high voltage of positive polarity is applied to the electrode, the electron acceleration apparently proceeds from the surface of the incoming plasmoids, and the accelerated electrons fall on the metallic end electrode and practically do not interact with the plasma.

In individual experiments, the thermal probe was replaced by a flat tantalum target, the plane of which made an angle of 45° to the longitudinal leading magnetic field, so that bremsstrahlung from the surface of the target could be registered by applying to the target a beam of accelerated electrons. Figure 6 shows the results of simultaneous measurements of the emission of bremsstrahlung from the magnetic trap and from the surface of the target, and also the diamagnetic plasma signal. The energy of the x rays from the surface of the tantalum target was always to (or somewhat lower than) the applied voltage, whereas the hardness of the radiation from the volume of the magnetic trap, as indicated above, exceeds the applied voltage by a factor of several times. The latter circumstance was noted earlier by Alexeff and Neidigh,[5] who studied plasma heating by an external electron beam.

We can thus conclude from the results of the

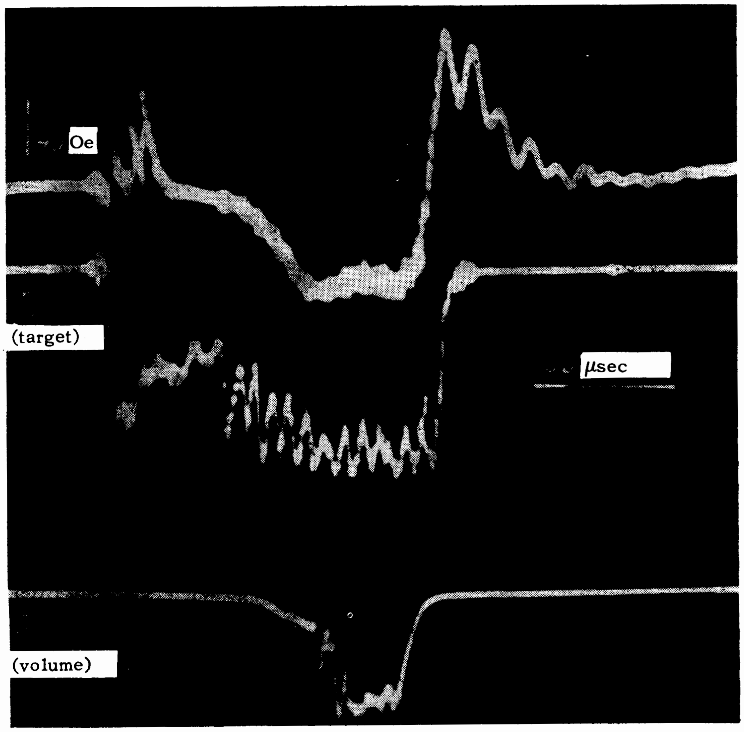

FIG. 6. Oscillograms of magnetic field in plasma and of x ray emission from the volume of the trap and from the surface of the target (arbitrary units); $V_{dir} = -21$ kV, $C_{dir} = 2$ μF, $H_0 = 900$ Oe.

foregoing experiments that during the time of the initial stage of the discharge there exists a beam of accelerated electrons, as a result of the interaction of which with the plasma there takes place generation of a group of fast electrons; the latter are revealed by the diamagnetism of the plasma and by the bremsstrahlung. An estimate of the efficiency of the two-stream heating of the plasma gives the following results. At a capacitor rating $C_{dir} = 2\,\mu F$ and a voltage $V_{dir} = 15$ kV (W = 225 J), the maximum measured value of nT of the plasma is 2.5×10^{15} eV/cm^3, corresponding to an energy of 2.5 J stored in the plasma. In the case when $C_{dir} = 0.1\,\mu F$ and $V_{dir} = 30$ kV (W = 45 J), the maximum energy content of the plasma is $nT = 5 \times 10^{14}$ eV/cm^3 (0.5 J). Thus, approximately 1% of the energy fed to the direct discharge is accumulated in the group of fast plasma electrons.

A characteristic feature of the described experiments is that the confinement time of the hot plasma is short and amounts to 50–70 μsec. This time does not agree at all with the time of escape of the plasma electrons from the trap as a result of Coulomb collisions, which in our case amounts to $\tau_{ee} = 0.3$ sec ($n_e = 2 \times 10^{12}$ cm^{-3}, $T_e = 50$ keV). An analysis of the oscillograms of the diamagnetic-signal decay shows that the anomalously rapid plasma decay is not monotonic; sharp dips are observed on the descending part of the diamagnetic signals (Fig. 5), and each break in the diamagnetic signal is accompanied by an appreciable increase in the intensity of the hard x rays from the volume of the trap (Fig. 5). It can be assumed that these phenomena are connected with the development of the cyclotron instability of the hot-electron plasma contained in the magnetic-mirror trap.[7, 8]

The efficiency of the heating by interaction between a fast-electron beam and a plasma turned out to depend strongly on the magnetic-field configuration. Figure 7 shows oscillograms of the diamagnetic signal upon excitation of a longitudinal discharge in a homogeneous magnetic field, when the supplementary coils No. 1 and No. 2 (Fig. 2) are connected separately, and finally, when both supplementary coils No. 1 and No. 2 are connected together, i.e., when the mirror-configuration magnetic field was produced. It is clearly seen that the *diamagnetic* signal of the plasma is much smaller in a homogeneous magnetic field than in the case of an inhomogeneous magnetic field, i.e., when one of the two coils producing the mirrors is turned on. The increased plasma-heating efficiency in the presence of inhomogeneity of the magnetic field cannot be attributed to accumulation of hot electrons in the plasma, since the magnitude of the diamagnetic signal is approximately the same whether the two mirrors are turned on, i.e., the magnetic trap is produced, or whether only one mirror is turned on and there is no containment of the particles. This conclusion is in qualitative agreement with the results of [9, 10], where it is noted that plasma heating by an external electron beam is more efficient in an inhomogeneous magnetic field.

B. Investigation of Plasma Heating by an Oscillating Direct-discharge Current

So far we have considered the mechanism and efficiency of plasma heating during the initial prebreakdown stage of the discharge. At the same time, several workers[11, 12] observed a significant heating of the plasma as the result of the flow of several cycles of a current having a pure oscillatory character. In these experiments, the current amplitudes were sufficiently large (up to 20 kA) at a discharge circuit frequently close to 100 kHz.[11, 12]

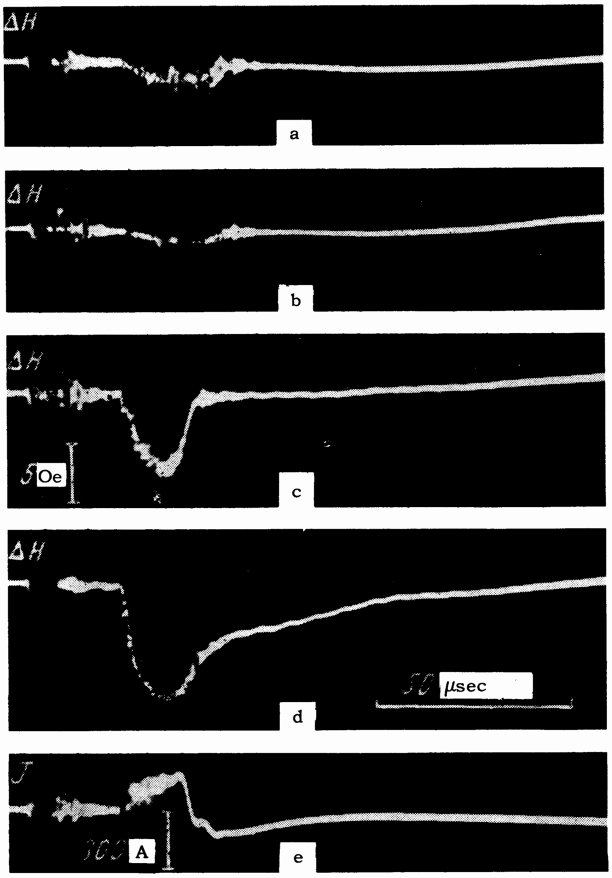

FIG. 7. Oscillograms of signals of diamagnetic loop and of direct-discharge current at different configurations of the magnetic field: a – homogeneous magnetic field, b – only coil No. 1 (see Fig. 2) of the mirror trap connected, c – only coil No. 2 of the mirror trap connected, d – both coils No. 1 and No. 2, of the quasistationary trap connected, e – direct-discharge current; $V_{dir} = -30$ kV, $C_{dir} = 0.1\,\mu F$, $H_0 = 900$ Oe.

Experiments in which a large-amplitude current was passed through a plasma situated in a mirror machine (probkotron) within a time on the order of several times ten microsceconds were also reported in [1, 2]. Unfortunately, when the strong-current discharge ($J \geq 10$ kA) was excited in the glass chamber, a strong increase in the plasma density was always observed ($n \geq 2 \times 10^{14}$ cm^{-3}). Consequently, no attempts were made in [1, 2] to determine the plasma pressure after the flow of large-amplitude current, and the possibility of plasma heating in such incorrect formulation of the experiment was not considered.

Nonetheless, the strong heating and the prolonged plasma containment, obtained in [11, 12], have stimulated a number of additional experiments in this direction. An attempt was made first of all to record the appearance of a hot plasma after the passage of an oscillatory large-amplitude current by determining the pushing-out of the magnetic field from the plasma. These measurements have shown that after passage of a large-amplitude oscillating current, diamagnetic signals are observed, corresponding to $nT \approx (2-3) \times 10^{15}$ eV/cm^3 and having a decay time of approximately 100 μsec. In all the experiments (just as in [1, 2]), the microwave power was always cut off in the 2-mm band, evidencing a large plasma density at that time, $n \geq 2 \times 10^{14}$ cm^{-3}. We note that the maximum density of the injected plasmoid is 2×10^{13} cm^{-3}, so that the appreciable increase in plasma density, to $n \geq 2 \times 10^{14}$ cm^{-3}, can be attributed only to the strong desorption of the gas from the walls of the glass tube upon passage of the discharge current ($J \approx 15$ kA).

Special control experiments have shown that in this case both the decay time and the plasma pressure, estimated from the diamagnetic signals, are completely independent of whether the strong-current discharge is excited in a trap with mirror magnetic-field geometry or whether the discharge develops in a homogeneous magnetic field with the mirrors turned off (Fig. 3a and Fig. 8). These experiments show that the observed diamagnetic signal cannot be attributed to confinement of heated plasma in the magnetic trap. It was noted in [1, 2] that adiabatic compression of such a plasma by a factor 10–20 did not lead to the appearance of x ray emission from the trap.

The experiments lead to the conclusion that under the described conditions the passage of several cycles of a powerful current produces a dense ($n \geq 2 \times 10^{14}$ cm^{-3}) and relatively cold ($T_e + T_i \leq 10$ eV) plasma, which diffuses slowly along the magnetic field, the decay time of such a plasma being comparable with the time of flight of the ions through the region of the glass chamber.

We are deeply grateful to I. K. Kikoin for interest in the work and to E. F. Gorbunov and V. N. Bezmel'nitsyn for great help with the present experiments.

Supplement (April 13, 1967). A recent paper by Babykin et al.[13] criticizes the conclusions of our papers [1, 2]. It is stated in [13] that the procedure chosen by us in [1, 2] does not make it possible to determine uniquely the fraction of the "hot" particles in a plasma turbulently heated by the current, and that the hard bremsstrahlung (with energy W_{X_1}) observed after adiabatic compression of the plasma by a factor of 5–15 is connected with the bremsstrahlung of the electrons from the "tail" of the Maxwellian distribution with temperature $T_1 \ll \epsilon_1$, where ϵ_1 is the electron energy, equal to W_{X_1}/α_1 where α_1 is the magnetic-compression coefficient.

To prove their statement, Babykin et al. start from the intensity ratio of x rays for a plasma compressed without heating by current and compressed after turbulent heating. Assuming that the x ray emission is determined by the electrons of the "tail" of the Maxwellian distribution, Babykin et al. obtain from this emission intensity ratio the inequality

$$1 < \frac{\alpha_1}{\alpha} \frac{W_X}{W_{X_1}} \frac{T_1}{T}, \tag{1}$$

where α is the coefficient of compression of the cold plasma, W_X the energy of the x-ray emission in adiabatic compression of the plasma without flow of current, W_{X_1} the x-ray energy upon compression of the heated plasma, and T is the cold-plasma temperature. Assuming that the plasma temperature after the turbulent heating is T_1

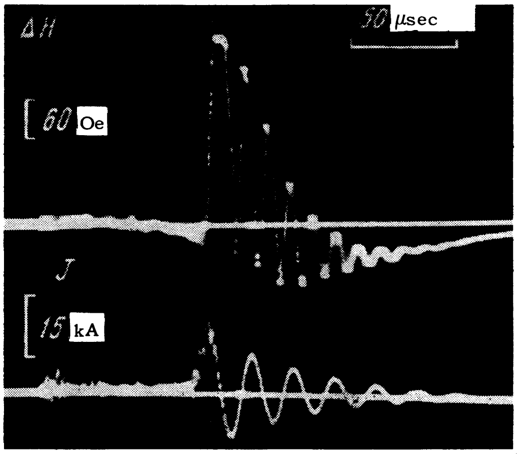

FIG. 8. Direct-discharge current and magnetic field in plasma; $V_{dir} = -20$ kV, $C_{dir} = 2$ μF, $H_0 = 900$ Oe, homogeneous magnetic field (coils No. 1 and No. 2 disconnected).

$< Q/\eta n_1 V$, where Q is the energy stored in the capacitor bank, η the fraction of the heated particles, n_1 the concentration of the current-heated plasma, and V the volume of the plasma, these authors get the following estimate for η:

$$\eta < \frac{\alpha_1}{\alpha} \frac{W_X}{W_{X_1}} \frac{Q}{n_1 VT}. \tag{2}$$

Substituting in (2) the experimental data of [2], they get $\eta < 0.4$. (We cited in [1, 2] the value $\eta \leq 0.001-0.01$.)

This estimate of η was obtained in [13] incorrectly, since the temperature T_1 of the plasma after the turbulent heating must be estimated by starting from the real efficiency of the turbulent heating, i.e., by starting from the real energy Q_1 stored in the plasma after the turbulent heating:

$$T_1 \lesssim Q_1/\eta n_1 V, \qquad Q_1 = Q\xi,$$

where ξ is the turbulent-heating efficiency (the notation is that of [13]). If we assume, for example, following Fig. 5 of [13], that $\xi = 5\%$, then the estimate for η takes the form $\eta < 0.02$. Actually, however, in our experiments[1, 2] the plasma heating efficiency, estimated from the diamagnetic measurements, was $\approx 2\%$ (see, for example, Fig. 7b of [1], leading for the concrete example considered in [13] to an upper bound $\eta < 0.008$.

We note that in [1, 2] the number of "hot" particles was estimated not from the ratio of the x ray intensities indicated above, but starting from data of two basic measurements: first, from measurements of the real heating of the plasma after the flow of the current, determined from the diamagnetism of the plasma, and second, from measurements of the temperature of the group of hot electrons, from the hardness of the x-ray emission of the compressed plasma estimated by the method of absorption in filters, in analogy with the measurements made of the temperature of the entire plasma by Babykin et al.[14] (p. 1633).

We cannot connect the observed x-ray emission with the bremsstrahlung of the electrons from the "tail" of the Maxwellian distribution with temperature $T_1 \ll W_{X_1}/\alpha_1$, for the following reasons. During the adiabatic compression, the electrons captured in the trap have an energy ϵ (eV) satisfying the inequality[15]

$$\varepsilon^{3/2} \geqslant t n_1 \frac{2}{45 \cdot 10^4 \alpha_1^{1/2}},$$

where t is the time of adiabatic compression. In our experiments, for $\alpha_1 = 17$, the electrons captured in the trap had an energy $\epsilon > 60$ eV. Therefore for $\alpha_1 = 17$ the electron energy in the trap will be equal to or larger than $\epsilon\alpha_1 \approx 1000$ eV. The x-ray emission threshold in the experiments of [1] was determined by a beryllium foil 0.2 mm thick and was 5 keV. Under these conditions, if we assume[13] that $T_1 \ll \epsilon_1$, then we should always have registered x rays emitted from the compressed plasma with energy equal to the transmission limit, i.e., 5 keV, rather than $W_{X_1} = 15-30$ keV, as was observed in [1, 2]. This is precisely why the estimates made in [13] on the basis of the ratio of the x-ray emission intensity of electrons from the "tail" of the Maxwellian distribution are not applicable at all to our experiments of [1, 2].

The estimate of η presented by us in [1, 2] is thus maximal, inasmuch as the plasma heating as revealed by diamagnetic measurements is ascribed fully to the "hot" component responsible for the x ray emission when the plasma is compressed.

In conclusion we note that we do not agree with the statement made by Babykin et al.[13] that our results of [1, 2] contradict the results obtained by others.[6, 16, 17]

---

[1] A. P. Babichev, E. M. Buryak, E. F. Gorbunov, A. I. Karchevskiĭ, and Yu. A. Muromkin, Plasma Physics and Controlled Nuclear Fusion Research **2**, IAEA, Vienna, 1966, p. 191.

[2] A. I. Karchevskiĭ, JETP **50**, 307 (1966) [Soviet Phys.-JETP **23**, 203 (1966)].

[3] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, L. I. Rudakov, and V. A. Skoryupin, JETP **47**, 1597 (1964) [Sov. Phys.-JETP **20**, 1073 (1965)].

[4] I. F. Kharchenko, Ya. B. Faĭnberg, R. M. Nikolaev, E. A. Kornienko, E. I. Lutsenko, and N. S. Pedenko, Nuclear Fusion, Supplement 3, 1962, p. 1101.

[5] I. Alexeff and R. V. Neidigh, Phys. Rev. Lett. **13**, 179 (1964).

[6] V. A. Simonov, V. V. Abozovik, and V. V. Ignat'ev, Plasma Physics and Controlled Nuclear Fusion Research **2**, IAEA, Vienna, 1966, p. 93.

[7] W. A. Perkins and W. L. Barr, ibid., p. 115.

[8] V. V. Alikaev, V. M. Glagolev, and C. A. Morozov, ibid., p. 877.

[9] L. D. Smullin and W. D. Getty, ibid., p. 815.

[10] P. I. Blinov, L. P. Zakatov, A. G. Plakhov, R. V. Chikin, and V. V. Shapkin, ZhETF Pis. Red. **2**, 426 (1965) [JETP Lett. **2**, 264 (1965)].

[11] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, L. I. Rudakov, and V. A. Skoryupin, Plasma Physics and Controlled Nuclear Fusion Research **2**, IAEA, Vienna, 1966, p. 851.

[12] L. V. Dubovoĭ and V. P. Fedyakov, Dokl. Akad.

Nauk SSSR **167**, 553 (1966) [Soviet Phys.-Doklady **11**, 239 (1966)].

[13] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, S. L. Nedoseev, L. I. Rudakov, and V. A. Skoryupin, JETP **52**, 643 (1967) [Soviet Phys.-JETP **25**, 421 (1967).

[14] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, L. I. Rudakov, and V. A. Skoryupin, JETP **47**, 1631 (1964) [Soviet Phys.-JETP **20**, 1096 (1965)].

[15] R. F. Post, Paper at Second Geneva Conference (Papers of Foreign Scientists, Atomizdat, 1959, p. 548).

[16] E. A. Sukhomlin, N. I. Reva, V. A. Suprunenko, and V. T. Tolok, ZhETF Pis. Red. **1**, No. 2, 45 (1965) [JETP Lett. **1**, 66 (1965)].

[17] 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)].

Translated by J. G. Adashko
1