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TURBULENT PLASMA HEATING BY CURRENT FLOW IN A MIRROR MACHINE

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Turbulent heating of a plasma has been investigated by passing a high-density current parallel to the magnetic axis of a mirror machine (probkotron).[1,2] It is shown that the observed plasma heating exceeds the heating corresponding to binary collisions by several orders of magnitude. The dependence of heating efficiency on time and voltage applied to the plasma have been studied. It is found that the conclusions reached by Karchevskiĭ et al.[6,7] are in error.

1. INTRODUCTION

IT has been shown earlier[1,2] that a high-density current flow parallel to the magnetic axis of a mirror machine (probkotron) between two electrodes located near the mirrors is capable of rapid and intense heating of a plasma; it has also been shown that the hot plasma produced in this way can be confined in a stable manner.

Inasmuch as the current flow was accompanied by the excitation of intense noise in the plasma, the anomalous heating was attributed to the development of collective motions in the plasma. The following pattern of the phenomenon has been assumed: at a current density exceeding some critical value, at which the directed velocity of the electrons u becomes larger than the critical velocity V_c, the plasma becomes unstable. The theory predicts that the quantity V_c should be larger than the ion-acoustic velocity for $T_e \gg T_i$ (ion-acoustic instability) or greater than the electron thermal velocity (current convective instability). If the current comprises a small fraction of the electrons and if the mean velocity of these electrons is greater than the electron thermal velocity in the plasma, the two-stream instability can arise.

In order to determine which of the instabilities can actually be excited in a given situation and in order to evaluate the importance of various instabilities it follows that in examining the passage of current through the plasma one should consider conditions for which an electron traversing the distance between electrodes does not undergo significant scattering by binary collisions.

The current established in the plasma should lead to a definite potential distribution along the axis of a plasma column. This distribution can depend on the distribution of plasma density along the axis, on the resistance of the plasma, and on phenomenon that occur near the cathode or anode. If the plasma trap is filled by injection from two injectors which operate simultaneously, at the beginning of the process the maximum potential gradient will be located in the central region, where the plasma density is a minimum. If the mirror machine is filled by a plasmoid from a single injector located, for example, at the anode (asymmetric injection), in the course of a certain time interval a high potential gradient will appear at the cathode so that the electric field is found to be concentrated at the cathode. The electrons leaving the cathode will acquire an energy in this field that is approximately equal to the potential difference applied to the plasma column. Evidently, a large cathode fall can also appear in uniform filling of a plasma discharge gap if the resistance of the plasma column is small and if the current flow is limited, for example, by the properties of the cathode. In this case a strong electron beam is produced and this beam can be retarded by the plasma by the development of the two-stream instability; in this case a large part of the beam energy is converted into energy associated with the random motion of the electrons in the beam and plasma.

According to theoretical estimates and experimental data[3] the retardation length for an electron beam in a plasma is given approximately by

$$\lambda = 10^{-8} \varepsilon \sqrt{n}/j. \tag{1}$$

Here, ϵ is the energy of the electrons in the beam in eV, j is the current density in the beam in $A\,cm^{-2}$ and n is the plasma density. Numerically, it is evident that ϵ is always smaller than the voltage V in volts applied to the discharge. Under typical conditions described in our earlier experiments[1,2] and in the present work the retardation length is always much smaller than the interelectrode distance, which is 1–2 m.

In addition to this energy dissipation mechanism, which operates near the electrode, the plasma can also be heated by a volume heating mechanism. At a distance from the cathode larger than several mean retardation lengths, the current comprises the main mass of electrons. If the directed velocity of these electrons is larger than the critical value, the entire length of the plasma column can be unstable against the current convective instability or the ion-acoustic instability. Electrons scattered on the electric fields due to oscillations associated with the instability will experience a frictional force; to maintain the current flow part or all of the applied voltage will be distributed over the plasma column and the electrons will be heated.

Any of the instability mechanisms considered above and the consequent heating can be of primary or secondary importance in a given experiment; a general feature for all of these instabilities is the fact that the plasma becomes turbulent by virtue of the electron current flow.

Let us introduce the heating efficiency ξ

$$\xi(t) = \frac{2U_V(t)}{CV_0^2 - C[V(t)]^2 - LI^2}, \tag{2}$$

where C is the capacitance discharged across the plasma, V_0 and $V(t)$ are the initial and instantaneous values of the voltage across C, L is the total inductance of the circuit, I is the current, and $U_V(t)$ is the energy deposited in the plasma at time t. In an experiment $U_V(t)$ can be determined by measuring the diamagnetism of the plasma:

$$U_V(t) = \frac{0{,}8 l H \tau_0 e_0(t)}{N} + 0{,}5 \cdot 10^{-9} l I^2(t) \ \ (\mathrm{J}). \tag{3}$$

Here, $\tau_0 = R_0C_0$ is the time constant of the integrating circuit in seconds, N is the number of turns on the diamagnetic probe, e_0 is the voltage of the integrated diamagnetic signal in volts, l is the length of the plasma column in centimeters and H is the magnetic field strength in Oersteds.

When the current through the plasma is turned off, (2) and (3) assume the simple forms

$$U_V = 0{,}8\, l H \tau_0 e_0 / N \ \ (\mathrm{J}), \tag{4}$$

$$\xi = 1{,}6\, l H \tau_0 e_0 / N C V_0^2. \tag{5}$$

The relations in (2)–(5) are very convenient for estimating the heating efficiency since they contain easily measured quantities and are independent of the density n and the radius of the plasma column r. The expressions given for U_V and ξ do not take account of the fact that the diamagnetic probe only gives the component of the plasma pressure that is perpendicular to the magnetic field; these relations also neglect electron loss out of the system through the loss cone. For a mirror ratio of 2 both of these corrections increase the values of U_V and ξ by approximately a factor of 1.7 as compared with the values given in (2)–(5). However, in making comparisons with experiment below we shall not introduce these corrections because the particle velocity distribution under heating conditions is not known and because it is difficult to make a reliable estimate of the true loss of energy through the mirrors.

In the experiments described below we have studied the anomalous resistance of the plasma, the diamagnetism of the plasma, the density n, the confinement time of the hot plasma in the trap, and the x-ray emission. In contrast with the experiments described in [2] the value of the capacitance for the direct discharge was taken from 0.2 to 0.025 μF rather than 2.5 μF, thus making it possible to reduce the discharge time considerably. In addition, the initial energy in the capacitance of the dc discharge has been reduced several times as compared with the earlier work.

2. EXPERIMENTAL APPARATUS

A diagram of the experimental apparatus is given in Fig. 1. The device is a mirror machine (probkotron); the distance between mirrors l = 2m and the mirror ratio varies from 1 to 3. The maximum magnetic field at the center of the device is 3.3 kOe. The vacuum chamber is made of glass, has an inner diameter of 17 cm and is 2.5 m long. The system is evacuated to 10^{-6} Torr. The plasma is injected into the trap from two titanium injectors located in the regions of maximum magnetic field in the mirrors. The plasmoids are injected simultaneously and form a highly ionized plasma column 2 m in length and 6–8 cm in diameter which is concentrated in the chamber and does not touch the walls. The density of the plasma column increases smoothly from the time at which the injectors are operated and reaches a value of $(1–2) \times 10^{13}$ cm^{-3} at approximately 50 μsec. The dc current through the plasma column flows between the buttons at the faces of the plasma injectors, to which, through a controlled discharge gap, is applied a voltage from a capacitor bank. The capacitor bank is charged to 50–150 kV. The return line for the current flow is located very close to the outer wall of the vacuum chamber so that the total inductance of the entire circuit is 0.85 μH while the period of

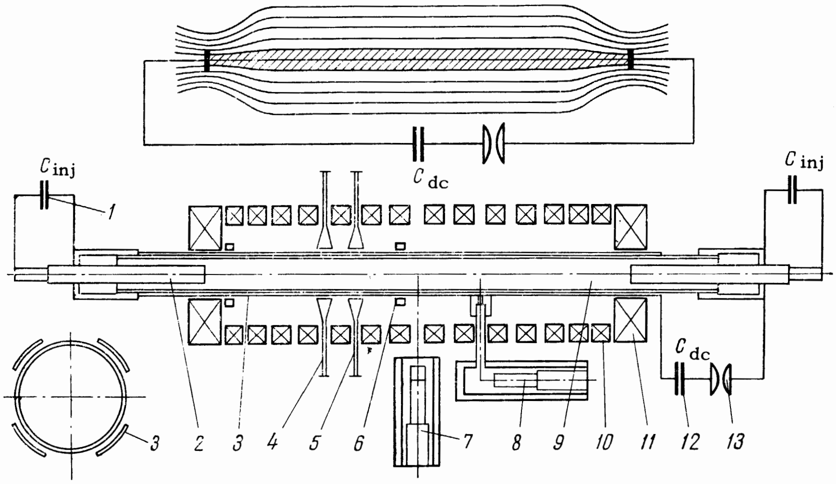

FIG. 1. Diagram of the TN-4 machine, 1) condenser C_{inj} for the plasma injector, 2) plasma injector with controlled trigger, 3) current return bus, 4) microwave interferometer, (3 cm), 5) interferometer (0.8 cm), 6) diamagnetic probe, 7) scintillation counter for hard x-rays, 8) scintilation counter for soft x-rays, 9) vacuum chamber, 10) solenoid for the longitudinal magnetic field, 11) magnetic mirror coils, 12) capacitor C_{dc} for the direct current circuit, 13) discharge gap. In the upper portion of the figure we show schematically the magnetic field configuration and the direct current discharge. Below to the left we show a section of the vacuum chamber in which the current return bus can be seen.

discharge circuit is 2.5 μsec for $C = 0.2\ \mu F$.

The diamagnetic measurements are carried out by means of diamagnetic probes which are coils consisting of one or more (5—20) turns wound on the vacuum chamber and the return lines of the dc discharge. By virtue of this arrangement the magnetic field associated with the discharge current does not link with the turns of the diamagnetic coil and does not make a contribution to the probe reading. The probes with a large number of turns are made of high-resistance wire in order to eliminate the possibility of parasitic oscillations of the coil associated with stray capacity of the winding. A great deal of attention has been given to careful electrical insulation of the turns from each other and from the coil shield. The copper shields for the probes have slots which allow the magnetic flux to freely link with the turns in the probe coil. The probe is connected by means of an ohmic resistance R_0' and a coaxial cable in a copper tube to a resistance equal to the characteristic impedance W and a capacitor C_0, so that the integrating circuit is characterized by a time constant

$$\tau_0 = (R_0' + R' + W)C_0 = R_0C_0, \qquad (6)$$

where R' is the resistance of the probe coil.

In different experimental configurations the value of τ_0 varies from 10^{-4} to 10^{-3} sec. The voltage from the capacitor C_0 is applied directly to the plates of a OK-25 oscilloscope or to a linear preamplifier with a bandwidth up to 5 MHz.

In the first experiments [2] we were able to observe appreciable diamagnetic signals with lifetimes ranging from 10 to 200 μsec under various conditions; in this case a dc discharge current of approximately 10^4 A was passed through a fully ionized plasma with a density of 10^{12}—10^{13} cm^{-3} which was isolated from the walls of the vacuum chamber.

3. RESULTS OF THE MEASUREMENTS

The general pattern of the phenomena observed with this device are as follows. The current through the plasma is 1—2 kA when the dc voltage is switched on with a small time delay with respect to the time at which the plasma injectors are operated; under these conditions the plasma density along the axis of the machine is highly inhomogeneous and relatively low $(1—3) \times 10^{12}\ cm^{-3}$. In this case the plasma resistance is 20—50 Ω and the plasma diamagnetism is small. Since the plasma resistance under these conditions is larger than the characteristic impedance of the discharge circuit, the current through the plasma is aperiodic. The confinement time for the hot plasma in the trap, as measured by the diamagnetic signal, is 100 μsec under these conditions and hard (10—30 keV) x-ray emission is observed from the plasma for several milliseconds. It follows that the hot electrons, which are responsible for this emission, do not make a noticeable contribution to the plasma diamagnetism.

If the dc voltage is switched on when the plasma density along the column is relatively large and high $(1—2) \times 10^{13}\ cm^{-3}$ the current through the plasma rapidly reaches a value of 10^4 A, the plasma resistance is several ohms, and the diamagnetic signal from the hot plasma is large (up to $4 \times 10^{16}\ eV \cdot cm^{-3}$); the plasma containment time in the trap is 10—30 μsec. Under these conditions no hard x-ray emission is observed.

The gradual transition from the first mode of operation to the second is characterized by the weakening and then complete disappearance of the hard x-ray emission with increasing plasma

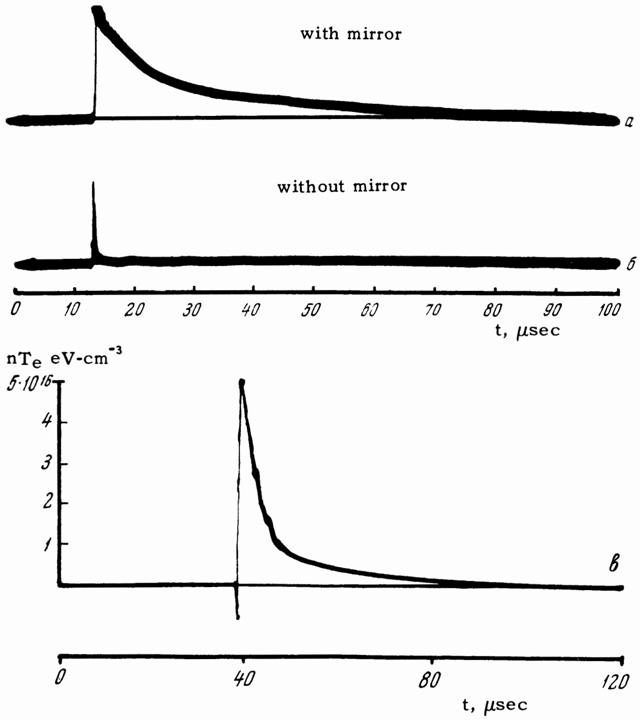

FIG. 2. Diamagnetic signal with the mirrors (a and c) and without the mirrors (b). The experimental conditions are the same in (a) and (b). In case (a) the maximum pressure $nT_e \approx 2 \times 10^{16}$eV $-$ cm^{-3}, $n \approx 2 \times 10^{13}$ cm^{-3}, H = 3 kOe and the ratio of plasma pressure to $H^2/8\pi$ is $\beta = 0.09$. In operation without the mirrors the diamagnetic signal diminishes by a factor of 20 in a time of about 4 μsec. The diamagnetism of the cold plasma that flows to the probe in 5 – 10 μsec after the discharge is less than 1% of the diamagnetism of the hot plasma and this diamagnetic signal does not appear in oscillogram (b). The diamagnetic signal of the plasmoids from the injectors is no more than 0.5 – 1% of the diamagnetic signal of the plasma after it is heated by the current and can only be seen by increasing the gain of the amplifier by the factor of 10. In cases (a) and (b) $C_{dc} = 0.025$ μF, $V_{dc} = 125$ kV, $V_{inj} = 12$ kV and B = 2.6. The oscillogram in (c) corresponds to a larger energy storage than in case (a) in the capacitance of the dc discharge and to a higher voltage on the plasma injectors. In this case $C_{dc} = 0.2$ μF, $V_{dc} = 60$ kV, $V_{inj} = 20$ kV, H = 3 kOe, B = 2.5, $\xi = 12.5\%$ and the value of the energy deposited in the plasma is $U_v = 45$ joules, $\beta = 8\pi\, Tn/H^2 = 0.22$ and $n \approx 10^{13}$ cm^{-3}. We note the paramagnetism of the plasma at the beginning of heating and the discontinuous drop in the diamagnetic signal as a function of time some 10 μsec after heating.

density, a smooth reduction in the confinement time of the hot plasma in the trap, and the transition from an aperiodic discharge to a periodic discharge with a high damping rate.

In Fig. 2 we show typical oscillograms of the diamagnetic signal from a plasma under various experimental conditions. The oscillograms marked a and b have been obtained with identical discharge parameters but in case b the magnetic mirrors are switched off and, after heating, the plasma must be cooled by contact with the injectors. The oscillogram marked c corresponds to a high initial energy in the capacitor bank for the dc discharge. In all cases the plasma heating time is less than or equal to 1 μsec.

A comparison of a and b shows that the magnetic mirrors increase significantly the lifetime of the hot plasma in the magnetic field and that the efficiency of plasma heating by the current is essentially independent of the magnetic mirrors. The oscillogram marked b indicates that the cold plasma that comes from the injectors after the dc current is passed through the plasma does not contribute to the diamagnetic effect (within the sensitivity limits of the probe). Measurements at higher sensitivity have shown that the contribution of this cold plasma to the diamagnetic signal is less than 1% of that due to the hot plasma. Approximately this same contribution (0.5—1%) to the diamagnetic signal comes from plasmoids that move through the diamagnetic probe before the heating current is switched on. The oscillogram marked c is interesting in that it exhibits a noticeably rapid discontinuous reduction in the plasma pressure in a time of ~10 μsec after heating; then, the drop proceeds more slowly and smoothly. In this experiment $nT_e \approx 5 \times 10^{16}$ eV-cm^{-3}, the initial $\beta = 8\pi nT_e/H^2 = 0.22$ $n \approx 3 \times 10^{13}$ cm^{-3} and $\xi \approx 12.5\%$.

In Figs. 3, 4, and 5 we show the dependence of ξ and nT_e on various operating conditions; in Fig. 6 we show the variation of n in time before and after plasma heating. These measurements

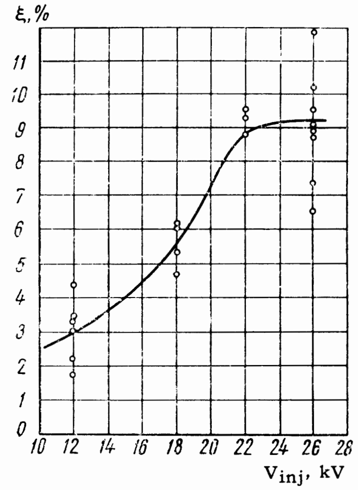

FIG. 3. The quantity ξ as a function of the voltage on the electrodes of the plasma injectors with $C_{dc} = 0.025$ μF, H = 3340 Oe, $V_{dc} = 140$ kV and B = 1.5. Increasing the voltage at the injectors leads to a more uniform filling of the trap and a higher plasma density (2 – 3) × 10^{13} cm^{-3}).

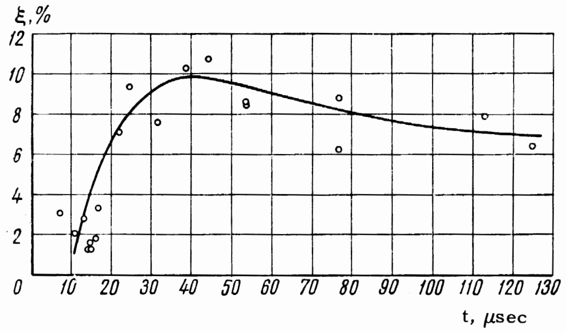

FIG. 4. The heating efficiency as a function of the delay of the direct discharge with respect to the triggering of the injectors with C_{dc} = 0.025 μF, H = 3350 Oe, V_{inj} = 12 kV and V_{dc} = 130 kV. At low values of the delay the plasma density η is relatively small and when $\tau \sim 50$ μsec it reaches (1.5 – 2) × 10^{13} cm^{-3} and then falls off slowly. The optimum plasma heat-heating corresponds to a delay time of approximately 40 μsec.

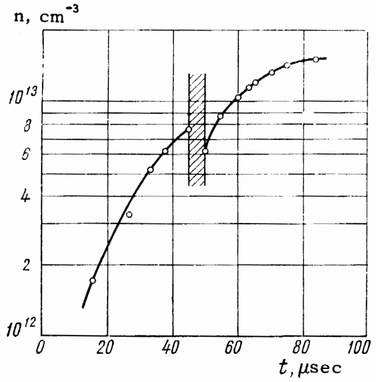

FIG. 6. The time dependence of the plasma density n computed from the microwave measurements before heating and after heating by current with C_{dc} = 0.1 μF, V_{dc} = 80 kV, V_{inj} = 12 kV and H = 3800 Oe. The cross-hatched region of 5 μsec corresponds to the time at which the heating current flows in which case the interferometer readings are unreliable because of the strong microwave radiation from the plasma and the spurious response in the interferometer. The reduction in plasma density in the heating region is evidently due to the diamagnetic expansion of the plasma column and, possibly, to the loss of particles through the loss cone of the mirrors. The subsequent increase in n is due to the influx of relatively cold plasma from injectors after the discharge.

indicate that the efficiency of heating and the plasma pressure after heating are extremely sensitive to the experimental conditions. The curve in Fig. 6 indicates a relatively small change in plasma density following heating. This change can be explained by the diamagnetic expansion of the plasma column and the loss of hot plasma particles through the loss cones.

In Fig. 7 we show the density of the plasma n as a function of time following the operation of the plasma injectors; we also show the dependence of the plasma heating parameters on the delay time for the dc discharge. To the right in Fig. 7 we show oscillograms for the hard ($h\nu \geq 15$ keV) x-ray emission. In this case we have determined the following parameters experimentally: n, the plasma density, nT_e, the plasma pressure after heating, and t the time for the diamagnetic signal to decay by a factor of 2.7. Using these data we compute the following: 1) T_e from the containment time of the plasma in the trap (lower limit) and 2) η the ratio of the number of "hot" particles to the total number of particles in the plasma after heating. The number of hot particles in the plasma is estimated as the quotient obtained by dividing the plasma pressure by T_e, computed as indicated above from the containment time t and the total plasma density. This estimate gives an upper limit for the number of hot particles since the temperature T_e can actually be higher in view of the fact that the confinement time could be determined by an instability.

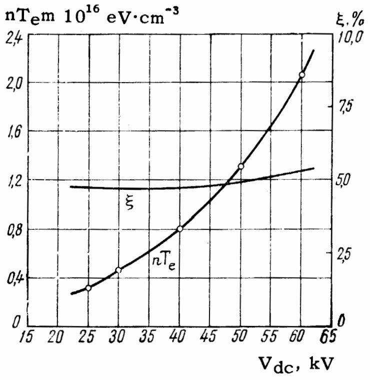

FIG. 5. The pressure of the heated plasma nT_e and the quantity ξ as functions of the voltage on the direct discharge condenser with C_{dc} = 0.2 μF, H = 2980 Oe, V_{inj} = 16 kV and B = 2:3. The quantity nT_e increases somewhat more rapidly than V^2.

The data in Fig. 7 yield an important result: as the intial plasma density at the point of heating is increased the intensity of the x-ray emission is reduced and, in the present experiments, disappears completely at densities $n \approx 2 \times 10^{13}$ cm^{-3}. In this case the energy density of the heated plasma, as determined from the diamagnetic signal, does not change significantly. This result allows us to draw the conclusion that if a group of fast particles is produced in the plasma in the heating process, as one reduces the energy contribution per particle (by increasing n) the energy of the fast particles is reduced in the same way as the energy of the main mass of particles. This dependence of the measured quantities should be observed, for example if the particle velocity distribution is Maxwellian.

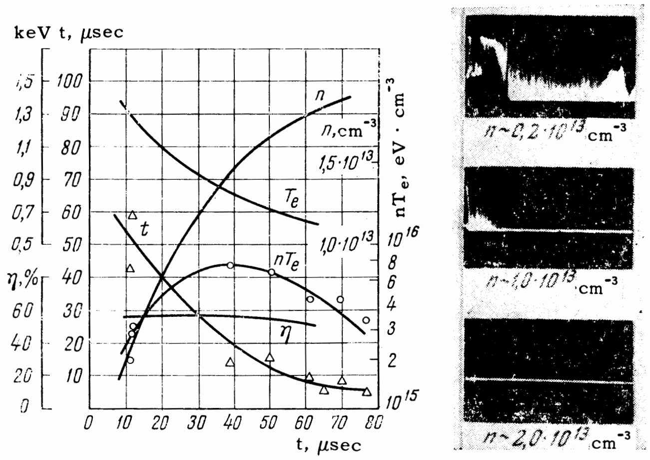

FIG. 7. The following quantities are given as functions of the delay time of the direct discharge with respect to the triggering of the plasma injectors: n initial plasma density as measured with the 8 mm microwave interferometer for the value $n \approx 1.7 \times 10^{13}$ cm^{-3} and extrapolated in the region $n > 1.7 \times 10^{13}$ cm^{-3} by the diamagnetic measurement; nT_e the plasma pressure after heating by the direct discharge current; t the time for the diamagnetic signal to diminish by a factor of 2.7; T_e the electron temperature in the plasma computed from the plasma confinement time in the mirror; η the ratio of the number of hot electrons computed from nT_e and T_e to the total number of electrons. The oscillograms to the right show the hard x-ray emission ($h\nu \geq 15 - 20$ keV) from the plasma as the initial density n is changed from 0.2×10^{13} cm^{-3} to 2×10^{13} cm^{-3}. The experimental conditions are as follows: $C_{dc} = 0.025$ μF, H = 2300 Oe, $V_{dc} = 140$ kV, $V_{inj} = 26$ kV and B = 2; the sweep length is 1.5 msec.

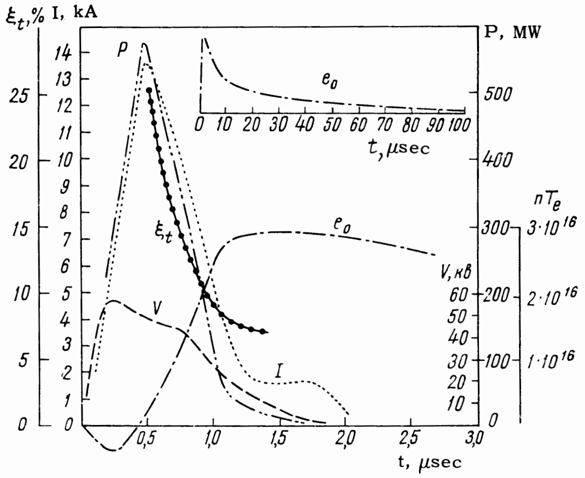

FIG. 8. The time dependence or various parameters in a deuterium discharge. The abcissa denotes the time measured from the application of the plasma voltage. The notation is as follows: V_{dc} is the plasma voltage, I is the plasma current, e_0 is the voltage from the diamagnetic probe in relative units, $P = IV_{dc}$ is the power, ξ_t is the instantaneous heating efficiency ([Eq. (2)]), nT_e is the plasma pressure computed from e_0. The upper part of the figure shows e_0 plotted on another time scale (t). The experimental conditions are as follows: $n \approx 2 \times 10^{13}$ cm^{-3}, $C_{dc} = 0.2$ μF, $V_{dc} = 60$ kV, $V_{inj} = 18$ kV and H = 2900 Oe.

In Fig. 8 we show the plasma heating process as a function of time. Along the abcissa axis is plotted the time following the application of the voltage to the plasma; e_0 is the signal from the diamagnetic probe, V_{dc} is the voltage on the condenser for the direct discharge, I is the current, $P = IV_{dc}$ is the power and ξ_t is the value of the heating efficiency at time t. It follows from Fig. 8 that after the appearance of voltage across the plasma, when the current is still small, the magnetic field due to the current compresses the plasma: but when the current reaches a value of approximately 12–13 kA the pressure due to the magnetic field produced by the current is balanced by the plasma pressure and the voltage e_0 changes sign. An analysis of e_0 and the current as functions of time shows that the maximum energy contribution to the plasma occurs at the region of the current peak, which corresponds to maximum power. When the current is diminished, the pressure associated with the magnetic field of the current is reduced rapidly and the diamagnetic signal increases. At a time 0.8 μsec the excess energy in the condenser is approximately 0.25 of the initial energy and the plasma heating process is essentially terminated. Calculations of ξ_t indicate that the heating efficiency is large in the first stages of current flow through the plasma (Fig. 8) and is reduced after the drop in voltage at the current source. It should be noted that in the region of maximum heating rate the ohmic resistance of the discharge, which is approximately 3Ω, is close to twice the value of the characteristic impedance of the discharge circuit:

$$2W = 2\sqrt{L/C} \approx 2{,}8 \text{ ohm};$$

this corresponds, as is well known, to the optimum impedance match between the source and the external circuit. This automatic matching of the plasma to the source has been noted over a variety of discharge conditions. This effect is evidently to be associated with the large range of variation of the ohmic resistance of the plasma from the time at which the plasma appears to the time at which the current flow is terminated; it follows that at some point within this range the impedance matching condition is realized automatically.

In Fig. 9 we show an oscillogram of the diamagnetic signal and the power curve for the discharge as computed from the voltage and current in an experiment in which the mirrors are turned off. The curve for e_0 allows us to determine the rate of cooling of plasma to the ends. Comparing the curves for e_0 and P we may state that the absence of the magnetic mirrors does not have any

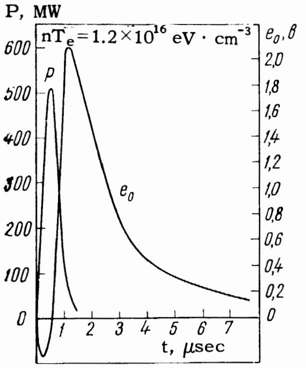

FIG. 9. The time dependence of the diamagnetic signal and the power $P = IV_{dc}$ (V_{dc} is the voltage applied to the ends of the plasma column, I is the current flowing through the plasma) in operation without the mirrors. $C_{dc} = 0.2\ \mu F$, $H = 2900$ Oe, $V_{dc} = 60$ kV, $V_{inj} = 18$ kV and $n \approx 10^{13}\ cm^{-3}$. The heating time for reaching a pressure $nT_e \approx 1.2 \times 10^{16}\ eV\text{-}cm^{-3}$ is approximately 1.2 μsec and the time in which the diamagnetic signal is reduced by a factor of 2.7 following heating is 2 μsec; this is in agreement with the time $\tau_a \approx 5$ μsec corresponding to ambipolar diffusion of the deuterium plasma along the magnetic field for $T_e = 1$ keV.

important effect on the plasma heating; after the current flow is terminated (in the absence of the mirrors) the plasma is cooled in approximately 2 μsec.

4. DISCUSSION OF THE EXPERIMENTAL RESULTS

The plasma heating effect reported here cannot be attributed to ordinary Joule heating. In the first place, an estimate of the limiting amount of energy U_q which can be evolved in the plasma during the heating process if one considers Coulomb collisions alone gives, under typical conditions for these experiments, a value $U_q \approx 0.25$ Joules. This is approximately 10^2 times smaller than the energy that is evolved in the heating process as observed in these experiments.

In the second place, if the heating were Joule heating the presence of the magnetic mirrors should not have an effect on the lifetime of the hot plasma in the trap because in Joule heating both the heating and the scattering of particles into the loss cone are determined by the same Coulomb collisions. However, in the present experiments, it is observed that turning on the magnetic mirrors, leaving all other conditions unchanged, increases the duration of the diamagnetic signal in a substantial way.

Thus, it would appear that the heating mechanism is related to collective processess in the plasma. Supporting evidence for this statement also comes from the noise that is excited in the plasma by the current.[2] Several well-known instability mechanisms which can be driven by current flow and which could be responsible for the effects reported here have already been discussed in other papers,[1,2,4,5] and in the present paper.

The turbulence excited by the current flow will obviously increase the number of collisions of the plasma particles ν^* and this should lead to an anomalously high diffusion both along and transverse to the magnetic field. It is then evident that effective plasma heating requires that the turbulent state should not be maintained for excessive times. The time scale is determined, on the one hand, by the necessity for introducing an adequate amount of energy into the plasma and, on the other, by the rate of diffusion of the plasma across the magnetic field, the rate of ambipolar diffusion and the turbulent heat conductivity along the magnetic field. We note that in the case of closed traps the latter effect is not an important one.

Let us estimate the effect of diffusion in the present experiments. As is well known, the transverse diffusion time $\tau_\perp$ is given by

$$\tau_\perp = r_0^2/\nu^* \rho_{He}^2, \qquad \nu^* = e^2SRn/lm. \tag{7}$$

Here, R is the resistance of the plasma column as measured experimentally, ρ_{He} is the electron Larmor radius, r_0 is the distance from the surface of the plasma to the side wall of the vacuum chamber. We now substitute in (7) values of the parameters that are typical for the present conditions: $r_0 \approx 6$ cm, $H = 3 \times 10^3$ Oe, $n \approx 10^{13}\ cm^{-3}$, $l = 2 \times 10^2$ cm, $S \approx 30\ cm^2$ and $R \approx 10\ \Omega$ and these yield the value $\nu^* \approx 4 \times 10^9\ sec^{-1}$ so that when $T_e \approx 1$ kev we have $\tau_\perp \approx 10^{-5}$ sec. Thus, the time $\tau_\perp$ is an order of magnitude larger than the heating time.

We now consider the question of plasma cooling along the magnetic field taking account of the fact that the plasma is in contact with the end electrodes of the injectors. An estimate of the time $\tau_{||}$ required for cooling the plasma at the end faces can be made if one assumes that the temperature distribution along the mirror machine is sinusoidal:

$$\tau_{||} = \frac{4l^2\nu^*}{\pi^2 C_e^2}, \qquad C_e = \sqrt{\frac{kT_e}{m}}. \tag{8}$$

To estimate $\tau_{||}$ we substitute the following values in (8): $\nu^* \approx 4 \times 10^9\ sec^{-1}$ $C_e \approx 2 \times 10^9\ cm \cdot sec^{-1}$; then we find that $\tau_{||} \approx 1.6 \times 10^{-5}$ sec, that is to say, $\tau_{||}$ exceeds the heating time in the present experiments.

When ν^* is large obviously the mirrors do not confine the plasma during the heating process. For this reason we must estimate the time τ_a required for loss of plasma energy by virtue of motion of the plasma along the magnetic field with a velocity $C_s = \sqrt{kT_e/M}$ (ambipolar diffusion):

$$\tau_a = l/2C_s, \tag{9}$$

and for deuterons at $T_e \approx 1$ keV we find $\tau_a \approx 5 \times 10^{-6}$ sec. This time is longer than the heating time. If the mirrors are switched off the cooling of the plasma occurs in a time which, in any case, is no greater than τ_a. This is in satisfactory agreement with the measured values (Figs. 2 and 9).

Thus, estimates of the diffusion and cooling of the turbulent plasma indicate that these effects are small for heating times less than 1 μsec. This result furnishes an explanation for the high value of the heating efficiency ξ_t in the initial states of current flow (Fig. 8) observed in the experiment.

In concluding our discussion of the experimental results we wish to dwell briefly on work reported by Karchevskiĭ et al.[6,7]

These authors describe experiments on plasma heating by means of a current flowing along the axis of a mirror machine. In the opinion of the authors the conditions in their experiments are approximately the same as the conditions for the work of the present authors on plasma heating by current in a dc discharge[1,2] and by shock waves.[8]

The basic conclusion reached by Karchevskiĭ et al[6,7] is essentially that one does not observe appreciable plasma heating by the dc current (the maximum heating that is achieved yields $nT_e \leq 5 \times 10^{14}$ eV-cm^{-3}) and that all the energy contributed to the discharge is transferred to a small group $(10^{-3} - 10^{-2})n$ of plasma electrons which acquire an energy of 10–15 keV. As proof of this assertion the authors have used a method which is based on the observation of x-ray emission from the plasma when it is compressed by a magnetic field (up to 12 kOe) in a time of 40 μsec. A comparison has been made of the intensity and hardness of the radiation when the plasma is not heated by the current ($T_e \approx 3$–5 eV) as compared with the case in which current does flow. The authors have observed that when the total energy discharged through the plasma by the capacitor is sufficient to raise the energy of all the particles by no more than 10–20 eV, the x-ray emission from the plasma is more intense and harder then in the case of magnetic compression in the absence of current heating; this result holds even if the coefficient for magnetic compression is appreciably smaller in the current-heating case. Absolute measurements of the intensity of the x-ray emission have not been carried out in[6,7].

We wish to call attention to the fact that the method used in[6,7] does not permit a unique estimate of the fraction of "hot" particles in turbulent heating of the plasma by a current.

In adiabatic compression of a plasma by a growing magnetic field those electrons are heated whose energies are such that they do not experience a collision in the time required for the magnetic field to increase by approximately a factor of 2. X-ray emission characterized by an energy $\geq W_x$ is produced by electrons for which the initial energy $\epsilon \geq W_x/\alpha$ where α is the compression factor. In a Maxwellian distribution the number of such electrons is

$$N = n\sqrt{\varepsilon/T}\, e^{-\varepsilon/T},$$

where T is the temperature and n is the plasma density.

Let us consider the point of view proposed in[6,7], i.e., that in turbulent heating by a current only a small number of particles are heated; we denote the fraction of heated particles by η. We shall also assume that the distribution function for the hot component is Maxwellian and characterized by temperature T_1. This temperature can be estimated from a knowledge of the energy Q stored in the capacitor bank used in the dc discharge

$$T_1 \leqslant Q/\eta n_1 V,$$

where n_1 is the density and V is the plasma volume through which the current of the dc discharge passes.

After adiabatic compression of this plasma with a compression coefficient α_1 the x-ray emission with energy W_{x_1} will be due to electrons which, before plasma compression, were characterized by an energy $\epsilon_1 \geq W_{x_1}/\alpha_1$. The number of such electrons is

$$N_1 = \eta n \sqrt{\varepsilon_1/T_1}\, e^{-\varepsilon_1/T_1}.$$

The ratio of the intensities for the x-ray emission for compression of a plasma heated by a current and a plasma without preliminary heating is

$$\frac{N_1}{N} = \eta \frac{n_1}{n} \sqrt{\frac{\varepsilon_1}{\varepsilon}\frac{T}{T_1}} \exp\left\{\frac{\varepsilon}{T}\left(1 - \frac{\varepsilon_1}{\varepsilon}\frac{T}{T_1}\right)\right\}.$$

This ratio is large if

$$\frac{\varepsilon_1}{\varepsilon}\frac{T}{T_1} < 1, \tag{10}$$

because under the experimental conditions[6,7]

$\epsilon/T \gg 1$. The inequality in (10) can be written in the form

$$\eta < \frac{\alpha_1}{\alpha} \frac{W_x}{W_{x_1}} \frac{Q}{n_1 VT}$$

Let us use the numerical values from the work reported by Karchevskiĭ et al.[6] Without heating (Fig. 2a): $T \approx 5$ eV, $n \approx 2 \times 10^{12}$ cm^{-3} $W_x \approx 10$ keV, $\alpha \approx 80$. With heating (Fig. 2d) $n \approx 10^{13}$ cm^{-3} $W_{x_1} \approx 15$ keV, $\alpha_1 = 17$ $V \approx 10^4$ cm^3 and $Q \approx 0.25$ joules. Substituting these values in the inequality we find that $\eta < 0.4$.

Thus, the sharp increase in x-ray emission after compression of the heated plasma observed in the experiments of Karchevskiĭ et al.[6,7] can be understood if one assumes that essentially all of the plasma electrons are heated rather than $10^{-3} - 10^{-2}$ of the total number of particles, as assumed by the authors in [6,7]. An estimate of the quantity η in [6,7] is actually based on the assumption that the x-ray emission characterized by $W_{x_1} \sim 15$ keV is produced by electrons with a mean energy, before compression, of $\epsilon_1 = W_{x_1}/\alpha_1$, and not by the tail of the Maxwellian distribution of the hot component with temperature $T_1 \ll \epsilon_1$. The authors in [6,7] have used the minimum estimate of η. The true value of η can only be estimated from measurements of the absolute intensity of the x-ray emission or by direct measurements of the electron distribution function.

Let us present a lower estimate for the fraction of hot particles in the experiments described here. In the experiment, the parameters of which are shown in Fig. 6, we have measured the energy spectrum of the x-ray emission. Using this result we estimate the electron temperature T_e corresponding to this radiation ($T_e \leq 30$ keV). If we assume that only a small fraction of the particles are heated and that the plasma pressure measured in the experiment ($nT_e \approx 2 \times 10^{16}$ eV $\cdot$ cm^{-3}) refers only to this fraction of electrons, the concentration of such electrons is approximately 10% of the total plasma density.

In contrast with [6,7] we wish to point out the interesting results stated in [1] obtained under the direction of Simonov,[9] in which turbulent current heating has been used successfully for producing and investigating the stability of a hot (10–30 keV) plasma in a mirror machine for a hot plasma pressure of approximately $(1-3) \times 10^{16}$ eV cm^{-3}; similar results are reported in [10-12].

CONCLUSION

In the present work we have reported new data that verify the conclusions reported earlier in [1,2] i.e., that the flow of a sufficiently high current density through a plasma produces an anomalously high plasma resitance as a result of the development of turbulence. In passing through the turbulent state the plasma is strongly heated and trapped; the plasma is confined for a time close to that required for an electron to be scattered through an angle of $\pi/2$. An explanation of the details of the heating mechanism will require additional investigation.

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