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PLASMA HEATING IN A TWO-STREAM INSTABILITY IN A STRAIGHT DISCHARGE

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It is shown that the development of the two-stream instability in a straight discharge with currents up to 400 A leads to the formation of a beam of accelerated electrons with energies of several k electron volts. The beam current is comparable with the total current of the discharge and reaches hundreds of amperes. The electron density in the beam is 2×10^9 cm^{-3}, corresponding to approximately 10^{-3} of the electron density in the plasma. The electric potential drop in the plasma at the time at which the instability develops is concentrated in a region approximately 20 cm in length which is localized from one discharge to another at various points along the plasma column. A bolometer method is used to show that the beam of accelerated electrons acquires up to 50% of the energy stored in the discharge circuit, whereas 1 to 3% of the energy in the external circuit is acquired by the hot electrons that are confined by the mirror device. It is shown that the heating of plasma electrons in the mirror device during the time in which the current of the straight discharge is interrupted, as observed in[1], is due to the interaction of the beam of accelerated electrons with the plasma.

IT was reported in an earlier work[1] that when a relatively weak current (100-400 A) flows through a plasma and conditions are suitable for electron runaway an instability arises which leads to the interruption of the current. When the current break occurs in a plasma located in a mirror device some of the plasma electrons are heated to temperatures of 2–4 keV for a plasma pressure $nT \approx 2 \times 10^{14}$ eV · cm^{-3}. In the present work we describe experiments that have been carried out in order to measure the current of accelerated electrons, their energy, and the distribution of electric potential along the plasma column during the time in which the current is interrupted. The experiments were carried out primarily on the Aspa device under conditions described in detail in[1].

A diagram of the apparatus and the basic diagnostics used in the present experiment are shown in Fig. 1. Into a glass tube 16, which is 150 cm in length and 10 cm in diameter, is admitted a jet of cold hydrogen plasma ($T_e = 1-2$ eV) from a coaxial injector 12. A voltage from a condenser bank $C = 2\mu F (V = 2 kV)$ is applied to the metal end plates 1 and 13 in the glass chamber. A straight discharge is excited in a longitudinal magnetic field which can vary from 300 to 1500 Oe. After the current flows in the plasma column the voltage across the chamber falls to 100–200 V and the spark gap in the plasma-condenser-bank circuit is switched off (crowbarred); the current in the discharge is then maintained by virtue of the energy stored in the inductance ($L = 850$ μH). Thus conditions are set up for the flow of a current with a peak value of approximately 100–400 A and a fixed exponential decay (determined by the discharge resistance and the inductance) amounting to several hundred microseconds.

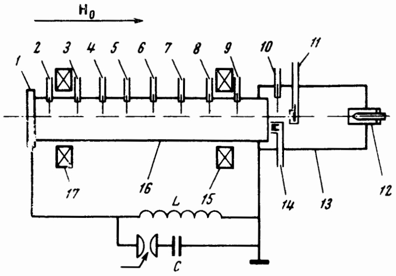

FIG. 1. Diagram of the apparatus: 1) end electrode, 2–10) identical electrostatic probes, 11) three-grid probe, 12) coaxial plasma injector, 13) metal chamber, 14) bismuth bolometer, 15) mirror coil, 16) glass chamber, 17) mirror coil.

After the quiescent flow of current for 100–200 μsec, at a plasma density of approximately $(1-2) \times 10^{12}$ cm^{-3} an instability arises which leads to the partial or total cutoff of the discharge current (Fig. 2a). Since the current in the plasma is maintained by the inductive storage, when the current is shut off an inductive voltage which reaches tens of kilovolts (Fig. 2b) is developed across the chamber. The plasma pressure (Fig. 2c) is measured by means of magnetic coils which are wound around the glass chamber and are terminated by an integrating RC network. In order to detect the current of the beam of accelerated electrons (Fig. 2d) use is made of a three-grid probe with an input aperture whose diameter varies from 0.2 to 0.5 mm.

The energy in the beam of accelerated electrons is measured with a bolometer. The bolometer is fabricated following the technique described in[2] with the small difference that its sensitivity is increased by depositing the bismuth layer on an aluminum substrate which is 8μ in thickness. The bolometer sensitivity is approximately 2×10^{-5} J/cm^2 for 100 μV of useful signal with a resolution time determined by the thickness of the oxide layer (several microseconds). The cooling time of the bolometer is several milliseconds.

The bolometer 14 is located inside the metal chamber 13 outside the mirrors, which are produced by means of two additional coils 15 and 17. The sensitive side of the bolometer is turned toward the glass chamber while the insensitive side is shielded by a copper wall from the direct incidence of the flux of cold plasma from the injector.

The three-grid probe 11, or a system of 10 three-grid probes (along a diameter of the chamber), is also located outside the mirror and the aperture of the probe is directed in the direction of the glass chamber.

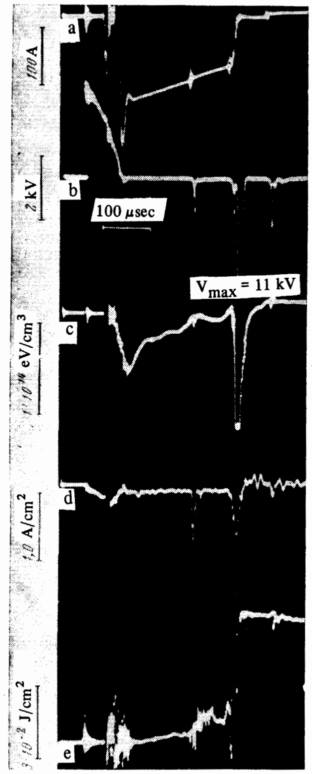

FIG. 2. Oscillograms: a) current, b) voltage, c) diamagnetic signal, d) current density in the beam, e) bolometer signal. The longitudinal magnetic field $H_0 = 250$ Oe; the operating gas is hydrogen.

Along the glass chamber there are nine identical probes 2–10 which measure the electric potential of the plasma. The probes are terminated by special compensated dividers and the probe signals are applied to the plates of OK-17 oscilloscopes.

EXPERIMENTAL RESULTS

The bolometer measurements and the measurements made with the three-grid probe allow us to observe a beam of accelerating electrons at the time the current is interrupted. The density and energy of these electrons can be measured. In the experiments the sensitive side of the bolometer and the aperture of the three-grid probe are always turned in the direction of electrode 1 so that the current and energy of the beam of accelerated electrons are recorded only when the acceleration of the electrons occurs in the direction of the injector 12. When the current flowing in the reverse direction is interrupted and an overvoltage of positive polarity appears at electrode 1 the beam of electrons is directed in the opposite direction to the face of electrode 1 and is not detected by the bolometer or the three-grid probe.

The radial distribution of energy in the beam of accelerated electrons is determined by means of two bolometers, No. 1 and No. 2, one of which is movable; the other is fixed and serves as a monitor. The ratio of the energies received by the two bolometers, as a function of radius, is shown in Fig. 3. It is evident from this figure that the energy density in the beam is uniform over the cross-section of the chamber to within ±30%. The inner radius of the glass chamber is 5 cm.

Measurements of the current density in the beam as a function of radius taken with the ten probes located with a spacing of 13 mm between probes along a diameter show that the current density of the beam that is generated during the current break is also constant over the cross-section of the chamber to within ±30%.

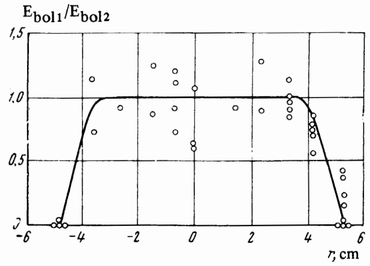

FIG. 3

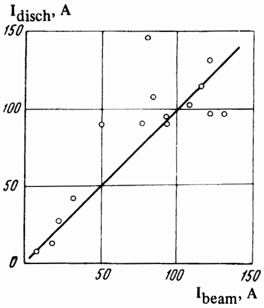

FIG. 4

FIG. 3. Energy distribution in the beam of accelerated electrons as a function of radius; $H_0 = 250$ Oe, the operating gas is hydrogen.

FIG. 4. The current of the beam of accelerated electrons as a function of total discharge current; $H_0 = 250$ Oe, the working gas is hydrogen.

From the data on the current density of the beam as measured with the multigrid probe it is possible to compute the total current over the cross-section of the chamber which is carried by the beam of accelerated electrons. It is found that at the time of the current break essentially all of the current (50–100%) flows in the form of the beam of accelerated electrons. This functional dependence of the beam current and the total current as measured with a Rogowsky loop are shown in Fig. 4; these data have been obtained from a large number of oscillograms in which current discontinuities of various magnitude are observed.

We note in passing that no correlation is observed between the magnitude of the current discontinuity and the magnitude of the current in the beam of accelerated electrons. The absence of a correlation is evident, for example, in Fig. 2a and Fig. 2d, in which there are three clear current breaks: the first break in the current at 270 μsec from the beginning of the sweep (the small current dip of a magnitude of approximately 7 A), a second current break at 360 μsec (the large current break of approximately 80 A), and finally the last at 420 μsec. The first two current breaks (7 and 80 A) correspond to a beam current of accelerated electrons of approximately 50 and 100 A; the total discharge current for these two cases is 120 and 100 A respectively.

If the current density in the beam is known $j = n'eu$, where n' is the electron density in the beam and u is the directed velocity of these electrons, then a measurement of the total energy of the electron beam as received on the bolometer in a time τ makes it possible to estimate the energy and density of these electrons. The energy density of the beam deposited per unit area of the bolometer is given by

$$E = {}^1/_2 mv^2 n' u\tau,$$

where $mv^2/2$ is the electron energy and τ is the lifetime of the beam. Since the directed velocity of the electrons u is much greater than the thermal velocity, we can take $mv^2/2 = mu^2/2$. Two quantities are measured in the experiment, these being j and E

$$j = n'eu, \qquad E = mu^3 n'\tau / 2. \qquad (1)$$

The time τ is estimated from the width of the peak in the beam current and is usually 5–10 μsec. Then, using Eq. (1) we can obtain the values of u and n′.

The calculations show, for example, that for the first current break (Fig. 2a) in which the current jump is approximately 7 A, heating of the bolometer associated with the electron beam is observed (8×10^{-3} J/cm^2); the current density of the beam is ~0.8 A/cm^2. For this case, assuming that $\tau = 7$ μsec we find that the energy of the beam electrons is 1.7 keV while the electron density in the beam is approximately 2×10^9 cm^{-3}. Correspondingly, the calculations for the second current break (Fig. 2a and Fig. 2d), in which the current jump is approximately 80 A, show an electron energy of approximately 3.2 keV and an electron density of approximately 2.5×10^9 cm^{-3}. At this point in time, the density of cold plasma n_e characterized by a temperature T = 1–2 eV is $(1-2) \times 10^{12}$ cm^{-3}. Before the acceleration period all of the current is carried by slow electrons. During the acceleration regime and following it all the current is carried by the accelerated electrons, which comprise a fraction 10^{-3} of the plasma electrons. An estimate of the total energy of the beam electrons shows that no less than 50% of the total energy stored in the external circuit goes into the acceleration of the electrons.

Measurements of the potential distribution along the plasma column allow us to determine the region in which electron acceleration occurs at the time the instability develops. The distribution of electric potential in the plasma at the time of the current break is shown in Fig. 5a and Fig. 5b, which pertain to current breaks in different directions. From an analysis of the oscillograms it follows that the basic potential drop is concentrated in a length of approximately 20 cm and that it is localized in a random way from one discharge to another in various points along the length of the apparatus. In Fig. 5 we show curves I and II which show the edges of the observed position of the region of potential drop.

The effective heating (or lack of heating) of the plasma is directly related to the location of the region of potential drop along the chamber in a mirror device, as we have described in[1]. Stable heating of the plasma is observed only in those cases in which the beam of accelerated electrons penetrates the entire plasma located within the mirror device. For example, this case corresponds to the potential distribution denoted by 1 in Fig. 5a and Fig. 5b. On the other hand, when the region of potential drop lies outside the mirrors and the beam of accelerated electrons does not penetrate the magnetic barrier (curve II in Fig. 5) no plasma heating is observed during the time of the current break.

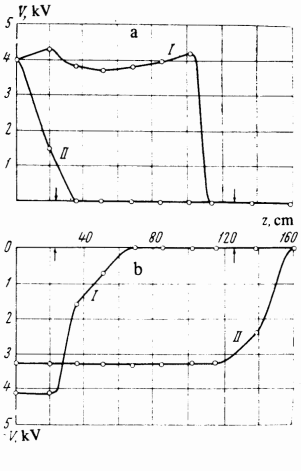

FIG. 5. The potential distribution along the plasma column at the time of development of the instability of the discharge current: a) these curves refer to a current break in one direction of current flow, b) these curves hold for a break in current flow in the opposite direction. For the curves marked II no plasma heating is observed in the mirror device at the current break. The arrows denote the positions of the mirror coils. The end electrode is located at the point z = 0.

On this basis we propose that heating of plasma in a mirror machine in the development of the two-stream instability due to current flow in the straight discharge[1] is caused by the beam of accelerated electrons that penetrate the plasma located within the mirrors.

In addition to making it possible to detect and measure the energy of the beam of accelerated electrons, the bolometer method that has been used here can be used to make a separate measurement of the electrons heated by the beam and to estimate the energy of these hot electrons. For this purpose we excite a break in the current that flows in a direction such that electrode 1 acquires a potential of positive polarity so that the electrons are accelerated to it. In this case the bolometer does not record the primary beam of accelerated electrons. Under these conditions, in principle the bolometer can record the energy of the hot electrons that escape along the axis of the mirror device.

In order to measure the energy of the hot electrons, mirror coil 17, which is far from the bolometer, is switched on, while mirror coil 15, which is close to the bolometer, is switched off. In this case all of the hot electrons formed by the beam of accelerated electrons are turned around and strike the bolometer after a single reflection from the magnetic barrier 17. This effect is shown in Fig. 6b. The energy of these hot electrons, as measured by the bolometer, amounts to 5% of the energy of the primary beam of accelerated electrons and, correspondingly, 1 to 3% of the total energy stored in the external circuit. These bolometer measurements of the energy of the hot electrons are in good agreement with the measurements of the energy content in the plasma carried out by means of the diamagnetic effect (Fig. 6b).

In Fig. 6a we show an example of anomalously rapid loss of hot plasma from the mirror device and find that the bolometer does not record the energy of particles that escape along the axis of the mirror (Fig. 6a). This result is related to the fact that the loss of plasma from the trap is evidently primarily across the magnetic field and no loss of hot electrons along the magnetic field is observed.

Finally, in Fig. 6c we show the case of a current break in a uniform magnetic field. In all three cases (6a, 6b, 6c) we show the distribution of potential along the axis of the system; these results show that the oscillograms for plasma heating and energy loss are taken under conditions that are uniform with respect to the point of formation of the beam of accelerated electrons.

We also note in passing that in the oscillograms in Fig. 6a and Fig. 6b there is a smooth heating of the

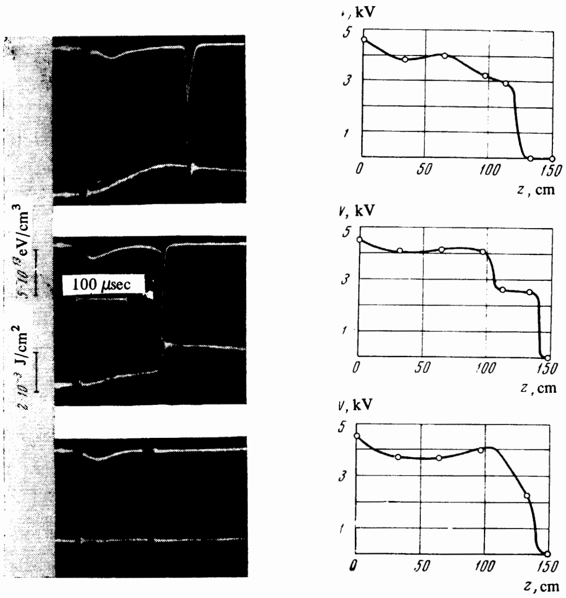

FIG. 6. The energy density of the hot electrons. The oscillograms of the diamagnetic signal (above) and bolometer (below) for various magnetic field configurations: a) with both mirror coils 15 and 17 in operation, b) with mirror coil 17 operating alone, c) with both mirror coils 15 and 17 off (uniform magnetic field). To the right we show the potential distribution at the current break for all three cases. The arrows denote the positions of the mirror coils. $H_0 = 300$ Oe, the operating gas is hydrogen.

bolometer which is related to the partial reflection of cold plasma (from the injector) at the magnetic barrier 15 (Fig. 6a) or the magnetic barrier 17 (Fig. 6b).

CONCLUSION AND DISCUSSION OF RESULTS

In the course of earlier work[1] it has been shown that in the two-stream instability the current in the straight discharge produces beams of accelerated electrons and that the entire discharge current is carried by the beam of accelerated electrons. The energy of the directed motion of the electrons in the beam is comparable to the potential drop in the plasma at the time of development of the current instability, amounting to several kiloelectron volts. The potential drop in the plasma is concentrated in a region no larger than 15–20 cm and this region varies in position from one discharge to another, occupying different points along the column. In this respect the behavior of the plasma column is very similar to that which has been observed in a turbulent straight discharge by Koĭdan et al.[3] One unimportant difference of a technical nature is the fact that in our case the external source of energy for the discharge appears in inductive storage; in[3] the energy was stored in a condenser bank. In the present experiment the beam current is approximately 100 A while the electron density in the beam n' is 2×10^9 cm^{-3}. Thus, approximately 10^{-3} of all of the plasma electrons participate in carrying the current.

From the data of bolometer measurements and the known distribution of electric potential along the column we can estimate the conductivity of the plasma in which n' electrons are accelerated to an energy $\bar{\epsilon}$ in a segment of length l. This conductivity is given by $\sigma = 2ln'e^2/mv$ where v is the velocity to which the electrons are accelerated in the region of active potential drop. Making use of the data obtained in the present work ($n' \approx 2 \times 10^9$ cm^{-3}, $l \approx 20$ cm, $\bar{\epsilon} \approx 3$ keV) we find $\sigma \approx 10^{10}$ cqs. Precisely this same value of σ_{eff} is observed in the plasma column at the time the two-stream instability arises. Since this conductivity is several orders of magnitude smaller than that which would be computed on the basis of Coulomb collisions, we may call it an "anomalous" plasma conductivity. But it is necessary to take account of the fact that the corresponding enhancement of the dissipation of energy is not due to the heating of the plasma, but rather to the transfer of energy into directed motion of the electron beam. It is only then in the interaction of the beam of accelerated electrons with the plasma that there is a dissipation of beam energy into the plasma.[4]

As in the preceding work,[1] we assume that the two-stream instability is associated with favorable conditions for a beam of runaway electrons, i.e., the electric field in the plasma reaches the critical value given by Dreicer.

In the present work it is clear that the heating of the plasma electrons in the mirror system is due to the interaction of the beam of accelerated electrons; the heating is only observed when the beam of accelerated electrons penetrates the entire plasma column in the mirror system. The parameters of the beam which heat the plasma of density and temperature $n_0 \approx 2 \times 10^{12}$ cm^{-3} and $T_{e0} \approx 2$ eV are $n' \approx 2 \times 10^9$ cm^{-3} with an electron energy in the beam of ~3.0 keV, a beam current of ~100 A and a beam lifetime of 5–10 μsec. As a result of the beam plasma interaction, some of the plasma electrons are heated, as in[1]. Supplementary methods of measurement in[1] have shown that a plasma is formed with electron temperature $T_h \approx 3$ keV, a hot electron density of $n_h \approx 10^{11}$ cm^{-3}, and a cold plasma density of $n_0 \approx 2 \times 10^{12}$ cm^{-3}.

There are two experimental results that are noteworthy: a) the coincidence of the energy of the electrons in the beam with the temperature acquired by the hot electrons confined in the mirror device, and b) the relatively small fraction (approximately 10%) of hot electrons compared with the density of cold plasma, which indicates that in the present experiment we are only observing the first stage of the interaction of the beam of accelerated electrons with oscillations excited in the plasma by the same beam, that is to say, randomization of the direction of the momenta of the electrons in the beam together with energy conservation of these electrons.[4] The observed plasma heating can be explained if only 3–5% of all the accelerated electrons that carry the beam current are trapped. The same mechanism for plasma formation with hot electrons has been considered by us in[5]. The hypothesis that the beam is a source of electrons which subsequently participate in the heating process by virtue of the energy of the plasma oscillations excited by the beam itself has also been given by Ryutov[6] and verified experimentally in[7].

On the basis of bolometer measurements, in the present work we find that the beam of accelerated electrons (at the time of the current interruption) carries up to 50% (and possibly even more) of the energy stored in the external circuit inductance; this energy appears at the anode of straight discharge. In conclusion, the authors wish to thank I. K. Kikoin, and B. B. Kadomtsev for valuable discussions, and L. L. Gorelik for advice in the fabrication of the bolometer. We are also indebted to the operating crew for their help.

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