TWO-STREAM INSTABILITY (SHARP DISCONTINUITIES) OF A CURRENT IN A PLASMA

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It is shown that current discontinuities are observed in a straight low current discharge ($J \approx 100-400$ A) under conditions when the electric field in the plasma is comparable to the critical Dreicer field. Two-stream instability of the current in the plasma is accompanied by heating of the electrons up to a temperature $T_e \approx 4-5$ keV. The density of the hot electrons is $n_h = 10^{11}$ cm^{-3} for a total plasma density $n_0 \approx 2 \times 10^{12}$ cm^{-3}. The heating efficiency depends on the configuration of the magnetic field and increases with the magnetic field gradient. Confinement of a hot electron plasma by magnetic mirror traps is restricted by the development of electron cyclotron instability and in these experiments is 30—50 μsec.

INTRODUCTION

In a number of relatively recent experiments it was observed that the flow of current through a plasma has an anomalous character if conditions are produced favoring the continuous acceleration of the electrons in the plasma, in other words, favoring the appearance of a group of "runaway" electrons.

Thus, collective effects connected with a beam of runaway electrons in a toroidal gas discharge were considered by Bernstein et al. [1] They observed for the first time sharp discontinuities in the discharge current in a stellarator; these discontinuities were attributed to excitation of a beam of accelerated electrons in the plasma. A similar current instability in a plasma (complete cessation of the current or partial discontinuities in the current) were observed in strong-current toroidal and in straight discharges [2-5], and also in experiments with a plasma beam [6].

The observed current instability was attributed in [2-5] to the fact that during the discharge process the electric field in the plasma becomes close to the critical Dreicer field [7], at which continuous acceleration of the plasma electrons sets in. Such conditions occur during the discharge automatically whenever the loss of the plasma to the chamber walls prevails over the intake of neutral gas from the walls and ionization of the latter within the volume, so that the plasma density decreases during the time when the discharge current flows [3,4].

The phenomenon of complete cessation of the discharge current (or of its partial interruption) was considered theoretically by Dreicer [8] and in the review of Kadomtsev [9]. In particular, Dreicer considered the model of an electron beam circulating in a closed setup (stellarator) and relaxing to an equilibrium, and explain the multiple repetition of the current discontinuities in the stellarator. Kadomtsev [9] made use of the idea of buildup of ion-acoustic oscillations in the plasma when the discharge current passes and the "blocking" of the drift motion of the electrons by the potential barriers of these oscillations.

Nezlin and Solntsev [6] considered the mechanism of electron-beam blocking by the space charge of the beam itself and attributed the phenomena observed by them to the instability of the spatially-inhomogeneous plasma.

In the present paper we describe experiments aimed at the investigation of the abrupt discontinuities of the current in a weak-current straight discharge in a magnetic field. Just as in experiments with the stellarator [1], they observed partial discontinuities in the current, repeating every 50—100 μsec, as well as complete cessation of the current. The conditions under which the current discontinuities were observed, as well as the current-cessation process itself, turned out to be close to the conditions of the experiments with the aid of the decay current plasma in a stellarator [1].

We investigated the current discontinuities in the straight discharge from the point of view of explaining the physical nature of the instability that interrupts the current in the plasma and observing different phenomena accompanying this current interruption. In particular, the use of magnetic probes, the use of x-rays, and the adiabatic compression of the plasma made it possible to observe under certain conditions heating of the plasma electrons upon interruption of the current.

PROCEDURE AND EXPERIMENTAL SETUP

The experiments were performed with the "Aspa" setup, which was described in detail in [10]. The setup (see Fig. 1 of [10]) consists of a large solenoid 4 meters long and 1 meter in diameter, producing a quasistationary magnetic field of intensity up to 3000 Oe (field half-cycle 0.2 sec). On the solenoid axis is located a sectionalized vacuum chamber with a coaxial plasma injector (Marshall injector) on one of the ends of the chamber. The working gas was usually hydrogen or deuterium, and in some experiments argon or xenon.

The chamber consists of a metallic tube 20 mm in diameter and 2.5 meters long, and a section of the glass tube 10 cm in diameter and 1.5 m long. The setup was evacuated by oil-vapor diffusion pumps with liquid-nitrogen-cooled traps. The maximum vacuum in the setup was 1×10^{-6} mm Hg.

Coils No. 1 and No. 2 (2 and 8 on Fig. 1 of [10]) were placed over the glass and were connected in series in the circuit of the main solenoid. They could produce in the glass-tube region a magnetic quasistationary trap with mirror ratio $R = 2 - 10$ and with distance 1.3 m between mirrors. Besides coils 1 and 2, two additional coils were located in the central part of the glass chamber to produce a pulsed magnetic field of mirror configuration ($R = 2.5$) with intensity in the mirrors up to

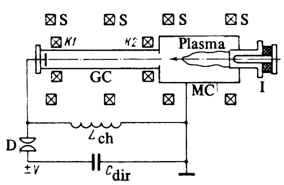


FIG. 1. Direct-discharge circuit: S – solenoid of leading magnetic field (length 5 m, diameter 1 m), MC – metallic vacuum chamber (length 3 m, diameter 25 cm), GC – glass chamber (length 175 cm, diameter 10 cm), K1 – mirror coil No. 1, K2 – mirror coil No. 2, I – coaxial plasma injector D – vacuum discharge gap.

25 kG and with distance 20 cm between mirrors. The pulsed magnetic field coils were used to compress the plasma rapidly (the time required for the field to grow to the maximum amplitude was 35 μsec). To investigate the confinement of the compressed plasma, the pulsed-field coils were short circuited by means of a special discharge gap at the instant when the maximum magnetic field intensity was reached. Under these conditions, the magnetic field in the pulsed trap decreased by a factor e within 350 μsec.

Different diagnostic methods were used in the investigation. The current in the plasma was measured with a Rogowski loop, the voltage of which was integrated with an RC network with a time constant 1 msec. The voltage applied to the plasma column was measured with the aid of a capacitive voltage divider connected between the end flanges of the glass chamber.

The plasma density was determined with the aid of a Wharton interferometer at a wavelength 2 mm and with a 2-mm interferometer using a phase-detector circuit. The plasma microwave radiation at wavelengths 0.2, 0.4, 0.8, 3, 6, and 10 cm was investigated with the aid of horn antennas, simple waveguide lines, and detector heads. The magnetic field crowded out by the plasma was measured with coils placed over the glass chamber (number of turns—20, integrating RC circuit with τ = 1 msec).

The x-ray bremsstrahlung of the plasma, which emerged from the volume through tubes covered with lavsan polyester film 20 μ thick, was registered with NaI scintillation crystals, covered with beryllium foil 0.2 mm thick.

The experimental setup used to excite current in the direct discharge is shown in Fig. 1. The 2 μF capacitor bank C_{dir} was charged to a voltage of approximately several kilovolts and discharged into an inductive load L_{ch} (100—1,000 μH) through a vacuum disc discharge gap. The inductive load (choke) was connected by a system of coaxial cables with the end electrode, which was placed inside the glass chamber, and with the flange of the metal tube of the setup.

The plasma injector was turned on 20—50 μsec after

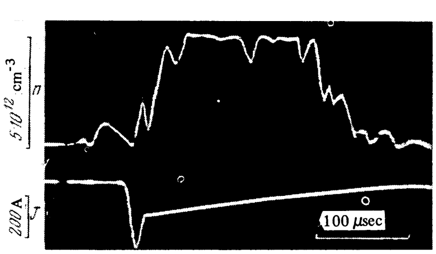


FIG. 2. Oscillograms of plasma density and discharge current. H_0 = 1000 Oe, C_{dir} = 2μF, U_{dir} = 2 kV, L_{ch} = 100 μH, working gas – hydrogen, mirror coils 1 and 2 connected.

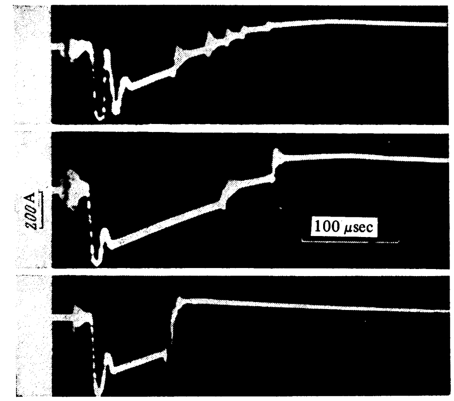


FIG. 3. Typical oscillograms of the discharge current in the "current interruption" regime.

the direct discharge circuit (C_{dir}, L_{ch}) was energized. The plasma jet, with density (0.8—3.0) × 10^{13} cm^{-3} and electron temperature $T_e \approx$ 2—3 eV fed from the injector shorted out the inductive load at approximately the instant when the current in the choke was maximal. After the end flanges of the glass chamber were shorted by the plasma jet, the current from the inductance was fed to the plasma. Its amplitude was usually 100—400 A, and the current fall-off time was determined by the ohmic resistance of the plasma column and by the inductance of the choke. This time ranged in our experiments from 300 μsec to 3 msec, depending on the inductance L_{ch}, and the current fell off exponentially (Fig. 2). The direct discharge circuit and the Marshall injector were triggered at the instant when the intensity of the leading magnetic field reached a maximum.

INVESTIGATION OF DISCHARGE WITH CURRENT DISCONTINUITIES

By varying the initial conditions for the excitation of the direct discharge it is possible to cause the flow of current through the plasma to cease to be monotonic: instead of the "quiet" exponential current fall-off (Fig. 2) one observes either a rapid or an abrupt cessation of the entire current, or else a stepwise decrease of the current (Fig. 3). Usually such conditions are attained by outgassing the walls of the chamber by the discharge, by decreasing the amount of working gas fed into the Marshall source by the pulsed valve, or by lowering the residual pressure in the setup below (1.0—1.5) × 10^{-5} mm Hg. The instant when the current discontinuities take place have a random character. The oscillograms of the direct-discharge voltage reveal at those instants sharp spikes (Fig. 4). The voltage occurring at the instant when the current is interrupted usually exceeds by several times the voltage to which the capacitor bank C_{dir} was charged.

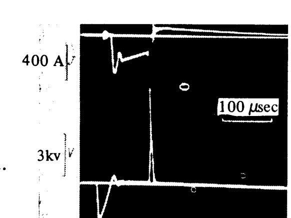


FIG. 4. Current and discharge-voltage oscillograms. H_0 = 200 Oe, C_{dir} = 2 μF, U_{dir} = 3 kV, L_{ch} = 100 μH, working gas – hydrogen, homogeneous magnetic field.

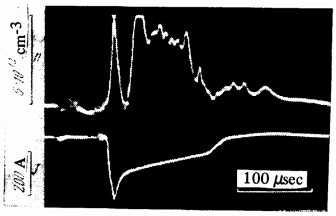


FIG. 5. Oscillograms of plasma density and discharge current. H_0 = 1000 Oe, C_{dir} = 2 μF, U_{dir} = 2 kV, L_{ch} = 100 μH, working gas – hydrogen. Mirror coils 1 and 2 connected.

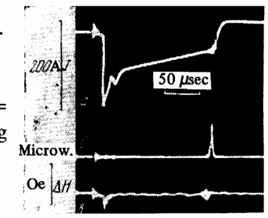


FIG. 6. Oscillograms: a – discharge current, b – microwave radiation (λ = 10 cm) during current discontinuity, c – diamagnetic signal of plasma; H_0 = 1200 Oe, C_{dir} = 2 μF, U_{dir} = 2.2 kV, L_{ch} = 100 μH, working gas – hydrogen, homogeneous magnetic field.

The overvoltages resulting during the instant of current interruption can be estimated from the relation

$$\Delta U = L_{ch} dJ / dt.$$

Substituting the experimental data (ΔJ = 200 A, Δt = 5 μsec, L_{ch} = 100 μH) we obtain ΔU = 4 kV, which agrees with the direct measurements of the voltage pulse produced at the instant of current interruption (Fig. 4).

Interferometric measurements of the density have shown that the flow of a current of 50–200 A through the plasma causes increased losses of the particles from the plasmoid transported in the glass chamber. As a result, the density of the plasma jet upon excitation of the discharge turns out to be several times (4–6) smaller than the density of the plasmoid without the current.

The interruption of the current always correlates with the time behavior of the plasma density, namely: during the course of the discharge, the decrease in the plasma density reaches a value on the order of (1–2) $\times 10^{12}$ cm^{-3}, and a break in the current occurs when this value, or a somewhat lower one, is reached (Fig. 5).

The voltage applied to the plasma column at this instant of time is usually 50–150 V; assuming that the electric field E in the plasma is uniformly distributed along the plasma column, we find that E = 1 V/cm prior to the interruption of the current. The plasma parameters at the instant of the interruption of the current are $n = (1-2) \times 10^{12}$ cm^{-3} and T_e = 2–3 eV; consequently, the critical Dreicer field, which determines the escape and continuous acceleration of the bulk of the electrons, is

$$E_{cr} \approx 10^{-12} n / T_e \approx 10^{-12} 2 \cdot 10^{12} / 2 = 1 \text{ V/cm},$$

that is, approximately equal to E in the plasma. Thus, the interruption of the current in the plasma arises when the drift velocity of the electrons turns out to be comparable with their thermal velocity, and a beam of runaway electrons can be accelerated in the plasma.

An analysis of the oscillograms of the current and of the plasma density during the course of the experiment in a magnetic field of intensity 300, 1000, 2500 Oe and for both polarities of the direct-discharge voltage leads to the conclusion that the conditions for initiating the current interruption do not depend on the intensity of the longitudinal magnetic field or on the direction of the current excited in the plasma jet.

When the direct discharge is excited in a chamber at a higher initial pressure, in the range from 5×10^{-5} to 2×10^{-4} mm Hg (this was done by letting gas to flow in continuously), no interruption of the current was observed, or else the discontinuity was very small, that is, the current fall-off had a quiet exponential character. At such high initial pressures, the plasma density barely drops during the discharge process, so that apparently no conditions are produced for the acceleration of the plasma electrons. A similar influence of the initial pressure on the discontinuities of the current in a strong-current toroidal discharge were observed earlier in [4], and also in experiments on the blocking of an electron beam [6].

In order to observe the influence of the mass of the plasma ions on the excitation of the current discontinuities, additional experiments were set up with argon and xenon plasma jets. To this end, argon or xenon was fed to the coaxial injector as the working gas. These experiments have shown that abrupt discontinuities occur in both argon and xenon plasma. These discontinuities are observed under conditions similar to those for a hydrogen (deuterium) plasma. Thus, we were unable to observe any influence of the ion mass on the excited instability, although the ratio of the average masses of the ions in the two extreme investigated cases (hydrogen and xenon) amounts to about 1/100 (taking into account the impurities in the hydrogen jet). We do not present the oscillograms showing the current discontinuities in the argon and xenon plasma, since they are identical with the oscillograms pertaining to discharge in hydrogen or deuterium.

Searches for microwave radiation accompanying the current discontinuity led to observation of a relative intense microwave radiation (Fig. 6). An investigation of the microwave radiation in the case of current discontinuities in fields 500–1500 Oe have shown that the microwave radiation power is concentrated essentially in the wavelength region from 6 to 12 cm. The microwave radiation power at ~ 10 cm wavelength, received with a broadband detector head and radiated by the entire plasma in a glass tube of 1.5 m length, is approximately 1 W. The power and the emission spectrum in the 6–12 cm band were independent of the type of gas (H_2, D_2, Xe, Ar).

In the range λ = 2, 4, 8 and 30 mm we were unable to observe the radiation, although the detector sections of the 8- and 30-mm bands could register a radiation power smaller by one or two orders of magnitude than the power of the observed radiation in the 10-cm band.

INVESTIGATION OF PLASMA HEATING IN THE DEVELOPMENT OF TWO-STREAM INSTABILITY OF THE CURRENT

The energy transferred to the plasma during the development of two-stream instability was determined with the aid of magnetic coils which measured the diamagnetic field of the plasma. The sensitivity of the magnetic probes made it possible to register a plasma pressure nT on the order of 1×10^{13} eV/cm^3. The paramagnetic field due to the flow of current in the plasma was small (smaller than 0.1 Oe), and was not determined in the experiments described below by means of

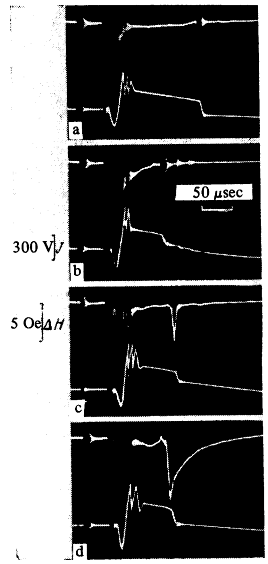


FIG. 7. Oscillograms of magnetic field in plasma (upper curves) and discharge current (lower curves): a – coils 1 and 2 disconnected (homogeneous field), b – only coil 1 connected, c – only coil 2 connected, 2 – both coils 1 and 2 connected. $H_0 = 1000$ Oe, $C_{dir} = 2\ \mu F$, $U_{dir} = 2.5$ kV, $L_{ch} = 100\ \mu H$, working gas – hydrogen.

magnetic probes. The current discontinuities could be excited both in a system with homogeneous magnetic field and with a system in which additional (one or several) mirror coils were connected. When current discontinuities were registered in a homogeneous magnetic field, noticeable diamagnetic signals (with $nT \geq 1 \times 10^{13}$ eV/cm^3) were observed, and consequently, there was no noticeable heating of the plasma as a result of the development of the current instability (Fig. 7a). If the current discontinuity occurs in an inhomogeneous magnetic field (one or two mirror coils are connected), the diamagnetic signal increases noticeably and corresponds to $nT \approx 5 \times 10^{14}$ eV/cm^3 (Figs. 7c, d).

When only one mirror coil was turned on (for example coil no. 1 or coil no. 2, Fig. 1), and the heating of the plasma in the central part of the glass section was measured, diamagnetic signals were observed at a definite current direction, namely: heating was observed only on that side of the mirror coil to which the drift of the plasma electrons was directed. For example, for the case of Fig. 7 the drift velocity of the electrons was directed from the high-voltage electrode towards the coaxial injector. In this case, diamagnetic signals were observed over the entire length of the glass chamber upon interruption of the current, provided mirror coil No. 2 was turned on (Fig. 7c). The plasma heating is much smaller if only one mirror coil, No. 1, is turned on (Fig. 7b). In investigations of the discontinuities of a current flowing in the opposite direction (electron drift directed from the coaxial injector towards the electrode), the picture is reversed: appreciable plasma heating takes place only when mirror coil No. 1 is turned on. Naturally, when both coils No. 1 and No. 2 are turned out and produce thereby a quasistationary magnetic trap, plasma heating is observed regardless of the direction of the current.

Comparison of the diamagnetic signals of the plasma in an inhomogeneous magnetic field (Fig. 7c) and in a mirror-configuration field (Fig. 7d) shows that no appreciable increase in the plasma pressure occurs as a result of accumulation of hot particles in the magnetic trap.

When the mirror ratio changes from 1.2 to 10, no noticeable increase of the diamagnetic signal obtained as a result of the current interruption was observed, and when the mirror ratio drops from 1.2 to 1 (homogeneous magnetic field), a rapid increase in the diamagnetic signal is observed.

The efficiency of plasma heating by current interruption is quite high. It can be estimated from the energy fed to the plasma and the energy stored in the inductance immediately prior to the current interruption. The energy fed to the plasma was estimated from the diamagnetic signals and was approximately 10% of the energy stored in the inductance, reaching $nT \approx 5 \times 10^{14}$ eV/cm^3 at $V \approx 5 \times 10^5$ cm^3, where V is the volume of the plasma in the trap.

In order to ascertain the degree to which the indicated diamagnetic signal is connected with the heating of electrons (or ions), an attempt was made to observe the x-ray bremsstrahlung of the plasma. Indeed, during the plasma confinement time, which was determined from the time of the decrease in the diamagnetic signal, soft x-ray emission was observed from the mirror trap, with energy of about 5 keV. The x-ray energy was determined by absorption in filters. Since the x-ray receiver was an NaI crystal covered with beryllium foil (0.2 mm thick) with a cutoff threshold of several keV, it was difficult to estimate the temperature of the hot electrons from the data on the x-ray emission energy.

To measure the electron temperature of a plasma heated as a result of the development of the two-stream instability we undertook therefore experiments on adiabatic compression of the plasma with the aid of the pulsed magnetic field coils, the supply circuit to the coils being turned on by a special electronic circuit at the instant when the discharge current was interrupted. These experiments have shown that the electron temperature of a plasma compressed adiabatically by a factor 5–6 ($H_{pulse} = 5$ Oe, $H_0 = 800$–1,000 Oe) is approximately 30 keV.

It can thus be assumed that the diamagnetism of the plasma after the current interruption is caused by electrons with energy of about 5 keV. The density n_h of these heated electrons can be estimated from the diamagnetic signal of the plasma, corresponding to the value $n_hT = 5 \times 10^{14}$ eV/cm^3, and turned out to be $n_h \approx 1 \times 10^{11}$ cm^{-3}. The total plasma density, measured with an interferometer, was $n_0 = (1-2) \times 10^{12}$ cm^{-3}.

The connection between the observed diamagnetic signals and the heating of the electronic plasma component was further confirmed by experiments on the adiabatic compression of the plasma at different configurations of the initial quasistationary magnetic field.

Oscillograms of the x-radiation of the compressed plasma in the case when the current was interrupted in a mirror trap (coils 1 and 2 connected) are shown in Fig. 8a. Similar oscillograms of the x-rays from the plasma compressed during the current interruption with one additional mirror coil (No. 2) turned on and in a homogeneous magnetic field, are shown in Figs. 8b and c. Comparison of these x-ray oscillograms with measurements of the diamagnetic signal at different magnetic-field configurations (Fig. 7) shows that the x-rays are observed only in those cases when a noticeable plasma diamagnetism is observed as a result of the

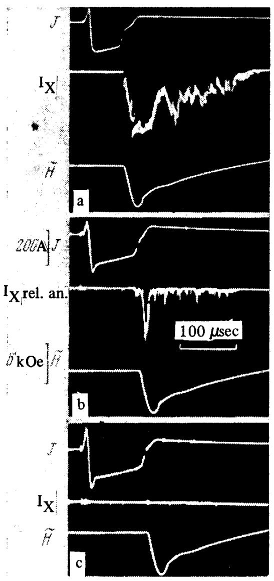
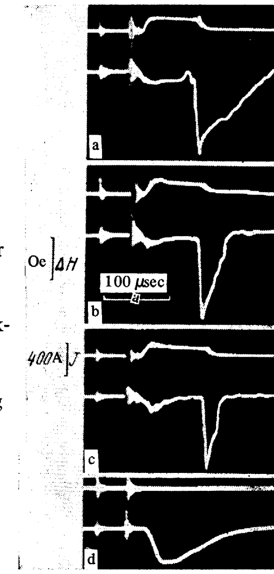


FIG. 8. Oscillograms of discharge current J, of pulsed magnetic compression field H, and x-ray bremsstrahlung intensity I_X from the trap: a – both coils 1 and 2 connected, b – coil 2 connected, c – coils 1 and 2 disconnected (homogeneous magnetic field). H_0 = 800 Oe, C_{dir} = 2 μF, U_{dir} = 2.5 kV, working gas – hydrogen.

FIG. 9. Typical oscillograms (a, b, c) of the discharge current (upper curves) and of the diamagnetic signal (lower curves) of a plasma contained in a mirror trap (R = 2), obtained under identical initial conditions. H_0 = 100 Oe, C_{dir} = 2μF, U_{dir} = 2.8 kV, L_{ch} = 100 μH; working gas – hydrogen, d – diamagnetic signal of plasmoid without excitation of discharge current, H_0 = 990 Oe, working gas – hydrogen.



current interruption.

The time of plasma containment in the stationary trap, measured from the time of the fall-off of the diamagnetic signal (Fig. 7d), is 30–50 μsec, that is, much lower than the time of the Coulomb collisions leading to the escape of the particles from the trap. On the order of several milliseconds for a hydrogen plasma), smaller by several times than the time of electron energy loss to ionization of the neutral gas, the amount of which in the trap can be assumed to be comparable with the density of the cold plasma (2×10^{12} cm^{-3}).

The escape of the plasma from the quasistatic mirror trap, determined from the time dependence of the diamagnetic signal, is not exponential. The features of the confinement of a hot plasma can be seen on the diamagnetic-signal oscillograms obtained under identical conditions (Fig. 9). It is clearly seen that the diamagnetic signal falls off jumpwise (Figs. 9a, b), and sometimes the diamagnetic signal drops jumpwise to zero (Fig. 9c) within several microseconds.

Intense microwave radiation in the electron cyclotron frequency band (λ = 10 cm) is observed at the breaks of the diamagnetic signal, and the frequency spectrum of this radiation is much narrower than the microwave emission spectrum at the current discontinuity (Fig. 10). Measurement (with a narrow-band microwave receiver) of the frequency spectrum of the microwave radiation accompanying the discontinuities of the diamagnetic signals of the plasma contained in the mirror trap have shown that the observed radiation is concentrated near a frequency $\omega \approx 1.4\omega_{He}$, where ω_{He} is the electron cyclotron frequency corresponding to the minimum magnetic field in the trap. The width of the band of this radiation does not exceed 5% of the fundamental frequency ω. Comparison of all these data shows that the anomalously rapid escape of the plasma from the trap is apparently due to the development of cyclotron instability of the plasma with hot electrons[11,12].

It should be noted that the cyclotron instability develops in our experiments under conditions when $\omega_{pe} > \omega_{He}$, where ω_{pe} is the plasma electron frequency.

The appearance of two-stream instability has much in common with the appearance of the anisotropic instability of a plasma with hot electrons in a simple mirror trap[11,12]. The abrupt cessation of the entire current or the stepwise decrease of the current, the microwave radiation during the current interruptions, the suppression of the current interruptions by increasing the neutral-gas density, etc., all correlate with the rapid development of the cyclotron instability of a plasma in a mirror trap[11,12] and with the suppression of the instability when neutral gas is added.[13] This analogy of the phenomena is apparently connected with the fact that the development of the two-stream instability occurs in both cases as a result of anisotropy of the electron distribution function. The question as to what causes this anisotropy—acceleration of the electrons along the magnetic field or the cutting of loss cones when the plasma is contained in the mirror machine—is not of decisive significance.[14]

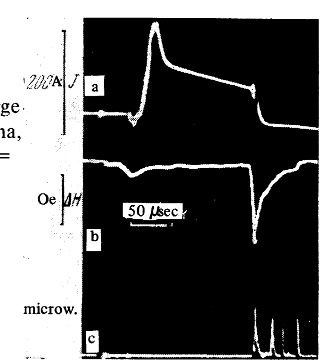
The foregoing experimental data can be combined in the following three main groups.

1. We investigated two-stream instability in a direct weak-current discharge.

2. We observed heating of the plasma electrons to $T_e \approx$ 4–5 keV during the development of two-stream instability in an inhomogeneous magnetic field.

3. Development of cyclotron instability was observed in the containment of a plasma with hot electrons in a magnetic mirror trap.

FIG. 10. Oscillograms: a – discharge current, b – diamagnetic field in plasma, c – microwave radiation from trap (λ = 10 cm). H_0 = 100 Oe, C_{dir} = 2 μF, U_{dir} = 2.5 kV, L_{ch} = 100 μH, mirror ratio R = 2 (mirror coils 1 and connected); working gas – xenon.



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[1]W. Bernstein, F. F. Chen, M. A. Heald, and A. S. Kranz, Phys. of Fluids 1, 430 (1958).

[2]A. Gibson and D. W. Mason, Proc. Phys. Soc. 79, 326 (1962).

[3]W. M. Burton, E. P. Butt, H. C. Cole, A. Gibson, D. Mason, R. S. Pease, K. Whiteman, and R. Wilson, Nucl. Fusion, Suppl. 3, 903 (1962).

[4]A. P. Babichev, A. I. Karchevskiĭ, and Yu. A. Muromkin, Zh. Tekh. Fiz. 33, 1400 (1963) [Soviet Phys.-Tech. Phys. 8, 1040 (1964)]; ibid. 36, 1775 (1966) [11, k322 (1967)].

[5]V. A. Suprunenko, E. A. Sukhomlin, and I. I. Reva, Atomnaya énergiya 17, 83 (1964).

[6]M. V. Nezlin and A. M. Solntsev, Zh. Eksp. Teor. Fiz. 49, 1377 (1965) [Soviet Phys.-JETP 22, 949 (1966)].

[7]H. Dreicer, Proc. 2nd Internat. Conf. on Peaceful Uses of Atomic Energy, Geneva, 1958. Selected Papers of Foreign Scientists, Gosatomizdat, 1959, p. 170.

[8]H. Dreicer and R. Mjolsness, Phys. of Fluids 5, 1531 (1962).

[9]B. B. Kadomtsev, in: Voprosy teorii plazmy (Problems of Plasma Theory) No. 4, Atomizdat, 1964, p. 188.

[10]A. P. Babichev, A. I. Karchevskiĭ, Yu. A. Muromkin, and E. M. Buryak, Zh. Eksp. Teor. Fiz. 53, 3 (1967) [Soviet Phys.-JETP 26, in press].

[11]W. A. Perkins and W. L. Barr, Plasma Physics and Controlled Nuclear Fusion Research 2, IAEA, Vienna, 1966, p. 115.

[12]V. V. Alikaev, V. M. Glagolev, and S. A. Morozov, ibid. p. 877.

[13]V. A. Simonov, V. V. Abozovik, and V. V. Ignat'ev, ibid. p. 93.

[14]A. V. Timofeev and V. I. Pistunovich, in: Voprosy teorii plazmy (Problems of Plasma Theory) 5, Atomizdat, 1967.

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135