CURRENT-CONVECTIVE INSTABILITY OF AN ELECTRON BEAM IN A PLASMA

M. D. RAĬZER, A. A. RUKHADZE, and P. S. STRELKOV

P. N. Lebedev Physics Institute, USSR Academy of Sciences

Submitted June 21, 1967

Zh. Eksp. Teor. Fiz. 53, 1891–1900 (December, 1967)

The passage of an electron beam through a plasma produced by the beam itself in a homogeneous magnetic field is investigated. It is shown that under certain conditions the time evolution of the process has two stages: stable and unstable. The transition to the unstable stage becomes manifest in a sharp decrease of the collector current and is accompanied by an increase of the plasma density and powerful microwave radiation. The duration of the stable stage was investigated experimentally as a function of the initial gas pressure, the electron beam density, the length of the system, and the intensity of the magnetic field. Stabilization by the magnetic field was observed. The current-convective instability was calculated in the case interaction between the beam and the electronic component of the plasma. The main experimental relations agree qualitatively with the theoretical results.

1. EXPERIMENTAL SETUP

THE experimental setup is shown in Fig. 1. The electron gun consists of a flat lanthanum-hexaboride cathode 1 of 3 cm diameter and of a reticular anode with transparency ~70%. The cathode-anode distance is 0.5 cm. The gun operates in a pulsed mode: a negative pulse of −10 kV and duration ~500 μsec is applied to the cathode. The electron beam (2.7 cm diameter) is focused by a homogeneous longitudinal quasistationary magnetic field (duration of the period ~25 msec) produced by a system of coils 2. The maximum reached by the magnetic field is ~4 kOe. The electron beam passes through a metallic pressure-reducing tube 3, 12 cm long and 3.4 cm in diameter, and a glass chamber of 9 cm diameter, after which it strikes a tantalum collector 5. The length of the system (from the cathode to the collector) is $L_1 = 55$ cm and $L_2 = 35$ cm. Gas is admitted to the glass chamber through a leak valve 6, and evacuation is effected in the cathode region. The main experiments were performed with krypton, in which case the pressure drop was $P_1/P_2 = 8$.

The electric circuitry of the setup made it possible to measure all the currents indicated in Fig. 1. At a voltage $U_0 = -10$ kV, the current picked off the cathode was $I_c = 14$ A and the anode current was $I_a = 4$ A, the collector current being $I_{col} = 10$ A and the current in the pressure-drop tube was $I_t = 0$. During the measurement process, a constant voltage U_0 was maintained, and the beam current was varied by decreasing the cathode temperature.

The microwave radiation from the plasma was measured by means of horn antennas 7, located at distances 10 – 100 cm from the glass envelope. The plasma density was determined by the passage of microwave signals at wavelengths λ = 8 mm (8 in Fig. 1) and λ = 14 cm. In addition, we measured the oscillations of the plasma-column charge. For these measurements, a metallic cylinder 9, 10 cm long, was placed over the glass envelope and was connected to ground through a capacitor C = 0.02 μF. The ac component of the voltage across this capacitance was recorded.

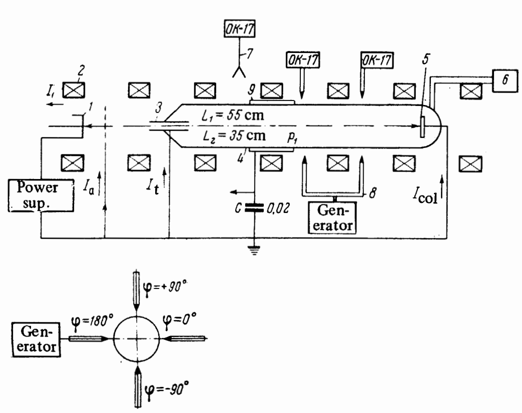

FIG. 1. Diagram of setup: 1—cathode, 2—magnetic-field coils, 3—pressure reducing tube, 4—glass chamber, 5—collector, 6—mechanical leak valve, 7—horn antenna, 8—antennas for λ = 8 mm radiation, 9—metallic cylinder for measurement of the charge oscillations (l = 10 cm).

2. STABLE AND UNSTABLE STATES OF THE PLASMA-BEAM SYSTEM

In this experiment the plasma was produced by the electron beam ionizing the gas in the higher-pressure region (P_1). In the case when $P_1 = P_2 = 10^{-6}$ mm Hg, a rectangular current pulse of duration T ≈ 500 μsec is picked off the collector. Under certain conditions, which depend on the pressure P_1 ($P_1 > 10^{-5}$ mm Hg), the magnetic field, and the beam current, the current flows through to the collector within a time $\Delta t < T$, and then at an instant of time t_c (see Fig. 8) the current decreases abruptly. This phenomenon is clearly seen

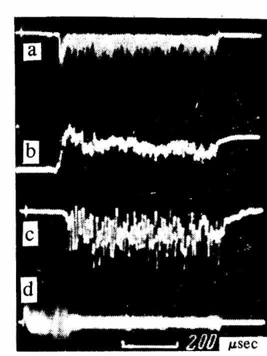

FIG. 2. $U_0 = 10$ kV, $I_{col} = 10$ A, H = 1500 Oe, $P_1 = 7.5 \times 10^{-5}$ mm Hg: a—microwave radiation from plasma; b—collector current; c—intensity of λ = 8 mm radiation passing through the plasma (downward deflection of the beam means decrease of the radiation transmitted through the plasma); d—oscillations of the charge of a plasma-cylinder section of length l = 10 cm.

in Fig. 2b. In this case $I_t = 0$, and I_a increases so that $I_c \approx I_a$. After the current "cut-off," during the time $T - t_c$, the current is smaller by a factor 5 − 10 than prior to cut-off.

Practically simultaneously with the current cut-off, within ~ 5 μsec after t_c, powerful radiation in the centimeter band is emitted by the plasma. Figure 2a shows this radiation in the frequency range $\Delta f = 4000 - 2100$ mHz, as received by the horn antenna (7, Fig. 1).

Figure 2c shows an oscillogram of the intensity of the microwave radiation with $\lambda = 8$ mm passing through the plasma. It is clearly seen that ~ 5 μsec after t_c the intensity of the transmitted radiation decreases, corresponding to an increase in the plasma density.

Figure 2d shows an oscillogram of the oscillations of the plasma-column charge. We see that at the instant of the current cut-off the amplitude of this oscillation increases somewhat, the oscillation frequency being ~ 1 MHz.

All these measurements show that there are two stages of passage of the electron beam through the plasma—stable and unstable. The transition from one stage to the other becomes manifest in a sharp decrease of the collector current and is accompanied by microwave radiation from the plasma and by an increase of the plasma density.

We investigated the duration of the stable stage as a function of the gas pressure (P_1), the magnetic field, the beam current, and the length of the system. It should be noted that the duration of the stable stage remains constant from pulse to pulse, within ~ 5%, if the other conditions remain unchanged. Figure 3 shows the duration of the stable stage of the current Δt as a function of the pressure for three values of the beam current I_{col} (2, 3.7, and 10 A), at two values of the magnetic field H (1500 and 3000 Oe), and for $L_2 = 35$ cm. Similar curves were obtained for $L_1 = 55$ cm. These measurements have made it possible to determine the main features of the current cut-off phenomenon.

At specified values of H_1, P_1, and L, there is a minimum beam current, starting with which cut-off occurs. Thus, at H = 1500 Oe, $P_1 = 10^{-4}$—6×10^{-5} mm Hg, and $L_1 = 55$ cm we have $I_{min} \approx 0.8$ A. At $L_2 = 35$ cm we have $I_{min} \approx 1.5$ A. At fixed values of H, L, and I_{col} there is a minimum pressure P_1, starting with which current cut-off sets in. As seen from Fig. 3, when H = 1500 Oe, $L_2 = 35$ cm, and $I_{col} = 2$ A, the pressure is $P_{min} = 5.5 \times 10^{-5}$ mm Hg. At the same values of H and I_{col}, but $L_1 = 55$ cm, we have $P_{min} = 3 \times 10^{-5}$ mm Hg. At fixed values of H and L in the pressure range $P_1 = 1.5 \times 10^{-4}$—7×10^{-5} mm Hg, the duration Δt of the stable stage first decreases with increasing current ($I_{col} = 2$ and 4 A), and then, at $I_{col} = 10$ A, it increases. This phenomenon takes place for both $L_2 = 35$ cm and for $L_1 = 55$ cm.

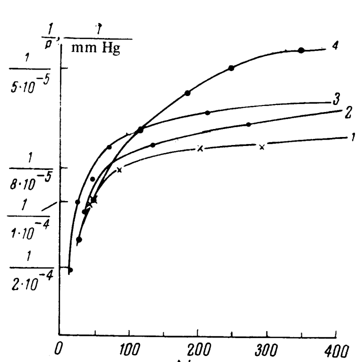

FIG. 3. Plot of $1/P_1$ vs. duration of the stable stage Δt. $L_2 = 35$ cm. Curve 1—I = 2 A, H = 3 kOe; 2—I = 2 A, H = 1.5 kOe; 3—I = 3.7 A, H = 1.5 kOe; 4—I = 10 A, H = 1.5 kOe and H = 3 kOe.

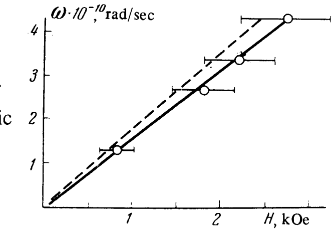

FIG. 4. Maximum frequency of radiation from a plasma vs. magnetic field. Dashed line—$\omega_H^e = eH/mc$.

At certain values of P_1 and I_{col}, the duration of the stable stage greatly depends on the magnetic field. As seen from Fig. 3, when $P_1 = 10^{-4}$—8×10^{-5} mm Hg and $I_{col} = 2$ A, the duration Δt increases somewhat when the magnetic field is doubled (1500—3000 Oe), but when $P_1 = (6—7) \times 10^{-5}$ mm Hg, Δt increases so strongly, that at a specified T = 500 μsec no current cut-off is observed at all. The measurements have shown that an increase of the field from 1500 to 3000 Oe affects strongly the duration of the stable stage at $L_1 = 55$ cm and $P_1 = (4—6) \times 10^{-5}$ mm Hg at beam currents $I_{col} \lesssim 1$ A, and when $L_2 = 35$ cm and $P_1 = (6—7) \times 10^{-5}$ mm Hg—at beam currents $I_{col} \lesssim 4$ A. At a current $I_{col} \approx 10$ A, an increase of the magnetic field to 4000 Oe has practically no effect on the duration of the stable stage.

3. RADIATION FROM THE PLASMA

As seen from the oscillogram of Fig. 2c, centimeter-band radiation is emitted by the plasma during the entire duration of the unstable stage. No radiation from the plasma in the investigated frequency range was observed during the stable stage even when the sensitivity of the measuring apparatus was increased by two orders of magnitude.

The upper limiting frequency ω_{max} of the radiation from the plasma was measured by two methods—with waveguides beyond cut-off and with resonators. Figure 4 shows the dependence of ω_{max} on the magnetic field. We see that ω_{max} depends linearly on H and coincides in absolute magnitude with the value of the electron cyclotron frequency ω_{He}, accurate to the absolute calibration of the magnetic field of the setup (~ ± 20%). This equality $\omega_{max} = \omega_{He}$ remains in force in the entire investigated pressure range, regardless of the beam current.

The presence of a sharply pronounced ω_{max} has made it possible to measure, with the aid of waveguides tuned beyond cut-off, the radiation power in a certain frequency band. It was also established that the intensity of the radiation received by the horn antenna is inversely proportional to the distance from the glass envelope (l = 10—100 cm). Assuming that the plasma is an isotropic radiation source, we estimated the radiation power in the frequency band $\Delta f = 3300—2100$ MHz. It turned out that 1 cm of the plasma cylinder radiates ~ 1.5 W.

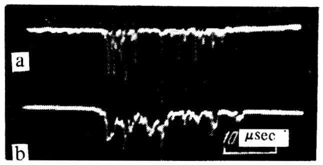

FIG. 5. Microwave radiation from plasma. $U_0 = 10$ kV, $I_{col} = 10$ A, H = 1200 Oe, $P_1 = 10^{-4}$ mm Hg. a—Radiation at frequency f = 2300 MHz, Δf = 1 MHz; b—integrated radiation in the frequency range Δf = 3300 – 2100 MHz.

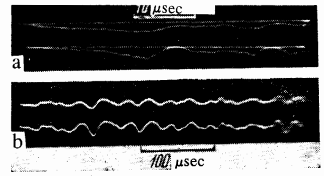

FIG. 6.

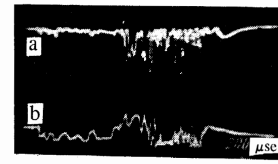

FIG. 7.

FIG. 6. Radiation intensity (λ = 8 mm) passing through the plasma at two points along the plasma (l = 20 cm). $U_0 = 10$ kV, $I_{col} = 6$ A, H = 1000 Oe, $P_1 = 4.5 \times 10^{-5}$ mm Hg.

FIG. 7. Radiation intensity (λ = 8mm): a—scattered at an angle $\varphi = 90°$, downward beam deflection corresponds to an increase of the received power; b—transmitted through the plasma, $\varphi = 0°$, downward beam deflection corresponds to a decrease of the received power. $U_0 = 10$ kV, $I_{col} = 6$ A, H = 1000 Oe, $P_1 = 4.5 \times 10^{-5}$ mm Hg.

In the frequency band Δf = 2300—1000 MHz, the radiation spectrum was investigated with the aid of the P-5-5 instrument (band width ~ 1 MHz). In this case the signal was picked up with a loop located 50 cm from the apparatus. By way of a characteristic example, Fig. 5a shows an oscillogram of the radiation from the plasma at 2300 MHz in a band ~ 1 MHz, and Fig. 5b shows radiation in the band Δf = 3300—2100 MHz. As seen from Fig. 5, individual lines are emitted spontaneously and the radiation duration of an individual line (at half-width) does not exceed ~ 1 μsec. Similar measurements were made in the band Δf = 2300—1000 MHz, and show that the radiation intensity is practically independent of the frequency.

4. DISTRIBUTION OF THE PLASMA DENSITY IN THE UNSTABLE STATE

We investigated the passage of electromagnetic waves of wavelength λ = 8 mm through a plasma cylinder at two points along the cylinder and at four points in azimuth (Fig. 1). Figure 2c above has shown that at the instant of time t_c the intensity of the transmitted radiation decreases, corresponding to an increase of the plasma density. The decrease of the transmitted radiation can occur at a plasma density lower than critical for λ = 8 mm ($n_{cr} = 1.67 \times 10^{13}$ cm^{-3}) as a result of interference effects. It is easy to show that for specified geometrical dimensions of the setup, the plasma density should be at least larger than 10^{12} cm^{-3}. The same Fig. 2c shows that after the termination of the current, the intensity of the transmitted radiation is modulated at a frequency ~ 100 kHz. The presence of such modulation of the signal is connected with the redistribution of the plasma density during the unstable stage.

Figures 6a and 6b show oscillograms of signals received by two antennas located at a distance 20 cm from each other along the cylinder. Such oscillograms show clearly that the variation of the density distribution occurs in a transverse direction and is perfectly the same in both points along the plasma cylinder.

Figures 7a and 7b show typical oscillograms of the signals received by antennas located at angles $\varphi = 90°$ and $\varphi = 0$ (Fig. 1). It is seen from Fig. 7b that there exist instants of time when the intensity of the signal reaches the same level as in the absence of plasma. During these instants of time, the scattered signal (Fig. 2a) is not equal to zero. This offers evidence that in the unstable state there are developed axially asymmetrical plasma-density perturbations in the transverse direction, i.e., the azimuthal wave number $k_\varphi \neq 0$, and there perturbations are perfectly identical over the length of the plasma cylinder.

5. PLASMA DENSITY IN THE STABLE AND UNSTABLE STATES

The electron beam ionizes the gas in the increased-pressure region (P_1) by electron impact. In the absence of ion loss from the system, the ion density is

$$n_i = n_1 P_1 \varepsilon u T, \tag{1}$$

where n_1 and u are respectively the density and velocity of the beam electrons, and $\epsilon \approx 1$ is the coefficient of relative ionization. In those cases when T amounts to hundreds of microseconds, it is necessary to take into account the loss of particles from the system, and

$$n_i = n_1 \frac{P_1}{P_h}(1 - e^{-TP_h \varepsilon u}), \tag{2}$$

where P_n is the neutralization pressure, i.e., the minimum pressure at which the equality $n_i = n_1$ can be attained.

Under the concrete experimental conditions, at H = 1500—3000 Oe, the Larmor radius of the krypton ions is $\rho_{Hi} < 1$ cm and it can be assumed that the losses are determined essentially by the drift of the ions along the system axis to the cathode. Then[1]

$$P_h = 0.145 \frac{I_{col}^{1/2}\,(0{,}5 + 2\ln(b/a))^{1/2}}{\varepsilon L M^{1/2} u^{3/2}}. \tag{3}$$

where M—ion mass, a—diameter of the electron beam, b—inside diameter of the turns of the magnetic-field coils, L—length of the region of increased pressure (P_1). For $I_{col} = 10$ A and $L_1 = 55$ cm, the neutralization pressure is $P_n = 6 \times 10^{-6}$ mm Hg, and for $L_2 = 35$ cm we have $P_n = 1.8 \times 10^{-5}$ mm Hg.

From formulas (2) and (3) we can determine the neutralization time τ_n, i.e., the instant of time when $n_i = n_1$. Calculation shows that in the entire investigated pressure and current range we have $\tau_n \ll \Delta t$. Thus, for example, for $I_{col} = 10$ A, $P_1 = 10^{-4}$ mm Hg, and $L_2 = 35$ cm the neutralization time is $\tau_n = 1.5$ μsec, and $\Delta t = 35$ μsec, while for $P_1 = 6 \times 10^{-5}$ mm Hg, $I_{col} = 2$ A, and $L_2 = 35$ cm we have $\tau_n = 3$ μsec and $\Delta t = 400$ sec. It should be noted that when $\Delta t \gg \tau_n$ the ion density is $n_i = n_e + n_1$ and inasmuch as $n_i/n_1 > 1$ we can put $n_i \approx n_e$.

The foregoing estimates are valid if prior to the instant of the current cut-off the secondary electrons do not take part in the gas ionization process. This was

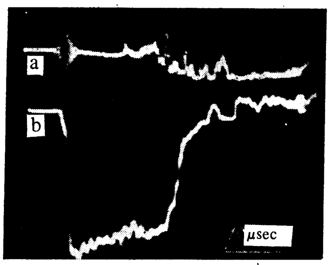

FIG. 8. Intensity of microwave radiation (λ = 14 cm) passing through the plasma: a—downward beam deflection corresponds to a decrease in the intensity of the received signal. Positive pips—radiation of plasma proper; b—collector current. $U_0 = 10$ kV, $I_{col} = 6.5$ A, H = 800 Oe, $P_1 = 10^{-4}$ mm Hg.

verified experimentally by measuring the transmission of the microwave signal at λ = 14 cm through the plasma cylinder. The oscillogram of Fig. 8a shows that the intensity of the transmitted radiation begins to decrease at the instant of current cut-off (Fig. 8b) (the oscillogram of Fig. 8a shows pulses of the proper radiation of the plasma). This means that at the instant of the current cut-off the plasma density is $n_e \leq 6.0 \times 10^{10}$ cm^{-3}, whereas calculation gives for that instant of time $n_e \approx 2 \times 10^{10}$ cm^{-3}. This confirms the hypothesis that up to the instant of current cut-off the gas ionization is effected by the electron beam.

Measurements of the transmission of the microwave signals at wavelengths λ = 8 mm and λ = 14 cm through the plasma cylinder have made it possible to establish that during the development of the instability the plasma density increases by at least two orders of magnitude within a time ~7 μsec. A similar result is noted by Getty and Smullin[2]. The foregoing estimates and measurements of the plasma density show that during the stable stage the frequency of the electron plasma oscillations ω_{0e} is smaller than the electron cyclotron frequency. In the unstable state $\omega_{0e} > \omega_{He}$.

6. MECHANISM OF CURRENT-CONVECTIVE INSTABILITY IN THE INTERACTION OF THE BEAM WITH THE ELECTRONIC COMPONENT OF THE PLASMA

Let us see what instability mechanisms can come into play in the plasma-beam system. Since the process of ionization by the electron beam is sufficiently slow, in the investigation of the possible development of high-frequency instability we can regard the plasma to be quasistationary at each instant of time. Recognizing furthermore that the experiments were performed with a heavy gas (krypton) so that all the characteristic oscillatory processes in the system were more rapid than the period of the Larmor rotation of the ions, we can assume that the ions can be regarded as not magnetized, while the electrons can be regarded as strongly magnetized (i.e., $\omega_{He} \gg \omega \gg \omega_{Hi}$).

Up to the instant of beam neutralization, the ion density is $n_i \lesssim n_1$. During this stage only slow instabilities, connected with the interaction of the moving electrons with the ions, such as current-convective instability[3] and Buneman instability[4], can develop in the system. Under these conditions, the dispersion equation for the longitudinal oscillations, in the geometrical optics approximation[5] and with allowance for $\omega_{He} \gg \omega_{L_1}$, is written in the form

$$k_\perp^2\left(1-\frac{\omega_{Li}^2}{\omega^2}\right)+k_z^2\left[1-\frac{\omega_{Li}^2}{\omega^2}-\frac{\omega_{L1}^2}{(\omega-uk_z)^2}\right] + \frac{k_\varphi\omega_{L1}^2}{\omega_{He}(\omega-uk_z)}\frac{\partial \ln n_1}{\partial r}=0, \tag{4}$$

where ω_{L_i} and ω_{L_1} are the Langmuir frequencies of the ions and of the electrons of the beam, $k_z = \pi n/L$ (n = 0, 1, 2, ...) is the longitudinal component of the wave vector, $k_\varphi = 2s/a$ (s = 0, 1, 2, ...) is the azimuthal component, and $k_\perp^2 = k_r^2 + k_\varphi^2$, where k_r is the radial component. When $n_i \leq n_1$, the unstable oscillations can occur in the frequency region $\omega \ll uk_z$ and the instability condition is

$$k_\perp^2-\frac{\omega_{L1}^2}{u^2}-\frac{k_\varphi}{k_z}\frac{\omega_{L1}^2}{u\omega_{He}}\frac{\partial \ln n_1}{\partial r}\leqslant 0, \tag{5}$$

the maximum growth increment of the oscillations being

$$\gamma_{max}\approx\frac{\sqrt{3}}{2}\left[\frac{m}{2M}\frac{n_i}{n_1}k^2k_zu^3\left[1+\frac{k_\varphi}{2k_z}\frac{u}{\omega_{He}}\frac{\partial \ln n_1}{\partial r}\right]^{-1}\right]^{1/3}. \tag{6}$$

This instability goes over into the Buneman instability[4] when $k_\varphi = 0$ (or $\partial \ln n_1/\partial r = 0$), and into a current-convective instability with $n_i \leq n_1$[3] when $k_\varphi \neq 0$.

In these experiments, the inequality (5) for the modes with $k_\varphi \neq 0$ is never observed, even under the most unfavorable conditions (i.e., for the modes s = 1, n = 1, $k_r = 0$). It is also easy to show that the Buneman instability can likewise not develop during this stage, since it is convective (drift-like), and the maximum increment of its development, $\gamma_{max} \lesssim (m/M)^{1/3}\omega_{L_1}$, is smaller than the reciprocal time of flight of the beam electrons through the system ($\gamma_{max} \approx 4 \times 10^7$ sec^{-1} < u/L ≈ 10^8 sec^{-1}).

After neutralization of the beam, when $n_e \approx n_i > n_1$, an electron two-stream instability can develop in the system, with a maximum increment (for modes with $k_\perp = 0$)

$$\gamma_{max}\lesssim\frac{\sqrt{3}}{2}\left(\frac{n_1}{2n_e}\right)^{1/3}\omega_{Le}$$

exceeding the reciprocal time of flight of the beam electrons through the system. On the other hand, the modes with $k_\perp \neq 0$ (i.e., $k_\perp \sim \pi/a$) are strongly stabilized for a pure two-stream instability under our experimental conditions. Therefore such modes should not be observed even in the nonlinear stage of two-stream instability development.

On the other hand, the turbulent plasma has a clearly pronounced axial asymmetry in the experiment, i.e., modes are observed with $k_\varphi \neq 0$. In addition, other experimental facts likewise do not agree with the assumption that the current cut-off is due to two-stream instability. These include the dependence of the duration of the stable stage on the value of the magnetic field and the length of the system, and the presence of an upper limiting frequency of the radiation from the plasma, which coincides with ω_{He} if $\omega_{He} < \omega_{Le}$. It should be noted that in the case of two-stream instability the wavelength of the longitudinal perturbation is λ = 6—10 cm. When L ≫ λ (in the experiments, L_1 = 55 cm and L_2 = 35 cm), the instant of instability development should not depend on L. It seems more probable to us, therefore, that the observed current cut-off is connected with excitation of electronic current-convective oscillations with $k_\varphi \neq 0$. For such oscillations, when $\omega_{He} > \omega_{Le}$, the dispersion equation is

$$k_\perp^2 + k_z^2\left[1 - \frac{\omega_{Li}^2}{(\omega - uk_z)^2} - \frac{\omega_{Le}^2}{\omega^2}\right] + \frac{k_\varphi \omega_{Le}^2}{\omega\omega_{He}}\frac{\partial \ln n_e}{\partial r} + \frac{k_\varphi \omega_{Li}^2}{\omega_{He}(\omega - uk_z)}\frac{\partial \ln n_i}{\partial r} = 0. \quad (7)$$

It is seen from this equation that in the frequency region $\omega \approx uk_z$ a purely electronic instability can result from the interaction between the beam and the electronic component of the plasma. The instability develops under the condition

$$\left(\frac{k_\varphi}{\omega_{He}}\omega_{Li}\frac{\partial \ln n_i}{\partial r}\right)^2 + 4k_z^2\omega_{Li}^2\left[k^2 - \frac{\omega_{Le}^2}{u^2} + \frac{k_\varphi \omega_{Le}^2}{k_z u \omega_{He}}\frac{\partial \ln n_e}{\partial r}\right] \leqslant 0. \quad (8)$$

When $k_\varphi = 0$ (or else in the case of a spatially homogeneous system) this condition corresponds to two-stream instability[6], and when $k_\varphi \neq 0$ it represents a modification of the electron current-convective instability, the development increment of which can reach a value

$$\gamma_{max} \approx \left\{k_z^2\omega_{Li}^2 \Big/ \left| k^2 - \frac{\omega_{Le}^2}{u^2} + \frac{k_\varphi}{k_z}\frac{\omega_{Le}^2}{u\omega_{He}}\frac{\partial \ln n_e}{\partial r}\right|\right\}^{1/2}. \quad (9)$$

The maximum increment corresponds to an excited-oscillation frequency $\omega \approx \omega_{Le}^2/\omega_{He}$. When such an instability develops, however, excitation takes place also of higher-frequency oscillations, up to $\omega \lesssim \omega_{He}$.

It is seen from the inequality (9) that the instability under consideration develops at plasma densities exceeding a certain critical value, namely

$$n_e > n_{cr} = \frac{1}{3\cdot 10^9}\left[k^2u^2 + \frac{k_\varphi^2 u^2 \omega_{Li}^2}{4k_z^2 a^2 \omega_{He}^2}\right]\left[1 + \frac{k_\varphi}{k_z}\frac{u}{\omega_{He}}\frac{1}{a}\right]^{-1} \approx 5\cdot 10^7 \frac{H}{L}\frac{n}{s} + 3.5\cdot 10^2 \frac{L}{H}\frac{s}{n} n_i. \quad (10)$$

We assume here that $\partial \ln n_i/\partial r \approx \partial \ln n_e/\partial r \approx 1/a$ and $k_\perp \approx 10$. We note that under the concrete experimental conditions $k_\varphi u/k_z\omega_{He}a > 1$ and when $I_{col} = 1-4$ A we have $k^2u^2 > k_\varphi^2 u^2\omega_{Li}^2/4k_z^2a^2\omega_{He}^2$, and when $I_{col} = I_{max} = 10$ A we get $k^2u^2 \lesssim k_\varphi^2u^2\omega_{Li}^2/4k_z^2a^2\omega_{He}^2$.

If we assume that the instant of the current cut-off $n_e > n_{cr}$ and take (1) into account, then we can write for small currents $n_{cr} \sim H/L$ and $\Delta t \gtrsim H/Ln_iP_i$. This implies the existence of a minimum current and a minimum pressure at which current cut-off can occur.

The duration of the stable stage should increase with increasing magnetic field, with decreasing length of the system, and with decreasing current of the electron beam. From the plots of Fig. 3 we see that all these rules agree well with the experimental data. At $I_{col} \approx 10$ A, both terms in the numerator of (10) are of the same order of magnitude and therefore the duration Δt should depend weakly both on H and on L. In experiment, at $I_{col} = 10$ A, the value of Δt does not actually depend on H, but the dependence on L remains the same as for small beam currents. It should also be noted that during the development of the instability, when the plasma density increases by two orders of magnitude within ~ 7 μsec and $\omega_{Le} > \omega_{He}$, the upper frequency of the radiation from the plasma remains equal to ω_{He}, which also agrees with the theoretical notions.

We see thus that the hypothesis that the instability of the electron beam in the plasma is of the pure electron current-convective type agrees well qualitatively with the main experimental results.

The authors are grateful to M. S. Rabinovich, Ya. B. Faĭnberg, G. M. Batanov, and L. M. Kovrizhnykh for a number of valuable remarks during the discussion of this work, and to V. A. Khozhevets, R. A. Latypov, and V. P. Solov'ev for help with the experiment.

[1] H. Hines and E. Hoffman, J. Appl. Phys. 26, 1157 (1955).

[2] W. Getty, and L. Smullin, ibid. 34, 3421 (1963). A. K. Berezin, Ya. B. Faĭnberg, L. I. Bolotin, G. P. Berezina, I. A. Bez'yazychnyĭ, Yu. M. Lyapkalo, and V. V. Lifshitz, Plasma Phys. and Contr. Nuclear Fusion Res., vol. 1, Int. Atomic Energy Agency, Vienna, 1966, p. 515.

[3] E. E. Lovetskii and A. A. Rukhadze, Nuclear Fusion 6, 9 (1966). L. S. Bogdankevich and A. A. Rukhadze, ibid. 6, 176 (1966). A. B. Mikhaĭlovskii, Zh. Tekh. Fiz. 35, 1933 and 1945 (1965) [Sov. Phys. Tech. Phys. 10, 1490 and 1498 (1966)].

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

[5] A. A. Rukhadze and V. P. Silin, Usp. Fiz. Nauk 82, 499 (1964) [Sov. Phys.-Usp. 7, 209 (1964)].

[6] A. I. Akhiezer and Ya. Yu. Faĭnberg, Dokl. Akad. Nauk SSSR 69, 555 (1949). Ya. B. Faĭnberg, Atomnaya énergiya 11, 313 (1961). D. Bohm and E. Gross, Phys. Rev. 75, 185 (1949).

Translated by J. G. Adashko
216