Low frequency instabilities in a linear plasma betatron

E. I. Lutsenko, L. M. Kontsevoĭ, V. A. Bondarenko, and N. D. Sereda
Khar'kov State University
(Submitted August 29, 1972)
Zh. Eksp. Teor. Fiz. **64**, 833-842 (March 1973)

Low frequency instabilities ($\omega_{Hi} \ll \omega \ll \omega_{He}$) leading to restriction of the beam current in a linear plasma betatron are investigated. Conditions for the appearance of oscillations and their dispersion properties (frequency characteristics and space structure) are studied. Development of the instabilities is accompanied by anomalous plasma diffusion and a displacement of the plasma across the magnetic field. Consequently the instabilities are a serious obstacle for formation of intense electron beams in a plasma. The experimental results are compared with theories of current-convective beam instability in an inhomogeneous plasma and of excitation of helical waves by a beam.

INTRODUCTION

Experiments with a linear plasma betatron[1,2] have shown that by applying an external electric field to a plasma it is possible to accelerate intense electron beams in the plasma. The use of plasma in a betatron makes it possible to compensate for the space charge of the accelerated electrons and to obtain beams with large currents (~10 kA). At the same time, the presence of a plasma through which a powerful electron beam passes leads to the onset of a number of instabilities that exert an appreciable influence on the beam. Thus, the development of high-frequency instabilities ($\omega \sim \omega_{pe}$) leads to partial deceleration of the beam and to a spreading of its energy spectrum. Earlier experiments[1] have shown that it is possible to stabilize the high-frequency instabilities and to narrow down considerably the energy spectrum of the accelerated electrons. However, together with high-frequency instabilities, the effect of which decreases with increasing accelerating voltage, there exist in the betatron also low-frequency instabilities ($\omega_{Hi} \ll \omega \ll \omega_{He}$), which apparently present the most serious danger for the acceleration of electrons in a plasma, since they produce abrupt changes in the parameters of the plasma itself, namely, a rise in temperature, a decrease in the concentration, and anomalous diffusion. All this affects seriously the parameters of the beam emerging from the accelerator, especially its duration. Further investigation of the conditions under which powerful electron beams are formed in a plasma calls therefore for a study of the low-frequency instabilities that occur in a betatron and for a determination of the conditions for their stabilization.

PROCEDURE AND RESULTS OF EXPERIMENTS

The experiments were performed with a small model of a linear plasma betatron[1]. The highly ionized beam plasma with concentration $2 \times 10^{12} < n < 2 \times 10^{13}$ cm^{-3} was produced in a glass chamber 100 cm long and 5 cm in diameter, in a longitudinal magnetic field of intensity 2 kOe. The initial diameter of the plasma column was ~2 cm. When a solenoidal accelerating voltage of 10–60 kV of 0.5 μsec duration was applied to the plasma, an intense electron beam was produced in the betatron, with current 500–1000 A. We measured the beam current, its distribution over the cross section of the plasma column, the amplitudes and frequency spectra of the low-frequency oscillations ($\omega_{Hi} \ll \omega \ll \omega_{He}$), the x-radiation from the walls of the accelerator chamber, and the plasma concentration, all as functions of the time.

The beam current was measured with a Rogowski loop with bandwidth 50 MHz, the signal from which was fed to the plates of a fast-sweep oscilloscope. To study the time distribution of the current density over the cross section of the plasma column, a diaphragm was placed at the exit of the beam from the betatron; the holes in the diaphragm collimated the beam current from different part of the cross section onto a system of concentric Faraday cylinders insulated from one another. The signals from the cylinders were fed to the plates of two-beam high-speed oscilloscopes and were registered simultaneously.

The low-frequency oscillations produced in the betatron following development of the instabilities were registered by three methods. First, the oscillations taken out of the plasma by the beam of accelerated electrons were selected with a system of coupled coils and fed to a fast-sweep oscilloscope directly or through a wavemeter. Second, the oscillations were received by a capacitive probe placed in the plasma at the exit from the betatron. Third, the LF oscillations radiated from the plasma were registered with loop antennas mounted at different points along the chamber, and were fed to the oscilloscope through wavemeters. In addition, the LF oscillations could be observed in the beam current itself. To investigate the spatial distribution of the oscillations, we used a system of two loop antennas placed in the same chamber cross section at equal distances from the axis and capable of moving in azimuth.

The x-rays from the accelerator-chamber wall, produced as a result of the scattering of the beam electrons by the oscillations and their deflection to the wall, were registered with a stilbene crystal and a photomultiplier. The x-ray photograph of the accelerator chamber was obtained with the aid of pinpoint camera.

Investigations of the behavior of the beam of accelerated electrons at initial plasma concentrations $n_0 < 1 \times 10^{13}$ cm^{-3} have established that variations of the voltage applied to the plasma changes not only the beam current, but also its waveform. Some $(2-3) \times 10^{-7}$ sec after the production of the beam, a dip appears in the current pulse; this dip increases with increasing voltage, and in final analysis imposes a limitation on the beam-current duration. The limitation (break) of the beam current occurs earlier at lower plasma concentrations. The effect of current limitations is particularly noticeable under good vacuum conditions after repeated preconditioning of the system with discharges.

An investigation of the oscillations radiated from the plasma by the beam has shown that intense low-frequency oscillations at frequencies $f \sim 50-1000$ MHz are produced shortly before the break in the plasma current. Figure 1 shows oscillograms of the beam current (upper trace), of the oscillations radiated from the plasma by the beam (central curve), and of the oscillations from an electric probe placed in the plasma. The sweep duration is 1.5 μsec, the initial plasma concentration is $n_0 \sim 7 \times 10^{12}\,\text{cm}^{-3}$, and the voltage is 40 kV. The oscillograms were obtained simultaneously with two high-speed oscilloscopes. The oscillations both from the coil and from the loop had a sufficient amplitude to be fed directly, without preamplification, to the oscilloscope plates. From a comparison of the oscillograms we see that the break in the beam current coincides in time with the development of intense oscillations in the plasma. With the exception of the initial section, the oscillations registered by a probe placed in the plasma coincide with the oscillations radiated from the plasma by the beam. The oscillations observed during the initial state of acceleration in the beam (central trace) and not observed at this instant in the plasma (lower trace) are apparently due to modulation of the beam current, during the instant of its formation, by space-charge oscillations in the cathode part of the plasma column. The same oscillations modulate also the beam current during the initial stage of its formation.

The dynamics of the development of the oscillations can be easily examined at low beam energies, when the amplitudes of the oscillations and the ensuing effects are small (the beam energy is determined by the voltage applied to the plasma). As a rule, there are initially produced in the plasma oscillations with frequency $f \sim 50-70$ MHz, which are weakly modulated by higher frequencies. With increasing beam energy, the amplitudes of the fundamental frequency and of the modulating frequencies increase. The oscillations span a large region of the frequency spectrum. Figure 2 shows oscillograms of oscillations obtained with a fast-sweep oscilloscope for two beam energies (15 and 25 keV, $n_0 \sim 5 \times 10^{12}\,\text{cm}^{-3}$). Zero time corresponds to the instant of beam formation. We see that oscillogram 1 constitutes almost harmonic oscillations with frequency $f \sim 60$ MHz, which become modulated at higher frequencies towards the end of the pulse. The oscillations are produced with a rather large delay ($\sim 10^{-7}$ sec) relative to the instant of beam formation. The growth increment is $\gamma \sim 5 \times 10^7$. With increasing beam energy (oscillogram 2), the oscillations develop much earlier and are strongly modulated by the high frequencies. Starting with the midpoint of the pulse, the oscillation frequency increases sharply. With further increase of the beam energy, the oscillations with higher frequencies shifts towards the origin and extend over practically the entire pulse duration. Figure 3 shows the spectrum obtained by reducing a section of a similar oscillogram ($n_0 \sim 5 \times 10^{12}$, W = 50 keV, $\tau \sim 0.3\ \mu$sec). The spectrum of the excited oscillations spans the frequency region $f \sim 50-1000$ MHz, which a maximum at $f \sim 200-400$ MHz. Besides measuring the intense oscillations directly in the plasma and in the beam, we registered them also with loop antennas placed near the accelerator chamber. The frequency spectra of the oscillations received by these antennas coincide with the frequency spectrum of the oscillations received with the coil and with the probe.

Increasing the plasma concentration exerts a strong stabilizing influence on the oscillations. Thus, when the initial plasma concentration is increased from $n_0 \sim 4 \times 10^{12}\,\text{cm}^{-3}$ to $n_0 \sim 3 \times 10^{13}\,\text{cm}^{-3}$, the amplitude of the oscillations decreases sharply, and the frequency spectrum becomes narrower on the low-frequency side. The dependence of the maximum frequency of the spectrum on the concentration is given approximately by the relation $f_{max} \propto n^{-1/2}$. The effect of the oscillations on the beam current also decreases with increasing plasma concentration. Figure 4 shows oscillograms of the

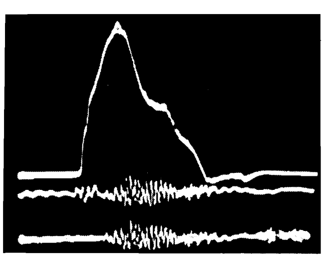

FIG. 1. Oscillograms of beam current (upper trace), of the oscillations carried out from the plasma by the beam (central trace), and of the oscillations from an electric probe (lower trace). Sweep duration 1.5 μsec, initial plasma concentration $n_0 \sim 7 \times 10^{12}$ cm^{-3}, V = 40 kV.

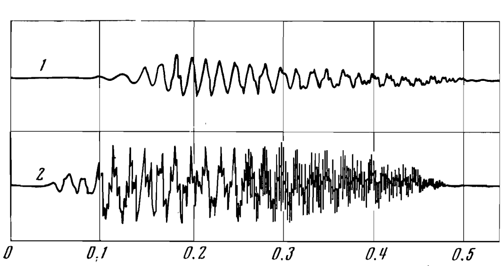

FIG. 2. Oscillation oscillograms obtained with fast-sweep oscilloscope: 1—W = 15 keV, 2—W = 25 keV; $n_0 \sim 5 \times 10^{12}$ cm^{-3}.

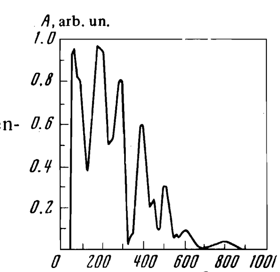

FIG. 3. Spectrum of oscillation frequencies ($n_0 \sim 5 \times 10^{12}$ cm^{-3}, W = 50 keV, $\tau \sim 0.3\ \mu$sec).

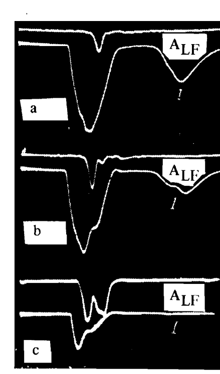

FIG. 4. Oscillograms of beam current (lower traces) and of oscillations (upper traces) with frequency $f \sim 200$ MHz at different plasma concentrations: a—$n_0 \sim 1 \times 10^{13}$ cm^{-3}, b—$n_0 \sim 8 \times 10^{12}$ cm^{-3}, c—$n_0 \sim 5 \times 10^{12}$ cm^{-3}; V = 40 kV, sweep duration 2 μsec.

beam current and of the oscillations with frequency $f \sim 200$ MHz for an accelerating voltage 40 kV and plasma concentrations $n_0 \sim 1 \times 10^{13}\ \mathrm{cm}^{-3}$ (a), $\sim 8 \times 10^{12}\ \mathrm{cm}^{-3}$ (b), and $\sim 5 \times 10^{12}\ \mathrm{cm}^{-3}$ (c). The sweep duration is 2 sec. At low plasma concentrations (c), the oscillations of frequency $f \sim 200$ MHz develop immediately after the onset of beam and have a large amplitude. The beam current at that instant decreases sharply. With increasing plasma concentration (b), the effect of the oscillations on the beam decreases, the amplitude of the oscillations decreases, and the oscillations themselves appear much later in time. Finally, at a large plasma concentration (a), the amplitude of the oscillations becomes so small that it exerts practically no influence on the beam. The dependence of the amplitude of oscillations with frequency $f \sim 200$ MHz and of their growth time to maximum on the plasma concentration is shown in Fig. 5 for an accelerating voltage 40 kV. The time is reckoned from the instant of beam production. The oscillations have a maximum at a plasma concentration $n_0 \sim (3-4) \times 10^{12}\ \mathrm{cm}^{-3}$. At a concentration $n_0 \sim 1.5 \times 10^{12}\ \mathrm{cm}^{-3}$, owing to the insufficient electron emission from the cold cathode, no beam is produced in the betatron (breaking of circuit). At a concentration $n_0 > 3 \times 10^{13}\ \mathrm{cm}^{-3}$, the excessively large emission of electrons from the cathode destroys the conditions for beam formation. In this case, the discharge current is carried by the main bulk of the low-energy plasma electrons.

An investigation of the oscillation frequencies in different gases has shown that the oscillations are not very sensitive to the ion mass. Thus, measurements of oscillations in argon and hydrogen show that both the oscillation amplitude and the maximum of the excited frequencies are 2—3 times larger for hydrogen. Depending on the plasma concentration and on the type of gas, the oscillation increments run in the range $\gamma \sim 5 \times 10^7 - 1 \times 10^8$. With increasing beam energy and with decreasing plasma concentration, the growth increments of the oscillations increase. An increase in the magnetic-field intensity, to the contrary, decreases the growth increment of the oscillations, increases the oscillation frequency, and reduces their amplitude.

Measurement of the oscillations at different points along the chamber has shown that the low-frequency oscillations are produced initially in the near-cathode part of the plasma column, and then propagate with velocity $\sim 10^9$ cm/sec (lower than the velocity of the accelerated electrons) along the accelerator chamber. Their amplitude is larger in the near-cathode region of the plasma column.

Measurement of the oscillations with two loop antennas in a single cross section have shown that the observed low-frequency oscillations are axially asymmetrical. Figure 6 shows oscillograms of oscillations at a frequency $f \sim 200$ MHz from two probes located at a single point of space (a) and shifted relative to one another by an angle $\varphi = 180°$ (b). The sweep duration is 2 μsec. When the antennas are separated, the signals from them differ both in amplitude and in waveform, thus indicating that the oscillations have no axial symmetry ($k_\varphi \neq 0$).

The development of low-frequency instabilities in the betatron is accompanied by the expansion of the beam, its motion to the wall, and an anomalous diffusion of the plasma across the magnetic field. Measurement of the beam-current density over the cross section of the plasma column at the exit from the betatron shows that the beam current density changes during the course of the pulse not only in time, in accordance with the change of the voltage applied to the plasma, but also in space.

Figure 7 shows oscillograms of the beam-current density on the plasma-column axis (lower trace) and at a distance 1 cm from the axis. The sweep duration is 1 μsec, the voltage is 40 kV, and the plasma density is $n_0 \sim 8 \times 10^{12}\ \mathrm{cm}^{-3}$. We see that the electron beam is initially formed in the axial part of the plasma column with a diameter smaller than 2 cm (there is no current at a radius 1 cm away from the axis). After $\sim 10^{-7}$ sec following the start of beam formation on the axis, a current is produced also in plasma-column cross-section regions that are remote from the axis, and the onset and growth of the current on the periphery of the cross section is accompanied by a decrease of the current density at the axis of the plasma column. The decrease of the current at the axis of the plasma column coincides in time with the onset of low-frequency oscillations in the beam. This indicates that the development of high-frequency instabilities apparently broadens the beam and deflects it to the wall. Measurements of the time of break of the beam current in the near-axis region as a function of the plasma concentration, the type of gas, and the beam energy indicates the following regularities:

First, the time of current interruption depends significantly on the type of gas and on the voltage. Figure 8 shows plots of the time when the current starts to decrease on the axis against the accelerating voltage for argon and hydrogen. The plasma density was $n_0 \sim 3 \times 10^{12}\ \mathrm{cm}^{-3}$. With increasing beam energy, the time of beam-current interruption decreases. The beam current breaks in hydrogen much earlier than in argon. Second, there exists a threshold beam current I_{thr},

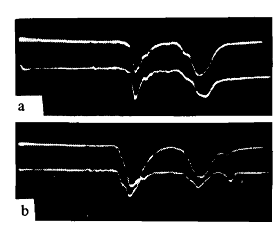

FIG. 6. Oscillograms of oscillations at frequency $f \sim 200$ MHz from two probes: a—at one point of space, b—located at an angle $\varphi = 180°$ relative to each other. Sweep duration 2 μsec.

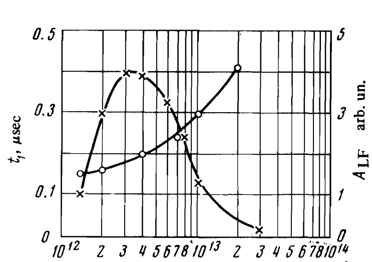

FIG. 5. Amplitude of oscillations of frequency $f \sim 200$ MHz (X) and their growth time (O) vs. the plasma concentration. $V \sim 40$ kV.

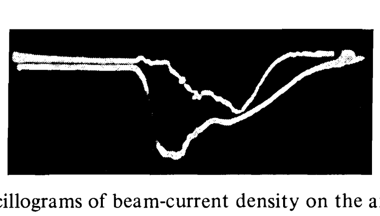

FIG. 7. Oscillograms of beam-current density on the axis of the plasma column (lower trace) and at a distance of 1 cm from the axis (upper trace). $\tau_{dev} \sim 1.0\ \mu$sec, $W = 40$ keV, $n_0 \sim 8 \times 10^{12}\ \mathrm{cm}^{-3}$.

starting with which low-frequency instability develops in the plasma and causes the beam current to break. Figure 9 shows the dependence of the threshold beam-current density j_{thr} on its energy. The initial plasma concentration is $n_0 \sim 8 \times 10^{12}\,cm^{-3}$. The threshold current increases with increasing beam energy. The threshold current is proportional to u^2, where u is the velocity of the beam electrons. The threshold beam current increases with increasing magnetic-field intensity.

The x-ray emission from the accelerator-chamber wall coincides in time with the instant when low-frequency oscillations occur in the plasma and the beam current breaks. This emission, just as the oscillations, occurs initially in the near-cathode part of the accelerator chamber, and then propagates along the chamber at the same velocity as the oscillation amplitude. Most γ quanta have energies not exceeding the beam-electron energy, but the emission spectrum does contain an appreciable fraction of γ quanta with energy up to 200 keV. X-ray photography of the accelerator chamber shows the trace of the beam as it is diverted to the wall. The beam is twisted into a helix with pitch $h \sim 10$ cm.

The development of low-frequency instabilities leads to anomalous diffusion of the plasma cross the magnetic field. Thus, within the lifetime of the intense oscillations (i.e., 0.3–0.4 μsec), the plasma concentration decreases by a factor 5–7. In a poorly outgassed system, the oscillation intensity decreases sharply and there is no decrease in the plasma concentration. To the contrary, the influx of gas from the chamber walls (due to gas desorption following bombardment of the walls by beam electrons scattered by the oscillations) and subsequent ionization of the gas in the HF field of the oscillations lead to an increase in the plasma concentration. Under such conditions there is no break of the beam current.

The onset of low-frequency noise in the betatron and the limitation of the beam current depend to a considerable degree on the homogeneity of the magnetic field along the chamber. A local inhomogeneity of the magnetic up to 50% (turning off one of the coils) leads to a more rapid development of the instabilities and to a break of the beam current within 0.2 μsec even at a high plasma concentration.

DISCUSSION OF RESULTS AND CONCLUSIONS

As shown by our investigations, the low-frequency instabilities arising when strong-current electron beams are accelerated in a plasma are characterized by the following features:

1. The oscillations are excited in the frequency range $\omega_{Hi} \ll \omega \ll \omega_{He}$, with a maximum at frequencies $f \sim 200$–400 MHz.

2. The frequency spectrum of the oscillations depends little on the type of gas, and the oscillation frequency spectrum broadens towards the higher frequencies with increasing beam energy and with increasing magnetic field. With changing plasma concentration, the maximum oscillation frequency behaves like $f_{max} \sim n^{-1/2}$.

3. The oscillations are axially asymmetrical ($k_\varphi \neq 0$). Their growth increments amount to $\gamma \sim 5 \times 10^7 - 1 \times 10^8$ and increase with decreasing plasma concentration and with increasing beam energy.

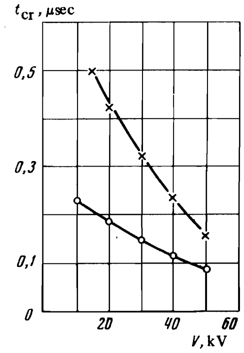

FIG. 8

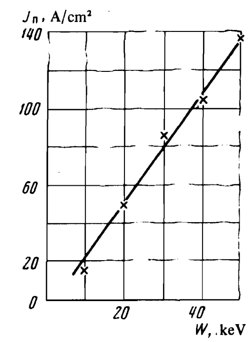

FIG. 9

FIG. 8. Time of current limitation vs. accelerating voltage (V): X–argon, O–hydrogen, $n_0 \sim 3 \times 10^{12}\,cm^{-3}$.

FIG. 9. Threshold values of the beam current density (j_b) vs. the beam energy, $n_0 \sim 8 \times 10^{12}\,cm^{-3}$.

4. The instability develops starting with a certain threshold value of the beam current, which is proportional to the square of the beam-electron velocity (u^2). With increasing magnetic field intensity, the threshold value of the beam current increases.

5. The low-frequency oscillations develop under conditions when intense high-frequency oscillations ($\omega \sim \omega_{pe}$) are present. The high-frequency oscillations smear out the beam-electron velocity distribution function[1].

6. An increase of the plasma concentration leads to stabilization of the instabilities, namely to a decrease of the oscillation amplitude and to a narrowing of the frequency spectrum.

7. The development of the instabilities is accompanied by limitation (break) of the beam current. The beam-current break is apparently due not to the onset of anomalous resistance in the plasma, but to a decrease in the plasma concentration as a result of anomalous diffusion and diversion of the beam to the walls of the accelerator chamber. The plasma deviation and the diversion of the beam to the chamber wall depend on the plasma concentration, on the beam energy, on the type of gas, and on the inhomogeneity of the longitudinal magnetic field. In an inhomogeneous magnetic field, the diffusion of the plasma across the magnetic field and the diversion of the beam to the wall occur within a shorter time when the plasma concentration is decreased, the beam energy is increased, and lighter gases are used.

8. The beam becomes twisted into a helix as it is diverted to the wall. It is very difficult to interpret the results by assuming that only one type of instability develops in the betatron. A distinguishing feature of the investigated oscillations is that their frequencies and increments increase with decreasing plasma concentration and depend little on the type of gas. This immediately eliminates, among the possible low-frequency instabilities, such rapidly developing instabilities as ion-acoustic and two-stream electron-ion (Buneman) instability, the limiting frequencies of which ($\omega \sim \omega_{pi}$ and $\omega \sim \omega_{pe}(m/M)^{1/3}$) and increments of which ($\gamma \sim \omega_{pi}u/v_{Te}$ and $\gamma \sim \omega_{pe}(m/M)^{1/3}$) decrease with decreasing plasma concentration and depend on the type of gas. In addition, the investigated oscillations have axial asymmetry and depend strongly on the inhomogeneity of the longitudinal magnetic field, and consequently on the inhomogeneity of the plasma concentra-

tion. This indicates that the cause of the beam-current interruption in the betatron may be current-convective instabilities resulting from transverse inhomogeneity of the beam and of the plasma (grad$(n_1, n) \neq 0$). Two-stream instabilities with convective effects were considered theoretically in[3,4]. The mechanism of such instabilities is based on the effect of convection of the charges in crossed fields, the azimuthal electric field E_φ of the oscillations and the longitudinal magnetic field of H. For long-wave oscillations ($k_\perp \ll \omega_{pe}/u$), the frequency and the growth increment of the instability of a fast beam ($u > \omega_{Hi}/k_z$) are of the order of[3]

$$\gamma \approx \omega \approx \left(\frac{n_1}{n} k_z u \omega_{Hi} a k_\perp\right)^{1/3} \left(1 + \frac{k_z^2}{k^2} \frac{M}{m}\right)^{1/3}. \quad (1)$$

Here n_1 and n are the concentrations of the beam electrons and of the plasma, a is the characteristic dimension of the spatial gradient of the beam, and $k_\perp^2 = k_r^2 + k_\varphi^2$. The dependence of the threshold beam current (j_{thr}) on the beam energy (W) in the case of convective buildup is given by[5]

$$j_{thr} \sim W\sqrt{H}. \quad (2)$$

Comparing the experimental results with the theoretical relations (1) and (2), we see that qualitatively the dependences of ω, γ, and j_{thr} on n, u, and H coincides with the dependences given by relations (1) and (2). However, the experimentally obtained values of ω and γ are larger by more than one order of magnitude than the values obtained from (1) ($n_1/n \sim 5 \times 10^{-2}$, $k_z \sim 10^{-2}$, $H \sim 2000$ Oe, $k_\perp \sim 1/a$, $u \sim 8 \times 10^9$ cm/sec). In addition, according to (1), the frequency and increment of the oscillations depend strongly on the type of gas. In the experiment, on the other hand, the dependence of these quantities on the type of gas is very weak. Therefore, in spite of the presence of a number of effects that indicate that current-convective instability develops in experiment, it is impossible to attribute the interruption of the beam current to only this one instability. Unfortunately, the theory of two-stream instability with convective effects has not been sufficiently fully developed. In particular, not enough attention has been paid to instabilities in three-component systems ($n \gg n_1$). Furthermore, the inhomogeneities of the longitudinal magnetic field of the betatron (up to 20%) obviously lead to additional effects that complicate the interpretation of the results.

Besides current-convective buildup of oscillations, the beam can give rise to helical-wave instability in the betatron[6,7]. Such an instability is produced in a dense plasma ($\omega_{pe}^2 \gg \omega\omega_{He}$). The oscillation frequencies, which lie in the interval $\omega_{Hi} \ll \omega \ll \omega_{He}$, are given by

$$\omega = \omega_{He} |\cos\theta| k^2 c^2 / \omega_{pe}^2, \quad (3)$$

where θ is the angle between the direction of wave propagation and the magnetic field. Since the phase velocity of these oscillations $\omega/k \ll c$, they can interact effectively with an electron beam passing through the plasma. For a cold plasma and a cold beam, the growth increment of the oscillations, for the case $\omega \sim k_z u$ takes the form[6]

$$\frac{\gamma}{\omega} = \frac{\sqrt{3}}{2^{4/3}} \left(\frac{\omega_{1e} kc \sin\theta}{\omega_{pe}^2}\right)^{2/3}. \quad (4)$$

Here $\omega_{1e} = (4\pi e^2 n_1/m)^{1/2}$ is the electron frequency of the beam. It is seen from relations (3) and (4), that both of the frequencies and the increments of the oscillations increase with decreasing plasma concentration and with increasing magnetic field (this is indeed observed in experiment), and do not depend on the type of gas. In addition, the condition $\omega_{pe}^2 \gg \omega\omega_{He}$ is satisfied in the experiment. Therefore buildup of helical waves in a betatron is apparently possible. However, the fact that the beam excites purely electronic oscillations does not explain the experimentally observed dependence of the anomalous plasma diffusion and of the time of beam-current interruption on the type of gas. Indeed, it is obvious that several instabilities develop simultaneously in the experiment, and it is impossible to separate them from one another at the present stage of the research. Oscillations of this type, which do not depend on the ion mass, are apparently observed also in a straight discharge[8].

To explain the picture of the phenomena in the betatron, we shall eliminate the existing inhomogeneities of the longitudinal magnetic field and investigate in greater detail the spatial characteristics of the oscillations.

In conclusion, the authors thank Y. A. Faĭnberg for a discussion of the results.

[1] E. I. Lutsenko, Ya. B. Fainberg, V. A. Vasil'chuk, and N. P. Shepelev, Zh. Eksp. Teor. Fiz. 57, 1575 (1969) [Sov. Phys.-JETP 30, 853 (1970)].

[2] E. I. Lutsenko, Ya. B. Faĭnberg, N. S. Pedenko, and V. A. Vasil'chuk, Zh. Tekh. Fiz. 40, 529 (1970) [Sov. Phys.-Tech. Phys. 15, 410 (1970)].

[3] A. B. Mikhaĭlovskiĭ, Zh. Tekh. Fiz. 35, 1945 (1965) [Sov. Phys.-Tech. Phys. 10, 1498 (1966)], Atomnaya énergiya 20, 103 (1966).

[4] L. S. Bogdankevich, E. E. Lovetskiĭ, and A. A. Rukhadze, Nuclear Fusion 6, 9, 176 (1966).

[5] A. B. Mikhaĭlovskiĭ, Teoriya plazmennykh neustoĭchevosteĭ (Theory of Plasma Instabilities), Vol. 2, Atomizdat, 1971.

[6] A. I. Akhiezer, I. A. Akhiezer, R. V. Polovin, A. G. Sitenko, and K. N. Stepanov, Kollektivnye kolevaniya v plazme (Collective Oscillations in Plasma), Atomizdat, 1974.

[7] A. B. Mikhailovskiĭ, in: Voprosy teorii plazmy (Problems of Plasma Theory), Vol. 6, Atomizdat, 1972, p. 70.

[8] N. K. Berger, V. S. Koĭdan, A. N. Papyrin, A. G. Ponomarenko, V. N. Stibunov, and B. A. Yablochkov, Zh. Eksp. Teor. Fiz. 56, 1463 (1969) [Sov. Phys.-JETP 29, 784 (1969)].

Translated by J. G. Adashko
92