Excitation of electromagnetic waves in a plasma in a homogeneous magnetic field by a strong-current relativistic electron beam

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We investigated experimentally the radiation of a relativistic electron beam following its injection into a smooth metallic waveguide partly filled with magnetized plasma. It is shown that in the case of a large angle spread of the injected electrons the radiation takes place at the cyclotron frequency of the relativistic electrons, and the radiation power increases with increasing plasma density by almost two orders of magnitude compared with the vacuum radiation. This result is attributed to the effect of charge neutralization of the beam as it is injected in the plasma.

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1. INTRODUCTION

In connection with the advances in the technology of high-power pulsed voltage generators, many recent papers have been devoted to the excitation of electromagnetic waves by high-current relativistic beams. The electron beams were injected in this case in various vacuum systems, mainly corrugated waveguides and systems with corrugated magnetic fields.[1-3] In such systems, as a rule, it is impossible to make full use of the accelerator power, owing to the limitations imposed by the space charge of the electrons and by the magnetic field of the beam current. It is known that these limitations are lifted in the presence of a plasma. As a result, it becomes possible to inject in a plasma practically arbitrarily large currents of relativistic electron beams, and this should lead to an appreciable increase of the beam power and of the effectiveness of the electromagnetic radiation in the plasma-beam systems. The excitation of electromagnetic waves by interaction of a relativistic electron beam with a plasma is therefore a timely problem.

Microwave radiation produced by Cerenkov interaction between a strong-current relativistic electron beam and a plasma in an iris-loaded waveguide was investigated by a number of workers.[4,5] The experimental conditions in our study differed from the others mainly in that we used a smooth cylindrical waveguide partly filled with plasma, the latter being produced independently and its density varied in a wide range, $n_p \approx 10^9-10^{13}$ cm^{-3}. The magnetic field was homogeneous in length, and the beam current in the plasma exceeded the vacuum current by 2.5 times. We investigated the influence of the initial electron velocity spread in angle on the excitation of the electromagnetic waves.

Two types of radiation were observed, short-wave at the cyclotron frequency of the relativistic-beam electron ($\sim$3 cm) and long-wave ($\sim$20 cm) due to Cerenkov interaction of the beam electrons with the plasma oscillations. It will be shown that the intensity of both types of radiation depends on the plasma density and on the spread of the electron velocities in angle. We analyze in detail in this paper the characteristics of the short-wave radiation and show that this radiation constitutes stimulated cyclotron radiation of the beam electrons.

2. EXPERIMENTAL SETUP AND DIAGNOSTICS

The "Terek-II" installation, on which the experiments were performed, was described in detail earlier.[6,7] An electron beam with electron energy up to 400 keV, current up to 2.5 kA, and pulse duration $\sim$30 nsec was injected into the plasma chamber, which was a round metallic waveguide 15 cm in diameter and 120 cm long. A plasma of 3 cm diameter and density up to $n_p \sim 10^{13}$ cm^{-3} was produced beforehand by ionizing xenon ($p = 3.7 \times 10^{-4}$ mm Hg) with a low-voltage electron beam of current 0.1–1 A, electron energy $\sim$1 keV, and pulse duration 100 μsec, injected by an electron gun placed on the opposite end of the installation (Fig. 1). The plasma density was varied by the current of the low-voltage beam and was homogeneous along the magnetic field, the intensity of which could reach 6 kOe. The homogeneity of the magnetic field was preserved accurate to 2% along the axis of the metallic waveguide.

The accelerator cathode was made of graphite. It is shown in Fig. 1. The cathode diameter was 55 mm. The anode was a convex grid of stainless steel, with transparency 77%, framed by a ring of 30 mm diameter. The curvature radius of the anode grid was 30 mm, and the minimum anode–cathode distance was 5 mm. A metallic foil separating the plasma from the diode accelerator

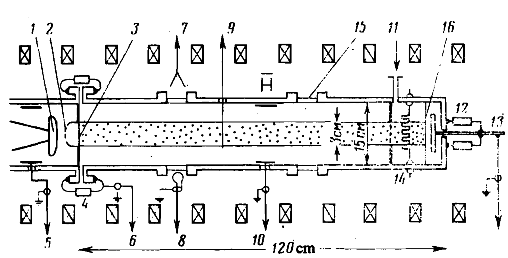

FIG. 1. Overall view of installation: 1—accelerator graphite cathode, 2—accelerator anode, 3—metallic foil, 4—low-inductance ohmic shunt to measure the chamber current, 5—capacitive voltage divider to measure the voltage; 6—cable for measurement of the chamber current; 7—3-cm microwave channel, 8—loop for the measurement of the plasma density, 10—capacitive divider for measuring the beam potential, 11—leak valve, 12—low-inductance ohmic shunt to measure the beam current, 13—beam-current collector, 14—electron gun to produce the plasma, 15—Teflon windows of 8 cm diameter, 16—tantalum foil 50 μ thick.

gap was located 10 mm behind the grid. This diode geometry was chosen in order, first, to shape a beam of 30 mm diameter with current close to the total diode current, second, to obtain a beam with a small velocity scatter, and third, to have a uniform beam-current distribution over the cross section. The latter circumstance has made it possible to produce more than 100 accelerator flash-ups without changing the 10-μ aluminum foil. In each accelerator flash-up we registered the following: the microwave radiation power in the 20-cm band; the microwave radiation power in the 3-cm band, the voltage on the accelerator cathode, the electron-beam current; the current in the chamber, the beam potential, the plasma density, and the intensity of the magnetic field. The first six parameters were recorded with the 6LOR-2M oscilloscope.

The beam-parameter measurement procedure was described in detail in [7]. With the aid of low-inductance ohmic shunts 12 and 4 we registered the current to the collector and the chamber current (Fig. 1). The collector was a stainless-steel plate separated from the plasma by a titanium foil 50 μ thick, and therefore the collector current was equal to the current of the beam passing through the waveguide. The chamber current was in this case equal to the sum of the beam currents and the plasma current. The beam potential was measured with capacitive voltage divider 10. This construction made it possible to measure sufficiently accurately the charge induced under the condition that there was no direct current of charged particles flowing to the capacitive divider. In our case this condition was satisfied, since the electrons were magnetized, and the plasma electrons could not reach the chamber walls in 30 nsec. The plasma density was measured by a single probe. The signal from the probe was calibrated with an 8-mm microwave interferometer in the range $n_p \sim 10^{11}$—10^{13} cm^{-3}.

The electromagnetic radiation from the system was registered only across the waveguide axis through four Teflon windows of 80 mm diameter, placed 28 and 70 cm away from the accelerator anode. The power of the short-wave radiation was measured with a 3-cm waveguide channel consisting of a horn antenna, a standard metallic waveguide 60 mm long, and the detector described in detail in [6]. The horn antenna was located opposite the Teflon window closest to the anode, at a distance 0—50 cm away. Variation of the distance between the window and antenna made it possible to introduce a calibrated attenuation of the radiation power. The long-wave radiation was registered with a loop of 20 mm^2 area, located 7.5 cm away from the beam axis. The signal from the loop was fed through a cable to oscilloscopes I2-7 (f_{max} = 3 GHz) and 6LOR-2M (f_{max} = 1 GHz). The receiving cable had an attenuation 3 dB at 1.5 GHz. To determine the spectrum of the short-wave radiation we used also a strip filter tuned to f = 8.75 GHz, the bandwidth at the 10 dB level being Δf = 1 GHz.

3. EFFECT OF ANGLE SCATTER OF THE BEAM ELECTRONS ON THE ELECTROMAGNETIC WAVE EXCITATION

In the first part of the study we investigated the influence of the angle scatter of the beam electrons on the character of the electromagnetic-wave excitation. The ratio of the transverse and longitudinal velocity components was varied by changing the thickness of the foil

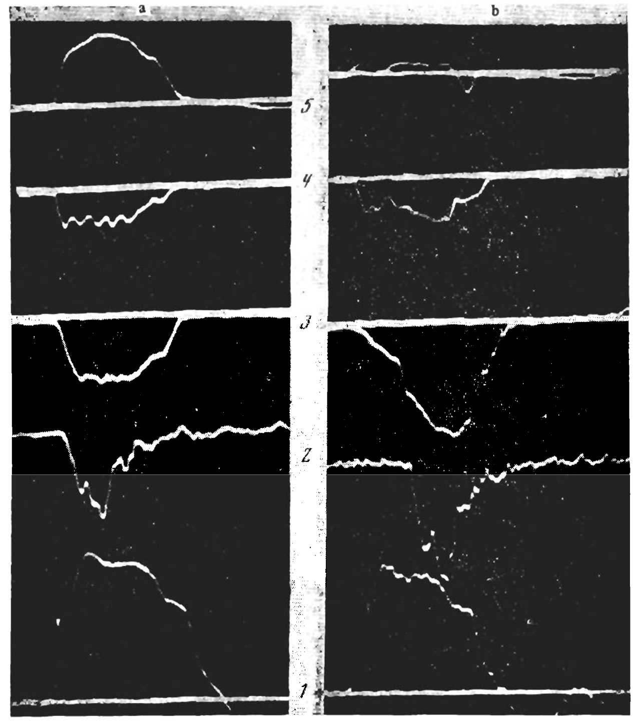

FIG. 2. Oscillograms of the cathode voltage 1, of the chamber current 3, of the beam current 4, of the beam potential 5, and of the short-wave microwave signal from the detector 2 on the 6LOR-2M oscilloscope, at H=4.8 kOe and W=350 keV in vacuum (a) and at $n_p=3\times10^{12}$ cm^{-3} (b). In curve 2 of case b the sensitivity of the receiving system is one fifth that of curve 2 of case a.

through which the electron beam was injected into the system. Two foils were used in the experiment: titanium 50 μ thick, which yields, according to calculations, [9] a scattering angle $(\overline{\theta^2})^{1/2} \approx 48°$ for electrons of energy 350 keV, which corresponds to an energy ratio $W_\perp/W_\parallel \approx 100\%$, and an aluminum foil 10 μ thick, which yields a scattering angle $(\overline{\theta^2})^{1/2} \approx 10°$ and $W_\perp/W_\parallel \approx 3\%$. In both cases, we plotted the dependence of the short- and long-wave radiation powers transverse to the system axis of the beam potential, the beam current, and the chamber current on the plasma density at a constant magnetic field.

Figure 2 shows typical oscillograms of the voltage, of the beam current, of the chamber current, and of the signal of the short-wave radiation detector at an electron energy W = 350 keV and a magnetic field intensity H = 4.8 kOe, in vacuum and in a plasma of density 3×10^{12} cm^{-3}. The waveform and the amplitude of the diode voltage did not change from flash-up to flash-up within 3%. The duration of the voltage pulse at half-height was ~35 nsec. The microwave detector had a near-logarithmic dependence of the signal amplitude on the incident power. It is seen from the oscillograms that the duration of the short-wave radiation is much less than the duration of the current pulse.

A. Tantalum Foil 50 μ Thick

Figure 3 shows the dependence of the power (P) of the short-wave radiation on the plasma density (curve 1) at a magnetic field 4.8 kOe and a titanium-foil thickness 50 μ. It is seen that when the plasma density n_p changes from 3×10^{10} cm^{-3} to 5×10^{12} cm^{-3} the power of the short-wave radiation from one Teflon window, measured

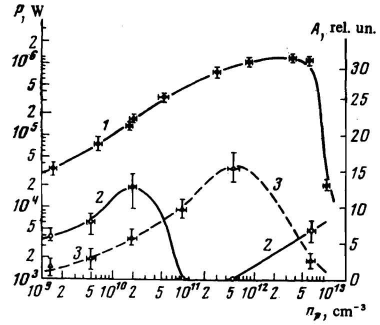

FIG. 3. Maximum radiation power P in the pulse vs. the plasma density in a magnetic field H=4.8 kOe. The intensity of the short-wave radiation is given in watts, and the intensity of the long-wave radiation is in relative units; curve 1—short-wave radiation power for a titanium foil 50 μ thick; W=350 keV; 2—short-wave radiation power for an aluminum foil 10 μ thick; W=380 keV; 3—long-wave radiation power for an aluminum foil 10 μ thick; W=380 keV.

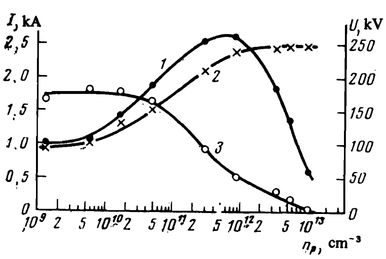

FIG. 4. Beam current (curve 1), chamber current (curve 2) and beam potential (curve 3) vs. the plasma density at B=4.8 kOe and W=350 keV.

by the 3-cm waveguide channel increases from 3×10^4 W to 2×10^6 W, and then, at a plasma density 5×10^{12} cm^{-3}, it decreases abruptly. The figure shows a plot of the average maximum power in the pulse for five flash-ups of the accelerator. The signal from the loop registering the long-wave radiation is equal to zero in this case.

The dependence of the chamber and beam currents I and of the beam potential on the axis U on the plasma density at H = 4.8 kOe is shown in Fig. 4. It is seen from the figure that the beam current I_b increases continuously with increasing plasma density; the potential on the beam axis decreases rapidly starting with $n_p > 10^{11}$ cm^{-3}. Thus, the growth of the beam current is connected with cancellation of the space charge of the electrons. The beam-current value 2.5 kA is close to the total diode current. The chamber current increases with increasing plasma density up to $n_p > 10^{12}$ cm^{-3}, after which it begins to decrease. This indicates that at $n_p > 10^{12}$ cm^{-3} part of the current returns not through the metallic waveguide but through the plasma.[7]

It is seen on Fig. 4 that at a plasma density $n_p \approx 2 \times 10^{12}$ cm^{-3} the chamber current exceeds the collector current. This is apparently connected with the incorrect measurements of the beam current. What was measured in the experiment was the absolute value of the chamber current, whereas the collector current was measured in relative units, since the transparencies of the anode and of the cathode of the electron gun producing the plasma were not known exactly, nor the transparency of the collector foil. It was assumed that in vacuum the beam and collector currents are equal to each other. The excess of the chamber current over the collector current at $n_p \approx 2 \times 10^{12}$ cm^{-3} seems to be connected with the different transparency of the collector foil for beams propagating in vacuum and in plasma. In vacuum at W = 350 keV the beam and chamber currents are ≈ 0.8 kA and U ≈ 180 kV.

B. Aluminum Foil 10 μ Thick

Figure 3 (curves 2 and 3) shows the dependence of the power of the short-wave radiation and of the intensity of the long-wave radiation on the plasma density at a magnetic field intensity H = 4.8 kOe and an aluminum foil thickness 10 μ. The electron energy in this case was W = 380 keV. It is seen from the figure that the power of the short-wave radiation decreased in comparison with the case of the titanium foil by an approximate factor 10, and moreover, in the plasma density region from $n_p \approx 10^{11}$ cm^{-3} to $n_p \approx 5 \times 10^{11}$ cm^{-3} there is no short-wave radiation. The long-wave radiation was registered with an I2-7 oscilloscope having an upper limiting frequency 3 GHz, which made it possible to determine the fundamental frequency of these oscillations. It was practically independent of the plasma density and equalled ~1.5 GHz.

The ordinates in Fig. 3 represent the amplitude of the signal from the loop in relative units. The sensitivity of the receiving apparatus was sufficient to measure the self magnetic field of the relativistic electron beam. This made it possible to estimate the ratio of the magnetic field of the electromagnetic oscillations with frequency 1.5 GHz to the self magnetic field of the beam. At a plasma density $n_p \approx 5 \times 10^{11}$ cm^{-3} this ratio is ~2%. It is seen from the diagram that the power of the long-wave oscillations is maximal in terms of the plasma density precisely in the region where the short-wave radiation power is minimal. The dependences of the beam current, the chamber current, and the beam potential at H = 4.8 kOe remained qualitatively the same as in the case with the titanium foil.

Thus, when a strong-current relativistic beam interacts with a plasma, intense electromagnetic oscillations are excited at centimeter and decimeter wavelength. Of fundamental significance for the character of the wave excitation is the presence or absence of transverse velocities of the beam electrons. In the case of a large transverse velocity scatter the power of the short-wave radiation in the plasma increases by two orders in comparison with vacuum. There are no long-wave oscillations in this case. On the other hand in the case of a small transverse scatter of the velocities, there exists a plasma-density region in which only long wave oscillations are intensely excited, and no short-wave ones are excited. The fundamental frequency of the long-wave radiation is of the order of 1.5 GHz and is practically independent of the plasma density in the investigated range.

4. SHORT-WAVE RADIATION

As already mentioned, in this article we confine ourselves to an analysis of only short-wave radiation. Much information on the nature of this radiation is obtained from investigations of the maximum radiation power in the pulse as a function of the magnetic field. This relation was obtained by injecting an electron beam through a tantalum foil in vacuum and in a plasma of density $(2-3) \times 10^{12}$ cm^{-3}. In the first case the current was limited by the space charge of the electrons, and in the second the space charge was cancelled out, the beam current increased by 1.5 times, and was determined by the diode

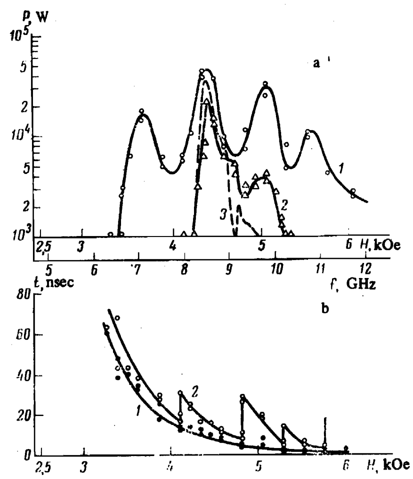

FIG. 5. a) Dependence of the maximum pulsed power of the short-wave radiation, registered with a 3-cm waveguide channel (1), passing through a band filter (2), and the calculated dependence of the radiation passing through the band filter (3) on the intensity of the magnetic field, using a 50-μ titanium foil at W=350 keV in vacuum. b) Dependence of the time of appearance of the microwave radiation pulse at the detector (1) and of the maximum radiation level (2) on the magnetic field intensity at the same parameters.

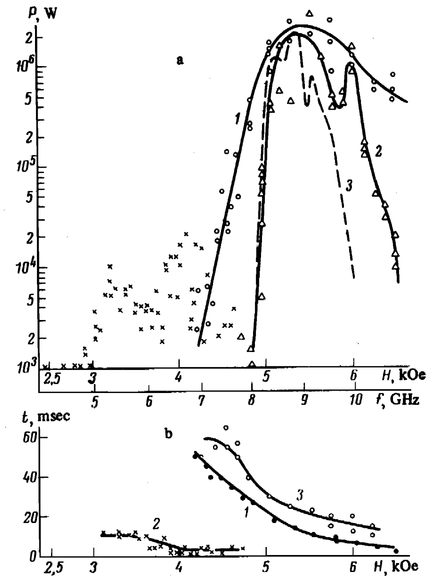

FIG. 6. a) Maximum power in the pulse of the short-wave radiation registered by the 3-cm waveguide channel (1), the radiation passing through the band filter (2), and the calculated dependence of the radiation passing through the band filter (3), vs. magnetic field intensity, using a 50-μ titanium foil at W=350 keV in a plasma of density $n_p=(2-3)\times 10^{12}$ cm^{-3}. b) Dependence of the time of appearance of the radiation pulse at the frequency $\omega=\omega_{He}/\gamma_0$ at the detector (1), of the higher-frequency radiation (2), and of the maximum radiation level (3) on the magnetic field at the same parameters.

current. When the beam was injected in vacuum, the radiation detected by the receiving system set in at a magnetic field H = 3.3 kOe (Fig. 5a, curve 1). We assume that the maximum radiation frequency is $\omega = \omega_{He}/k$, where ω_{He} is the cyclotron frequency of the nonrelativistic electron and k is a certain number. Then the onset of radiation at H = 3.3 kOe is due to the fact that at this field intensity the radiation frequency has become larger than the critical frequency of the receiving waveguide. This yields k = 1.44 ± 0.15. The accuracy of k is governed by the 10% accuracy of the absolute calibration of the magnetic-field intensity.

The radiation power passing through the band filter is shown in Fig. 5a (curve 2). The dashed line shows the calculated characteristic of the filter under the assumption that $\omega = \omega_{He}/1.44$ and that the radiation level varies in accord with curve 1. It is seen that the maximum radiation frequency agrees well with the value $\omega_{He}/1.44$. The discrepancy between the experimental and calculated curves indicates that the radiation spectrum does not consist of a single line $\omega = \omega_{He}/1.44$, but has a certain width.

We now recognize that the cyclic frequency of the relativistic electron in a magnetic field is equal to ω_{He}/γ, where γ is the relativistic factor in drift space. If upon injection of the beam in the vacuum the initial electron energy is W = 350 keV, then the electrons have $\gamma_0 = 1.7$ at the injection point. In drift space, on the other hand, the electrons on the beam axis have $\gamma \approx 1.2$, while on the edge of the beam γ is somewhat larger ($\gamma \approx 1.3$). Thus, the radiation frequency is close to ω_{He}/γ. It can then be assumed that the peaks on curve 1 of Fig. 5a correspond to satisfaction of the resonance conditions $\omega_{He}/\gamma = \omega_\alpha$, where ω_α are the natural frequencies of the system. This assumption is confirmed also by the dependence of the times of the appearance of the radiation pulse at the detector on the magnetic field (Fig. 5b, curve 1). At H = 3.3 kOe, the radiation pulse at the detector appears with a large delay, $\Delta t \sim 60$ nsec, in accordance with the fact that at H ≈ 3.3 kOe the radiated frequency is close to the critical frequency of the receiving waveguide. At H = 6.5 kOe we have $\omega \gg \omega_{cr}$ and $\Delta t \to 0$.

The same figure shows the dependence of the instant of the onset of the maximum radiation level on H (Fig. 5b, curve 2). It should be noted that the duration of the radiation pulse at the 1 kW level is constant and coincides with the duration of the collector current pulse (~35 nsec). On the other hand, as the magnetic field is varied the maximum radiation level is observed at different delays relative to the start of the radiation pulse. This means that the maximum generation occurs at different instants of the voltage pulse at the diode. At certain values of H, 4.1, 4.8, 5.3, and 5.8 kOe (always at the minima of curve 1 of Fig. 5a), two radiation power maxima are observed—at the start and at the end of the voltage pulse. The course of curve 2 of Fig. 5b is explained as follows: The voltage pulse on the diode has a fast rise time, ~10 nsec, and then two descending sections, with $\Delta t_1 \sim 20$ nsec (W = 380—350 keV) and $\Delta t_2 \sim 10$ nsec (W = 350—250 keV) (see Fig. 2). Thus, at H equal to 4.1, 4.8, 5.3, and 5.8 kOe the condition $\omega_{He}/\gamma = \omega_\alpha$ is satisfied for two resonant frequencies at the start of the pulse at large γ and at the end for small γ. With increasing magnetic field intensity, the radiation maximum shifts towards the start of the pulse, since γ must decrease when H is increased. Thus, an analysis of the curves of Fig. 5b confirms the assumption that the radiation frequency is connected with the electron energy, namely $\omega \approx \omega_{He}/\gamma$, and that the peaks on curve 1 of Fig. 5a correspond to the conditions $\omega_{He}/\gamma = \omega_\alpha$.

We consider now the analogous dependences of the short-wave radiation power for the case when an electron beam propagates in a plasma of density $n_p \approx (2-3) \times 10^{12}$ cm^{-3}. Curve 1 of Fig. 6a is a plot of the maximum power in the radiation pulse against the magnetic field intensity. It must be noted first of all that the maximum radiation level in the plasma exceeds the radiation power in vacuum by almost two orders of magnitude (the current in the plasma exceeds the maximum vacuum current by 1.5 times) and that the maximum of the radiation power in the plasma shifts towards larger values of the magnetic field. The radiation passing through the 3-cm waveguide channel starts to be registered at a magnetic field intensity H = 4.1 kOe (Fig. 6a, curve 1), and the radiation passing through the band filter starts to be registered at $H \approx 4.8$ kOe (Fig. 6a, curve 2). These values of the magnetic field exceed the corresponding values for vacuum. It follows therefore that a lower frequency $\omega = \omega_{He}/k$, where k = 1.7 is radiated in a plasma in a given field than in vacuum. At $n_p = (2-3) \times 10^{12}\ cm^{-3}$ the space charge of the beam is cancelled out (see Fig. 4) and $\gamma = \gamma_0 = 1.7$ for W = 350 keV. Thus, in a plasma the radiation frequency is equal to $\omega \approx \omega_{He}/\gamma_0$. A comparison of the calculated characteristic of the filter (curve 3) with the experimental one (curve 2) on Fig. 6a shows that in this case the radiation spectrum consists not of one line, but has a certain width.

Besides the radiation at the frequency $\omega = \omega_{He}/\omega_0$, a weak higher-frequency radiation (crosses on Fig. 6a) is observed in a plasma in the magnetic-field range 3 kOe $< H <$ 5.6 kOe. These two radiations can be separated because of the difference in the time of passage of pulses with different carrier frequencies through the receiving channel. Figure 6b (curves 1a and 2) shows the dependence of the time of appearance of the radiation pulse on the value of the magnetic field. At $H \approx 4.5$ kOe there are observed on the oscilloscope sweep two pulses in succession. One radiation pulse is delayed by $\Delta t \sim 50$ nsec, in accordance with the fact that at $H \approx 4.5$ kOe the frequency is $\omega_{He}/\gamma_0 \approx \omega_{cr}$. At the same value of the field H, the second radiation pulse is delayed by $\Delta t \sim 5$ nsec and when the magnetic field is varied the time of its appearance does not change (see Fig. 6b, curve 2). This means that the radiation frequency exceeds ω_{He}/γ_0. Curve 3 of Fig. 6b is a plot of the instant of appearance of the maximum of the radiation at the frequency ω_{He}/γ_0 on the field H. In contrast to the vacuum, in a plasma the maximum radiation level with varying H is reached after a constant time $\sim$10—15 nsec. This agrees with the fact that in the plasma, on curve 1 of Fig. 6a, there are no humps, as is the case in vacuum on curve 1 of Fig. 5a.

5. DISCUSSION OF RESULTS

It was shown experimentally that upon injection of a relativistic electron beam with large transverse velocity scatter in a direction perpendicular to the beam axis, radiation with frequency $\omega = \omega_{He}/\gamma$ is registered both in vacuum and in a plasma, with $\gamma = \gamma_0$ in a plasma and $\gamma < \gamma_0$ in vacuum. In addition, a weaker radiation was registered in the plasma, at frequencies $\omega > \omega_{He}/\gamma_0$, and long wave radiation (f $\sim$ 1.5 GHz) is registered in the case of a small angle scatter of the electrons. It is very important to note that under conditions when the intensity of the radiation at the frequency $\omega = \omega_{He}/\gamma$ is maximal, other forms of oscillations are not registered (see Fig. 3 and Fig. 6). The long-wave radiation and the radiation at the frequencies $\omega = \omega_{He}/\gamma_0$ have apparently a pure plasma character. The nature of the plasma radiation will not be discussed here, since it calls for further experimental study.

As to the short-wave radiation at the frequency $\omega \approx \omega_{He}/\gamma$, all the experimental results indicate that this is cyclotron radiation of relativistic oscillators (electron beam with large transverse velocity scatter) in a smooth metallic waveguide.[10] This is confirmed by measurements of the radiation frequency, by the dependence of the radiation intensity on the transverse energy of the electrons, and by the resonant character of the radiation power as a function of the magnetic field. These resonances, in the case of vacuum, should satisfy the condition

$$\omega_{He}/\gamma=\mu_s c/R, \tag{1}$$

where R = 7.5 cm is the waveguide radius, and μ_s are the roots of the Bessel function $J_1(\mu_s) = 0$. The radiation peak for H = 4.3 kOe at f = 8.4 kHz (Fig. 5a) corresponds to $\mu = 13.2 \approx \mu_4 = 13.3$. Then the resonance for $\mu_3 = 10.3$ should be observed at H = 3.3 kOe, which does not contradict the experimental results. Resonance for $\mu_5 = 16.5$ should be observed at H = 5.3 kOe, whereas in experiment two maxima are observed, at H = 5 and 5.5 kOe. Thus, there is no exact agreement between the experimental data and formula (1). This may be due to the variation of γ over the beam cross section.

As already noted above, the value $\gamma = 1.44$ in the expression $\omega = \omega_{He}/\gamma$, which differs from $\gamma_0 \approx 1.7$ at the entry of the beam into the waveguide, is due to the deceleration of the beam by the electron space charge as the beam is injected in vacuum. If the beam is injected in a plasma, then it is known[11] that at $\omega_p > c/r_0$, where $r_0 = 1.5$ cm is the beam radius, an appreciable neutralization of its charge takes place. Under our conditions this neutralization should set in at plasma densities $n_p > 2 \times 10^{11}\ cm^{-3}$, which agrees with the experimental data given in Fig. 4.

Starting from these considerations, the experiments on the radiation produced when an electron beam is injected in a plasma were carried out at $n_p \approx (2-3) \times 10^{12}\ cm^{-3}$, when almost complete neutralization of the beam charge set in. Under these conditions there is no deceleration of the electrons, and the frequency of the cyclotron radiation, as expected, is $\omega \approx \omega_{He}/\gamma_0$. If the plasma density satisfies in this case the inequality

$$\omega_p^2 \leqslant \omega^2(\gamma_0^2-1)=\omega_{He}^2(\gamma_0^2-1)/\gamma_0^2,$$

which is satisfied at H = 4.8 up to plasma densities $n_p \lesssim 2 \times 10^{12}\ cm^{-3}$, then the plasma only neutralizes the charge of the beam and has practically no effect on the resonance conditions:

$$\omega_{He}/\gamma_0=\mu_s c/R. \tag{2}$$

This corresponds to the experimental fact that the maximum radiation power, both in vacuum and in plasma, is observed at approximately the same frequency f $\sim$ 9 GHz. At larger densities n_p, on the other hand, the field of the cyclotron wave excited by the beam is screened by the plasma, and the depth of penetration of the field in the plasma is $\lambda \approx c/\omega_p$. As a result the efficiency of the interaction between the beam immersed in the plasma and the wave decreases, and the radiation power decreases sharply in full agreement with experiment (see curve 1 of Fig. 3).

We note, finally, that in a plasma, unlike in a vacuum, only one resonance is observed (see Fig. 5a, curve 1). This may be due to the small range of variation of the magnetic field. Indeed, if at H = 5.4 kOe the frequency f = 9 GHz corresponds to $\mu = 14 \approx \mu_4 = 13.3$, then the resonance should be observed at $H \approx 4.1$ kOe for $\mu_3 = 10.3$ and at $H \approx 6.7$ kOe for $\mu_5 = 16.5$. No radiation can be registered at H = 4.1 kOe, since the radiation frequency is lower than the critical frequency of the receiving waveguide, while the value H = 6.7 kOe is outside the limit of the investigated magnetic-field radiation.

The radiation power in the plasma at a beam current 1.5 kA (limiting current of the diode) exceeds by almost two orders of magnitude the radiation in vacuum at a current of 1 kA (limiting vacuum current in the system). This result, from our point of view, is most important and is attributable to the effect of charge neutralization of the electron beam in the plasma, as a result of which the beam becomes uniform in energy in the entire cross section, and all the electrons participate in the excitation of the cyclotron wave, being at resonance (2) with it. In vacuum at the same currents, close to the limiting vacuum current in the system, the beam becomes not uniform in energy under the influence of the electron space charge, the resonance (1) is satisfied for only a small part of the electrons, and consequently the beam-utilization efficiency and the power of the cyclotron radiation are low. All the foregoing indicates that an appreciable increase of the generation power at the cyclotron radiation is possible [10] on going to neutralized plasma-beam systems with superlimiting current of the relativistic electron beam.

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