Relativistic plasma microwave oscillator

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A description is given of the first experiments on a prototype of a relativistic plasma microwave oscillator and a theoretical analysis of the experimental results given. Measurements are reported of the dependences of the microwave radiation parameters (wavelength, field structure, and power) on the parameters of a relativistic beam and a plasma, and the conditions for optimal generation of centimeter wavelengths (oscillator efficiency of 20% with an output radiation power of ≈ 100 MW) are found. The experimental results agree with theoretical predictions deduced in a model postulating an infinitely strong magnetic field.

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1. INTRODUCTION

The possibility of generation of electromagnetic waves was essentially predicted in Refs. 1 and 2 where a discovery of the two-stream instability was reported. Immediately afterward the first experimental investigations aimed at constructing plasma oscillators were started. Two features accounted mainly for the interest in such oscillators. On the one hand, it seemed that it would be relatively easy to tune the emission frequency of such oscillators by altering the plasma density and, on the other, the effect of neutralization of the charge and beam current by the plasma itself should make it possible to use high-current electron beams and to attain very high absolute output powers.

Experimental investigations of the phenomenon of the two-stream instability with the aid of unmodulated nonrelativistic beams did not, however, result in construction of plasma amplifiers and oscillators generating coherent electromagnetic radiation.

On the other hand, it was found that when a beam was modulated by an external electromagnetic field, the spectrum of the excited oscillations became much narrower and amplification of the field at the modulation frequency took place.[3] The possibility of excitation of regular oscillations by an electron beam in a plasma of relatively low density near the critical value $n_{p\cdot\mathrm{cr}}$, when $\omega_p^2 > \omega_{p\cdot\mathrm{cr}}^2 = u^2\gamma^2/S_p$, [$\omega_p$ is the plasma frequency, S_p if the plasma cross section, u is the beam electron velocity, and $\gamma = (1 - u^2/c^2)^{-1/2}$], was pointed out in Ref. 4. The beam electron velocity was also found to be important because a nonrelativistic electron beam excites irregular oscillations in a plasma which are characterized by a low phase velocity $v_{\mathrm{ph}} \approx u \ll c$, and which can be described with a high degree of accuracy as potential; such oscillations are emitted weakly from a plasma. The first experiments involving the use of a high-current relativistic beam[5] confirm the possibility of excitation in a plasma of intense regular oscillations emitted as radiation and, consequently, the possibility of constructing a single-mode plasma microwave oscillator based on the use of a relativistic electron beam[6] (see also Refs. 7 and 8). A general theory of a plasma oscillator is now basically complete.[9,10] Some specific aspects have not yet been studied and these include the selection of the optimal plasma and beam parameters, matching of a plasma resonator to the emitting device, etc. It is natural to analyze these aspects by considering a specific plasma microwave oscillator, which will be done below in discussing the experimental results on a prototype of such an oscillator. Examples of specific plasma oscillators similar to that investigated in our experiments are considered in Ref. 11, from where the main theoretical results of the present paper are taken.

2. EXPERIMENTAL METHOD

Our experiments were carried out on a high-current relativistic-electron accelerator Terek-II with the following beam parameters: the electron energy was 480 keV, the injection current was 0.9 kA, and the pulse duration was 45 nsec. The electron beam was injected to a cylindrical resonator which was filled earlier with a plasma. The apparatus used is shown schematically in Fig. 1. A diode consisted of a graphite cylindrical cathode 1, which was 14 mm in diameter, and a graphite anode 2, with an aperture 11 mm in diam-

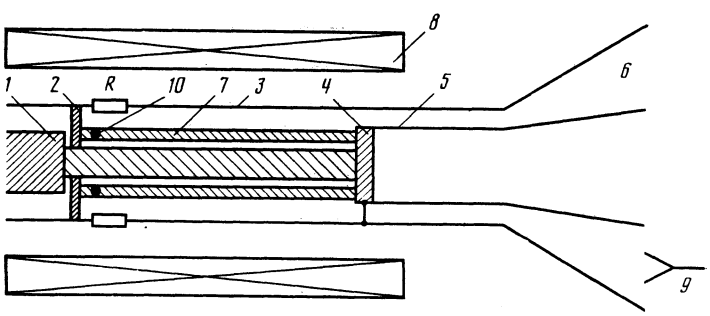

FIG. 1. Schematic diagram of the apparatus: 1) graphite cathode; 2) graphite anode; 3) cylindrical waveguide; 4) graphite collector; 5) central conductor of coaxial waveguide; 6) exit coaxial horn; 7) tubular plasma; 8) solenoid; 9) receiving horn; 10) annular cathode of plasma source.

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eter. The anode–cathode distance was 6 mm. The major proportion of the experiments were carried out with the anode aperture open, but in some cases this aperture was covered by a graphite foil which was either 90 or 34 μ thick; this resulted in the scattering of the beam electrons through angles of $(\bar{\theta}^2)^{1/2} = 21°$ and 12°, respectively. A plasma resonator was a circular waveguide 3, 29 mm in diameter and up to 30 cm long, which was closed by a graphite collector 4. The collector 4 acted also as the termination of a central conductor of an output coaxial waveguide 5, which ended with a coaxial radiating horn 6. The diameter of the collector and the central conductor of the coaxial waveguide was 18 mm.

Plasma was generated by an additional tubular electron beam ($\mathscr{E} = 1.5$ keV, $I \lesssim 10$ A, beam diameter 14 mm, beam thickness 0.6 mm), which was switched on for 20 μsec before the relativistic electron beam accelerator and which, by ionizing krypton at a pressure of 10^{-3} Torr, created (by the time of injection of the electron beam) a tubular plasma 7 with an average diameter 14 mm and a concentration up to 2×10^{14} cm^{-3}. The relativistic electron beam and the plasma were focused by a strong homogeneous quasistatic (with a period of 4 msec) magnetic field up to 3.0 T intensity created by a solenoid 8. The microwave power measurements were made with a four-channel recording system. Each channel represented a receiving horn 9 (which was the open end of a waveguide of 23×10 mm dimensions), a terminating waveguide, and a detector calibrated in the power range from 20 to 350 kW. The microwave radiation spectrum was determined using terminating waveguides included in the microwave receiving channels. It was thus possible to record three points of the spectral density of the radiation in one shot. The terminating waveguides used in our experiments had critical wavelengths $\lambda_{cr} = 4.6$, 3.8, 3.2, 2.6, 2.2, and 1.8 cm, corresponding to the emission bands 4.2 ± 0.4, 3.5 ± 0.3, 2.9 ± 0.3, 2.4 ± 0.2, and 2 ± 0.2 cm, i.e., the width of each band was 20%.

The beam current was measured with a shunt R placed in a cut in the wall of the waveguide 3. The shunt resistance was 0.2 Ω. When the electron beam was injected into vacuum the shunt measured the beam current in the resonator, and when the beam was injected into a plasma, it measured the total beam and plasma current.

The plasma density profile was not determined in the present series of experiments. However, earlier experiments carried out using a similar system indicated that the plasma thickness δ at the 0.5 level of the maximum density amounted to one or two thicknesses of the tubular beam creating the plasma, and the density of the background plasma was at least two orders of magnitude less than the maximum density. In the present paper we assumed that $\delta = 0.6$ mm. In the plasma density range $n_p > 2.10^{12}$ cm^{-3} an estimate of n_p was obtained from the reverse current generated by the relativistic electron beam in the plasma at the moment of injection. (It should be pointed out that this method actually gave the product $n_p\delta$.)

3. EXPERIMENTAL RESULTS

All the experiments were carried out using an injected beam current $I_b = 0.9$ kA, which was less than the maximum vacuum value $I_0 = 2.4$ kA. In this case the compensation of the space charge of the beam by the plasma did not increase the beam current, i.e., this current, i.e., this current was independent of the plasma density.

Two types of experiments were carried out: first, we determined the conditions under which generation of radiation took place (construction of a system of coupling radiation out of the resonator, range of magnetic field and plasma density values, initial angular scatter of the beam electrons, resonator length) and, second, we measured the parameters of microwave radiation (frequency spectrum, nature of the mode, absolute values of the power). In the former case the microwave radiation measurements were carried out with a wide-band ($\lambda \leqslant 4.6$ cm) single-channel recording system and in the second case the four-channel mentioned above was normally used.

3.1. CONDITIONS FOR GENERATION OF MICROWAVE RADIATION

a) Coupling-out system

In coupling out of microwave power along the axis of the plasma resonator the exit end should satisfy two requirements: it should limit the length of the region of interaction between the beam and plasma, i.e., it should cover the waveguide cross section, and at the same time it should transmit as much as possible of microwave radiation because high-power high-current oscillators can only have low Q factors. In the simplest case when the radiation was coupled out with the aid of a cylindrical waveguide and the interaction length was limited by an abrupt azimuthally symmetric deflection of the plasma to the waveguide walls by the diverging lines of force of the magnetic field, no radiation was recorded. The radiation was observed in the exit horn (when the waveguide was cylindrical) either in the case of an azimuthally asymmetric deflection of the plasma to the waveguide walls (achieved by rotating the lines of force of the magnetic field with a transverse coil) or when a collector (a graphite disk 18 mm in diameter) was used to cover the plasma cross section leaving an annular gap (in this case amounting to 5.5 mm) between the collector and the waveguide wall. The last two cases differed from the first in that the gap between the plasma and its resonator wall was either partly separated by the plasma from the exit waveguide or not separated at all. Moreover, in the former case there was a plasma-filled zone in the exit waveguide where the conditions for electron cyclotron resonance were satisfied.

From the last two variants we selected the coupling-out system with the graphite collector. The exit waveguide was then coaxial and the diameter of the central cylinder was equal to the collector diameter. The coaxial waveguide considered as an electrodynamic system was closest to a plasma coaxial, so that the change in the structure of the field in the transformation of a plasma into a guided wave was then minimal. Our experiments showed that the wave structure at the aperture of a coaxial horn was simpler and more reproducible than in the case of a coupling-out system in the form of a circular waveguide. Therefore, all the subsequent experiments were carried out using the coaxial method for coupling out microwave power.

b) Range of magnetic fields

We established experimentally that the radiation power was practically independent of the magnetic field intensity H_0 in the range $1.5 \leqslant H_0 \leqslant 3$ T. In lower fields $1 < H_0 < 1.5$ T the power decreased and this was clearly due to a reduction in the diode voltage, and, therefore, in the beam current. Breakdown of the diode gap began in fields $H_0 < 1$ T. All the experimental results given below were obtained in a field of $H_0 = 2.25$ T.

c) Range of plasma densities

The plasma density was deduced from the degree of magnetic neutralization η of the beam current. When the relativistic electron beam was injected into the plasma waveguide, a current $I_p = -\eta I_b$, was generated in the plasma and this current was opposed to the beam current; the value of η depended on the plasma density and on the beam and plasma geometries, as well as on time if dissipation took place. In the simplest case (when there was no dissipation of the reverse plasma current and a cylindrical beam of radius r_b was injected into a tubular plasma of radius r_p and thickness δ, where $\delta \ll r_b < r_p$), the degree of neutralization was[12]

$$\eta=\omega_p^2 r_p \delta \ln (R_0/r_p) [c^2+\omega_p^2 r_p \delta \ln (R_0/r_p)]^{-1}, \qquad (1)$$

where c is the velocity of light in vacuum and R_0 is the waveguide radius. The expression (1) is valid if $c/\omega_p > \delta$ and $\ln (R_0/r_p) \gtrsim 1$. It was also shown in Ref. 12 that at low beam currents ($I_b \lesssim 1$ kA) the decrease in the reverse current was due to insufficient emission of electrons from the collector end of the drift camera, which suppressed the reverse current. This occurred after a time $t^* \approx 2L/u$, where L was the distance from the point of measurement to the collector; in our experiments it was found that $t^* \approx 2.3$ nsec. It was also shown in Refs. 12 and 13 that at times $t < t^*$ the dissipation of the reverse current was weak and the degree of neutralization η was given by an expression of the (1) type. We determined the plasma density by measuring the total current $I = I_p + I_b$ at a time $t = 2$ nsec and using the ratio I/I_b to calculate the product $\eta_p \delta$. Figure 2 shows the experimental points representing the dependence of the microwave radiation power emitted in the wavelength range $1.5 \leqslant \lambda \leqslant 4.6$ cm on the plasma density. In the same figure an arrow identifies the plasma density $n_p^* = 2.8 \times 10^{13}$ cm^{-3} at which the maximum phase velocity of the wave v_{ph} in the plasma waveguide was equal to the beam velocity u. The value of n_p^* can be found as follows. If a slowing-down structure is a thin-walled plasma cylinder of thickness $\delta \ll r_p$, the phase velocity of long-wavelength oscillations ($\lambda \gtrsim R_0$) depends on the product $\eta_p \delta$, and (for details see below) we then have $\beta_{ph} = v_{ph}/c = \eta^{1/2}$. It follows that the Cherenkov condition for oscillation is related to the degree of current neutralization $\eta > \eta^*$. For the experiments in question we have $\eta^* = 0.73$. The arrow in the graph identifies the experimental value of $\eta^* = 0.73$, i.e., it corresponds to $n_p^* = 2.8 \times 10^{13}$ cm^{-3} if $\delta = 0.6$ mm.

We can see from Fig. 2 that oscillations were observed in the plasma density range $n_p \gtrsim 10^{13}$ cm^{-3} and the oscillation "zone" extended at least to plasma densities $n_p = 2 \times 10^{14}$ cm^{-3}.

d) Initial angular scatter of beam electrons

Figure 3 shows the dependence of the radiation power on the thickness of a graphite anode foil obtained when the beam current was kept constant. Each point in Fig. 3 was determined for a specific foil thickness and a particular plasma density in the range from 10^{13} to 10^{14} cm^{-3}. The scatter of the microwave radiation power was primarily due to the scatter of the plasma densities from one shot to another. Clearly, the microwave radiation power depended strongly on the foil thickness, decreasing almost twentyfold for a graphite foil 90 μ thick compared with the case when there was no foil. This was an additional confirmation that radi-

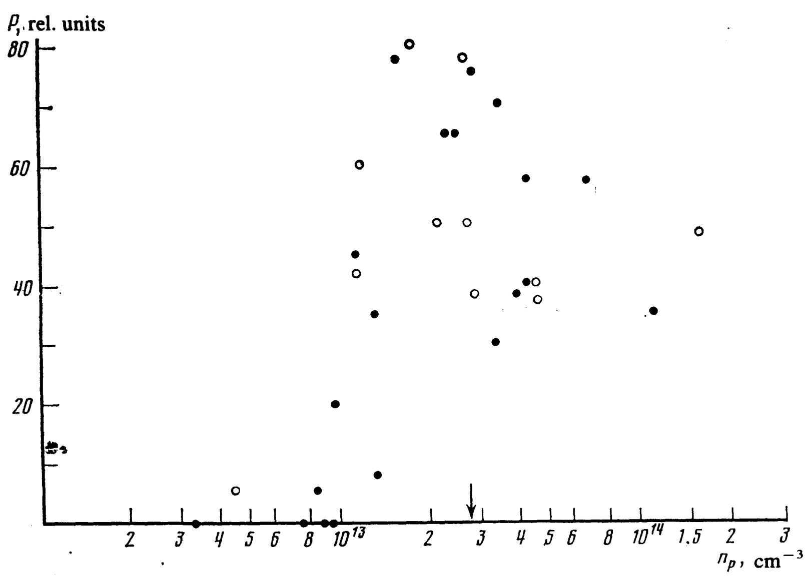

FIG. 2. Dependence of microwave radiation power on the plasma density.

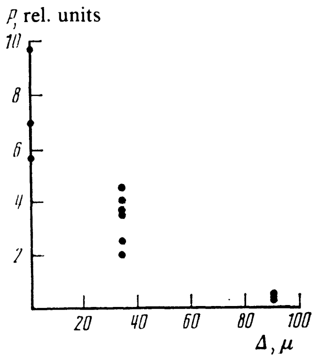

FIG. 3. Dependence of microwave radiation power on the thickness of a graphite anode foil.

ation was emitted as a result of Cherenkov buildup of plasma oscillations for which the growth increment was maximal when the scatter of the longitudinal velocities in the beam was minimal.[1)]

e) Dependence on the resonator length

In the oscillation regime there should be, in contrast to the amplification regime, a threshold interaction length L_{cr} beginning from which the radiation power should rise rapidly. In our experiments the resonator length was varied by moving the collector and changing correspondingly the length of the central conductor of the coaxial waveguide. The dependence of the microwave radiation power on the resonator length is plotted in Fig. 4. Each point represents one shot for specific plasma density in the range 10^{13}–2×10^{14} cm^{-3}. It is clear from Fig. 4 that the radiation power rose steeply (by a factor of at least 100) when the resonator length was increased from 10 to 15 cm. Consequently, in resonators longer than 15 cm the system became an oscillator. The majority of our experimental results was obtained for a resonator length of 24 cm.

3.2. PARAMETERS OF MICROWAVE RADIATION

a) Emission spectrum

The emission spectrum was determined under the conditions of a "single-angle" beam (in the absence of the anode foil) when the generated microwave power was maximal.

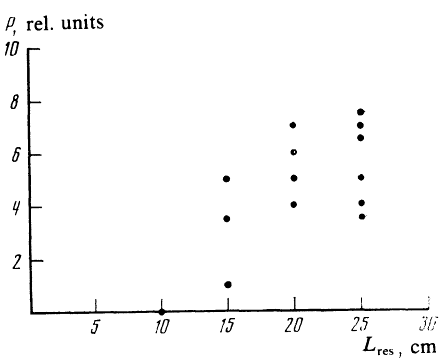

FIG. 4. Dependence of the microwave radiation power on the length of the plasma resonator.

Figure 5 shows oscillograms of the signals obtained from four detectors of microwave radiation. Each vertical column in the oscillograms was obtained in one shot from the accelerator and the shots *a*, *b*, *c*, and *d* differed in respect of the plasma density. Each horizontal row of the oscillograms corresponded to a specific terminating waveguide included in the microwave-signal-recording channel with the following values λ_{cr} (cm): 1) 4.6; 2) 3.8; 3) 3.2; 4) 2.6; 5) 2.2; 6) 1.8. All the oscillograms were obtained at the same sweep rate (the time scale is given in the oscillogram *a*6). The scale of the microwave radiation power in the receiving channel was that given in the oscillogram *a*1. In the interpretation of these measurements we would like to draw attention only to the great differences between the signals, for example those obtained in case *a* in channels 3 and 4. The slight difference between the signals, for example, in channels 1, 2, and 3 in case *a* is due to imperfections of the recording apparatus.

A comparison of the oscillograms 1, 2, 3, and 4 in the column *a* shows that the radiation generation in this shot was in the wavelength range $2.6\leqslant\lambda\leqslant3.2$ cm; in the case of the oscillograms 3, 4, 5, and 6 in the column *b* the range was 3, 4, 5, 6–$2.2\leqslant\lambda\leqslant2.6$ cm; for 3, 4, 5, 6–$1.8\leqslant\lambda\leqslant2.2$ cm for 3, 4, 5, and 6 in the column *c* it was 3, 4, 5, 6 –$\lambda\leqslant1.8$ cm; for 3, 4, 5, and 6 in the column *d* it was 3, 4, 5, 6–$\lambda\leqslant1.8$ cm. The oscillograms *a*, *b*, *c*, and *d* were selected so that the emission wavelngth decreased from *a* to *d*, and the width of the emission band for *a*, *b*, *c* was $\Delta\omega/\omega<0.2$, whereas for *d* it was $\Delta\omega/\omega>0.2$. The plasma densities (cm^{-3}) for the oscillograms in Fig. 5 were as follows: a) 2.2×10^{13}; b) 6×10^{13}; c) 4.5×10^{13}; d) 1.6×10^{14}. In the range of plasma densities from 10^{13} to 2×10^{14} cm^{-3} we did not observe a single-valued dependence of the emission wavelength on the plasma density, although there was a tendency for an increase in the emission frequency on increase in the plasma density. However, the emission frequency was always several times less than the Langmuir plasma frequency.

b) Wave structure in the exit horn

The ratio of the power densities of the azimuthal component of the electric field $P_\varphi\sim E_\varphi^2$ to the radial density $P_r\sim E_r^2$ for $r=(R_1+R_2)/2$, where R_1 and R_2 are the internal and external radii of the coaxial waveguide, depended on the wave mode. In particular, in the case of an exit horn with $R_1=3.7$ cm and $R_2=17.5$ cm this ratio assumed the values 0, 0.22, 0,43, 0.53, and 0.42 for the *TEM*, H_{11}, H_{21}, H_{31}, and H_{41} modes, respectively. Measurements indicated that the experimental value of the ratio P_φ/P_r varied from shot to shot ranging from less than 0.03 to 0.25.

The measured radial profiles of the power density *P* are plotted in Figs. 6c and 6d. For most shots the distribution was of the type shown in Fig. 6c. The measurements were carried out using four receiving horns (the dimensions of the waveguide ends were 23×10 mm. It is clear from Fig. 6c that P_r was maximal near central conductor of the coaxial horn R_1 and then fell on increase in *r* rising somewhat in the limit $r\to R_2$. The ratio $P_r(R_2)/P_r(R_1)$ for Fig. 6d was within the range 0.6–1.24 and it was 0.3–0.7 for Fig. 6c. The error in the determination of the power density was related to the preci-

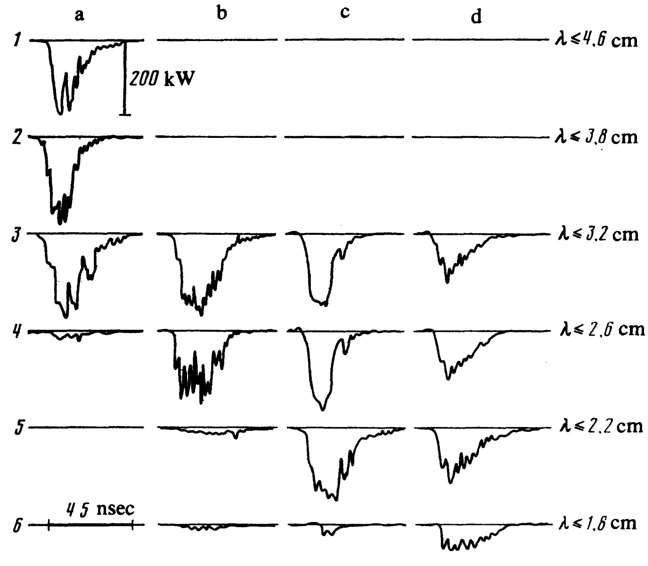

FIG. 5. Microwave emission spectra obtained for different plasma densities given in the text.

sion of the detector calibration, which was $\pm 20\%$. A calculation of the power densities P_r gave the following values for the ratio $P_r(R_2)/P_r(R_1)$: 0.044, 0.13, 1, 12.7, and 25 for the *TEM*, H_{11}, H_{21}, H_{31}, and H_{41} modes, respectively. Therefore, the measured ratio P_φ/P_r corresponded closest to the *TEM* and H_{11} modes, whereas the ratio $P_r(R_2)/P_r(R_1)$ corresponded to the H_{11} and H_{21} modes.

c) Absolute radiation power density

The total radiation power was found by measuring not only the radial but also the azimuthal distribution of the radiation power density P_φ. This gave the results given in Figs. 6a and 6b. The experimentally observed distributions were either uniform in respect of φ (Fig. 6b) or had one

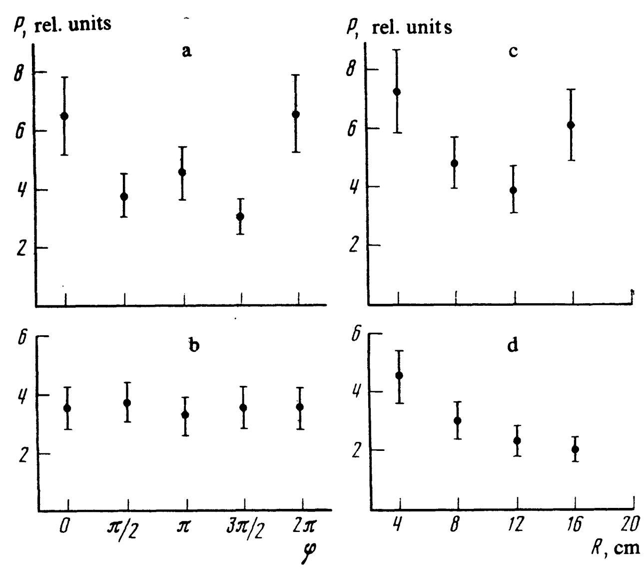

FIG. 6. Distributions of microwave radiation intensity in the exit horn: a), b) azimuthal; c), d) radial.

strong maximum (Fig. 6a). The total radiation power was found by numerical integration of the power density P_φ with a radial profile corresponding to Fig. 6c and a uniform azimuthal distribution (Fig. 6b). When the beam current was 0.9 kA and the electron density was 480 keV, the microwave radiation power (in the radial component) was 90 ± 20 MW, corresponding to an efficiency of $\approx 21\%$.

The azimuthal distribution of the density of the microwave radiation power shown in Figs. 6a and 6b corresponded qualitatively to the pattern of microwave breakdown in air. Breakdown occurred when the exit coaxial horn was reduced to $R_1 = 3.7$ cm and $R_2 = 4.2$ cm, i.e., when the microwave radiation power density reached ≈ 7 MW/cm^2. Breakdown between the waveguide walls was deduced by recording plasma radiation with a photographic camera. The breakdown patterns were either uniform along the azimuth or had one maximum, and the coordinate of this maximum varied from one shot to another.

4. THEORETICAL RESULTS AND ANALYSIS OF THE EXPERIMENTAL DATA

We shall account for the experimental data by invoking the results of a theoretical analysis of the oscillator problem for the specific geometry of our plasma oscillator on the assumption that the magnetic field H_0 is infinitely strong. We shall begin by writing down the dispersion relationship for an E-type mode (with nonzero components E_z, E_r, and B_φ), which is the only mode that can be excited by an electron beam in a plasma waveguide[11]:

$$\beta_{\rm ph}^2 = \frac{\omega^2}{k^2c^2} = \frac{\omega_p^2}{\omega_p^2 + [k_\perp^2 + k^2(1-\beta_\Phi^2)]c^2}, \quad k_\perp^2 = \left[\delta r_p \ln\frac{R_0}{r_p}\right]^{-1}. \qquad (2)$$

Here, k and $k_\perp$ are the longitudinal and transverse wave numbers of the oscillations, and the solution of Eq. (2) with the minimum value of $k_\perp$ corresponds to the dominant cable mode.

Equating the phase velocity $v_{\rm ph}$ to the beam electron velocity u, we find the frequency of the excited mode and the condition for its excitation:

$$\omega^2 = \omega_p^2 - k_\perp^2 u^2 \gamma^2. \qquad (3)$$

When the plasma density is increased, the first to be excited is the dominant cable mode. Near the minimum density we find that $\omega_p^2 = k_\perp^2 u^2 \gamma^2$, and the frequency of the excited mode is $\omega \ll \omega_p$. The excitation of the next radial mode E_{11} occurs at a higher plasma density not attained in our experiments. It should also be pointed out that the minimum plasma density above which the dominant cable mode is excited can be found from Eq. (3) and for our experimental conditions it is of the order of $n_{p\text{-min}} \approx 2.6 \times 10^{13}$ cm^{-3}. This value is in agreement with the experimental value given above.

The structure of the field of the dominant cable mode in the range of higher phase velocities when $v_{\rm ph} \approx c$ and $\delta \ll r_p$, has the form

$$E_s \propto -k^2 \gamma_{\rm ph}^{-2} \begin{cases} 1, & 0 < r < r_p \\ \ln(r/R_0)/\ln(r_p/R_0), & r_p < r < R_0 \end{cases}, \qquad (4a)$$

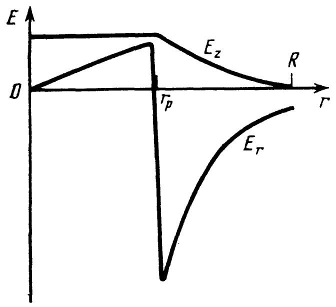

FIG. 7. Structure of the field of the dominant cable mode in a plasma waveguide.

$$E_r = B_\varphi \propto ik \begin{cases} k^2\gamma_{ph}^{-2}r/2, & 0<r<r_p \\ [r \ln (r_p/R_0)]^{-1} + o(k^2\gamma_{ph}^{-2}r), & r_p<r<R_0 \end{cases} \quad (4b)$$

where $\gamma_{ph} = (1-\beta_{ph}^2)^{-1/2}$, and it is shown in Fig. 7; here,

$$o(k^2\gamma_{ph}^{-2}r) = 1/2k^2\gamma_{ph}^{-2}r[\ln(r/R_0) - 1/2].$$

In this region the cable plasma mode is strongly nonpotential and practically the whole energy flux of the electromagnetic wave is concentrated in the outer (relative to the plasma) part of the waveguide[2)] and it is transformed efficiently into a *TEM* cable mode propagating in the emitting device (Fig. 1). Moreover, since the field E_z differs from zero in the beam region, this wave is readily excited by a relativistic electron beam. It should also be noted that the reflection coefficient of a fast cable mode from the emitting device is of the order of $\varkappa \approx 1/4\gamma_{ph}^2$ and for $\gamma_{ph} \approx \gamma$ under our experimental conditions it amounts to $\varkappa \approx 1/14 \ll 1$. A very different field structure is obtained for plasma waves at low plasma densities when the phase velocity of the waves is low compared with the velocity of light and the waves may be excited by a nonrelativistic beam. The component B_φ of these waves is $\sim uE_r/c \ll E_r$. Consequently, the electromagnetic energy flux is low and, moreover, the reflection coefficient of the emitting device is of the order of $\varkappa \approx 1 - 2\beta_{ph} \approx 1$, for these waves, so that the wave is essentially locked inside the plasma.

We can readily determine also the gain of a cable plasma mode and of the minimum relativistic electron beam current needed to excite an oscillator generating this mode:

$$I_{st} = 1.75\times 10^{-2} S_p \frac{\omega_p^2}{c^2}\frac{u^4}{c^4}\gamma^5(\ln 12\gamma^2)^3\left(\frac{\lambda}{L}\right)^3 [\text{kA}],$$
$$S_p = 2\pi r_p \delta. \quad (5)$$

The minimum resonator length found from this expression for a beam current of $I_b = 0.9$ kA, a plasma density $n_p = 4\times 10^{13}$ cm^{-3}, and a frequency $\omega = 10^{11}$ sec^{-1} (i.e., for $\lambda \approx 2$ cm) is $L_{min} \approx 15$ cm, in good agreement with the experimental value.

An important characteristic of an oscillator is its efficiency which, as shown in Ref. 10, depends mainly on the parameter $\mu = (\gamma S_b n_b / S_p n_p)^{1/3}$, where S_b is the cross-sectional area of the electron beam. The maximum efficiency is obtained for $\mu = 0.6$ (which in our experiments corresponds to a beam current of $I_b \approx 1.5$ kA) and it amounts to $\approx 30\%$. Such values again are not in conflict with the experimental results.

We shall conclude by noting that the above results of a theoretical analysis are valid in the limit of a sufficiently strong magnetic field when the following inequality is obeyed:

$$\alpha = \omega_p^2 \delta r_p / c\omega_H R_0 \ll 1, \quad \omega_H = eB_0/mc. \quad (6)$$

This small parameter determines the smallness of the ratio ratio E_φ/E_r, i.e., the smallness of an admixture of an *H*-mode in a plasma microwave oscillator. For our experimental conditions this small parameter is $\alpha \approx 0.065$–0.65 and, consequently, we have $P_\varphi/P_r \approx 0.004$–$0.4$, in good agreeement with the experimental values.

We can thus see that all the experimental data can be explained satisfactorily by a theory of a plasma microwave oscillator emitting the dominant cable mode excited by a rectilinear relativistic electron beam in a strong longitudinal magnetic field. It therefore follows that it should be possible to construct other types of plasma oscillators and to increase the output power, as well as the generate shorter wavelengths.

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[1)]The strong dependence of the nature of excitation of oscillations on the scatter of the beam electron velocities was pointed out back in Ref. 5.

[2)]The ratio of the energy fluxes inside (P_1) and outside (P_2) the plasma is $P_1/P_2 = (\pi r_p/\gamma\lambda)^4 \ln(R_0/r_p)$, which in our case does not exceed a few percent.

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