Microwave radiation from a strong-current relativistic beam of microsecond duration interacting with a spatially-periodic magnetic field

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We present the results of investigations of microwave radiation from a strong-current relativistic beam of microsecond duration, 3 kA current, 230 keV energy, and 1.2×10^{-6} sec duration. It is shown that microwave radiation of several megawatt power is observed when an annular beam of these parameters is injected into a spatially-periodic magnetic field.

The use of strong-current relativistic beams has made it possible to obtain microwave radiation with a power level 10^9 W at a duration 5×10^{-8} sec.[1] Sometimes, however, it is necessary to generate microwaves of 10^8-10^9 W power and pulse duration $10^{-6}-10^{-5}$ sec. The generation of microwave radiation with these parameters entails a number of difficulties. One of them is the lack of injectors capable of shaping strong-current relativistic beams of large duration and suitable for production of generation, even though some progress was made recently in this direction.[2,3] Another difficulty consists in the following: At power levels 10^8-10^9 W, the microwave field intensity reaches 10^6 V/cm, and the duration of the radiation pulse is sufficient for cascade development. Under these conditions a high-frequency breakdown develops in the generation region owing to the gas released from the walls and ionization of this gas by the electrons produced by field emission in the microwave fields even under high-vacuum conditions. It is this breakdown, properly speaking, which limits the generation power level. This is precisely the reason why it is necessary to go over, at high levels of high-frequency power and at large durations, to generators in which HF breakdown can be avoided at large power fluxes. We investigate in this paper one such type of generator,[1,4] based on the interaction of a large-duration strong-current spatially-modulated relativistic beam with fast waves in a round waveguide.

The generation was attained with the setup illustrated in Fig. 1. The injector was a cold-cathode gun of the magnetron type. The choice of this type of gun was necessitated by the following considerations: The relativistic-beam pulse duration is determined by the time of short-circuiting of the anode-cathode gap by the plasma coming from the cathode and anode flares. The short-circuiting time, and consequently the duration of the relativistic beam, can be increased by decreasing the number of electrons reaching the anode, and by lowering the cathode-plasma propagation velocity. These two conditions are simultaneously satisfied most fully in a gun of the magnetron type. In our installation we used a magnetron-type gun fed from a Marx generator that developed a voltage pulse of amplitude up to 300 kV and of duration 1.2×10^{-6} sec; the gun was placed in a magnetic field whose intensity could reach 18 kOe. The electric field intensity in the gun reached 150 kV/cm. The application of an ex-

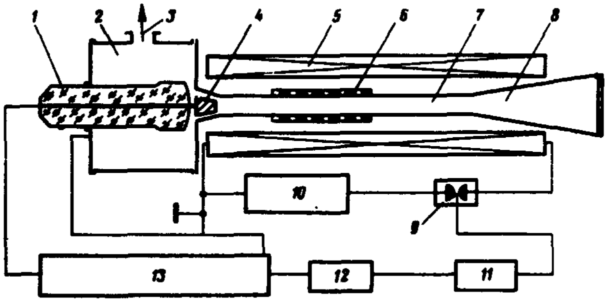

FIG. 1. Block diagram of setup: 1—insulator, 2—gun chamber, 3—vacuum duct, 4—gun cathode, 5—solenoid, 6—periodic structure, 7—waveguide, 8—horn, 9—discharge gap, 10—capacitor bank, 12—adjustable delay, 13—voltage-pulse generator.

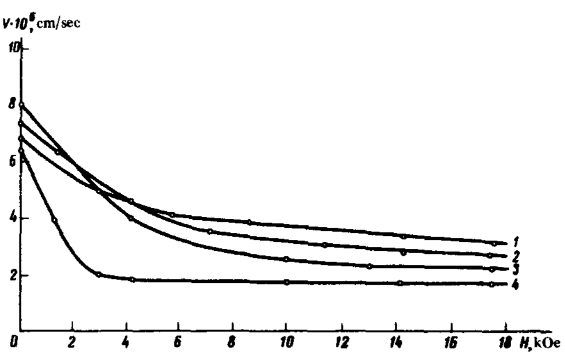

FIG. 2. Variation of the rate of shorting of the diode with the field H: 1) cathode angle $\alpha = 18°$, cathode length $L = 2$ cm, gap $d = 2$ cm; 2) $\alpha = 18°$, $L = 8$ cm, $d = 1$ cm; 3) $\alpha = 54°$, $L = 5$ cm, $d = 2$ cm,: 4) $\alpha = 18°$, $L = 2$ cm, $d = 1.2$ cm).

ternal field and the choice of its configuration and intensity at the cathode had made it possible to decrease appreciably the velocity of the plasma short-circuiting the diode. A plot illustrating the effectiveness of the magnetic insulation is shown in Fig. 2. We see that application of an external longitudinal magnetic field greatly decreases the plasma velocity down to $(1.5-2) \times 10^6$ cm/sec. The plasma velocity was calculated from the known anode-cathode distance and from the measured short-circuiting time. The short-circuiting time was determined experimentally from the duration of the hard x-ray pulse from the anode region, picked off an ELU-FT transducer, with a time resolution 10^{-9} sec.

The described gun shaped an annular electron beam with a ring width 2–3 mm and a current 3 kA. The gun current was measured with shunts and with a Faraday cup, on the output of which a Rogowski loop was placed. The particle energy was calculated from the bremsstrahlung x-rays produced when the beam was stopped by the target, and reached 230 keV at a gun-probe voltage 250 kV. The shaped annular beam with outside diameter 37–38 mm was injected into a round waveguide of 40 mm diameter placed in a spatially-periodic magnetic field whose variation along the waveguide axis is given by

$$H(z) = H_0[1 + a \sin(2\pi/L)z], \tag{1}$$

where L is the magnetic-field modulation period. The modulation was produced by a structure consisting of alternating iron and aluminum rings. In our experiments the length of the modulated section was 24 cm, the modulation depth was 5–6%. This was followed by a drift region in the homogeneous magnetic field.

Generation was observed upon interaction of the cyclotron waves and the waves of the space charge of the beam modulated in this manner with the fast H_{01} and E_{11} waves in the round waveguide. The interaction of the waves propagating in the spatially-modulated beam with the waveguide modes is possible if the following relations are satisfied[1]:

$$\begin{aligned} (k + K)V_{\parallel} - \Omega_c &= (k^2c^2 + \omega_{\text{cr}}^2)^{1/2}, \\ (k + K)V_{\parallel} - \omega_b^* &= (k^2c^2 + \omega_{\text{cr}}^2)^{1/2}. \end{aligned} \tag{2}$$

Here Ω_c and ω_b^* are the electron-cyclotron and the relative plasma frequency of the beam, respectively. ω_{cr} is the waveguide cutoff frequency, V_{11} is the longitudinal component of the electron velocity, and $K = 2\pi/L$. Generation is observed in this case at the frequency

$$\omega = [\Omega_c/(1 - \beta^2)][1 \mp \beta\sqrt{1 - (1 - \beta^2)(\omega_{\text{cr}}^2/\Omega_c^2)}]. \tag{3}$$

The maximum generation power was obtained at λ ~ 3 cm and $L = 3$ cm and at a magnetic field intensity 6 kOe, and reached several megawatts at a pulse duration 0.6–0.7 μsec at half-height. The power was extracted with an evacuated horn having an exit cross section area 79 cm². Figure 3 shows oscillograms of the generation pulse, of the beam current, and of the x radiation from the anode region of the gun. The microwave generation power was measured with a waveguide calorimetric pickup having a time constant not worse than 5×10^{-8} sec, the radiation to the input of which was applied after calibrated attenuation. From the measured energy and radiation pulse duration (with allowance for the attenuation) we calculated the generation power, assuming the number of generated modes to be small.

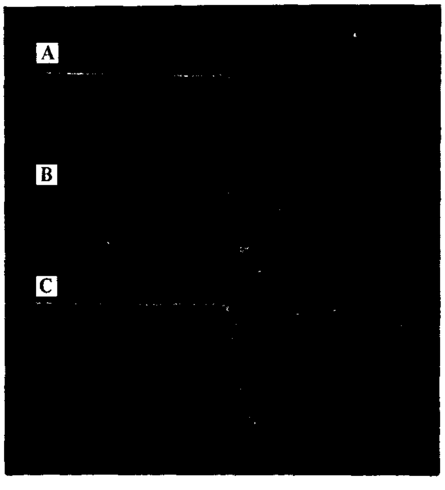

FIG. 3. Oscillograms of microwave generation pulses, of the current beam, and of the x-ray emission.

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