Generation of High Peak and High Average Power Subnanosecond-Width 10-GHz Microwave Pulses

V.V. Rostov, A.A. Eltchaninov, S.D. Korovin, G.A. Mesyats*
S.N. Rukin*, V.G. Shpak*, and M.I. Yalandin*

Institute of High-Current Electronics SB RAS,
4, Academichesky Av., Tomsk, 634055, Russia, 3822-491-641,
3822-492-410, rostov@lfe.hcei.tsc.ru
** Institute of Electrophysics, UB RAS,*
106, Amundsen Street, Ekaterinburg, 620016, Russia

Abstract – Excitation of 10-GHz gigawatt-range radiation pulses ~ 1 ns long in relativistic backward-wave oscillators with an elongated periodic slow-wave system has been studied. Accelerators based on a compact pulsed-periodic high-voltage generator type SINUS-160 and a generator employing an inductive energy storage, a semiconductor opening switch and a peaking hydrogen-filled spark gap have been developed for formation of high-current electron beams (particles having an energy of 350–600 keV, a current of 3–5 kA and a length of 4–7 ns) at repetition frequencies of (100–700) p.p.s. in bursts 1 s long or more. Optimization of the regime of interaction between fields and particles provided an average power of microwave radiation in the burst mode of up to 2.5 kW at the focusing magnetic field (~ 0.6 T) below the cyclotron resonance region.

1. Introduction

Experiments concerned with the study of non-stationary regimes of HPM generation in relativistic microwave generators of the backward-wave oscillator (BWO) type [1–6] confirmed theoretical results [5, 6], according to which a short (on the interaction length scale) forward radiation peak can be excited if the electron beam current is much larger than the starting current. Moreover, similarly to calculations, it was shown that the power level is not limited by the power of the electron flow. The length of a microwave pulse envelope at FWHM in the X-band is about 1 ns, i.e. nearly 10 periods of the RF field. Earlier we studied generation regimes of single gigawatt-range microwave pulses in the 10-GHz band [4, 5]. The "electron beam – microwave radiation" power conversion factor $K \approx 1.4$–1.8 was achieved for pulses up to 3 GW at high values of the guiding magnetic field ($B_z \approx 2.5$ T, which was larger than the backward-wave cyclotron resonance). An analogous regime was realized [4] for a compact Ka-band generator ($B_z \approx 6.5$ T and $K \approx 1.5$). A hybrid modulator, which formed stable accelerating pulses [7], was used [2] for generation of microwave pulses in the 38-GHz band in a focusing field $B_z \approx 2$ T (below the cyclotron resonance value). The power conversion factor of about 0.5 was achieved at a pulse repetition frequency of 3500 p.p.s.

The objective of the present study was improvement of power conversion in relatively small magnetic fields and development of a source of gigawatt-range X-band pulses generated at a high repetition frequency.

2. Problem Statement

Earlier investigations demonstrated that the main factor limiting conversion of power in small magnetic fields was considerable transverse oscillations of electrons in the field of an incident electromagnetic wave. This effect was enhanced against the background of "not the best" structural characteristics of the formed electron flow. For example, with the 10-GHz band and particle energies of about 500 keV one have a relatively narrow interval of working magnetic fields below the cyclotron resonance (the inductance of 0.5–0.6 T), over which it is possible to form an electron tube with reasonable amplitudes of transverse oscillations of particles. If the magnetic field is smaller than the aforementioned interval, the structure of the formed beam is impaired. The increase of the field is useless because oscillations of electrons in the electromagnetic wave are enhanced until the current is lost on the slow-wave system (SWS) wall. The task is made easier by decompression of the electron beam, for which purpose the explosive emission cathode is placed in a stronger field and the beam is widened before it enters the SWS with a small field (0.5–0.6 T). One more idea, which was used in this study, is that the rate of energy extraction from the electron beam is optimally distributed over the whole SWS length and the maximum amplitude of RF fields of an incident pulse is localized at the SWS inlet. It was shown [6] that this condition corresponds to a linear increase in the power of a RF pulse as it moves from the collector to the cathode side of the system. In this case, if the electron flow ends upon arrival of a pulse to the reflector, one may expect not only an optimal extraction of energy from the main portion of the beam, but also a minimum loss of the microwave pulse energy for pumping of transverse oscillations of particles. In addition to an appropriate longitudinal dition to an appropriate longitudinal distribution of coupling between particles and the synchronous harmonic, it is important to properly choose the length of the beam current and its rise-time.

3. Generation of Accelerating Pulses

Two setups (Figs. 1 and 2), which differ by principles of formation of accelerating voltage pulses and their power, have been developed and constructed. 1) A SINUS-160 compact high-voltage generator employing a Tesla transformer, which was built into an oil-filled forming line, provided a high-voltage pulse with an amplitude of 340 kV across the electron injector cathode at the beam current of 3 kA and FWHM equal to 4.5 ns. The electron beam power was ~ 1 GW and the pulse repetition frequency was 100 p.p.s.

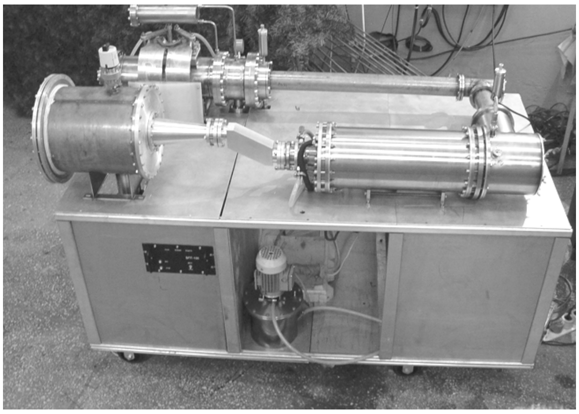

Fig. 1. Appearance of high power microwave source based on the SINUS-160 accelerator (the length is about 2 m)

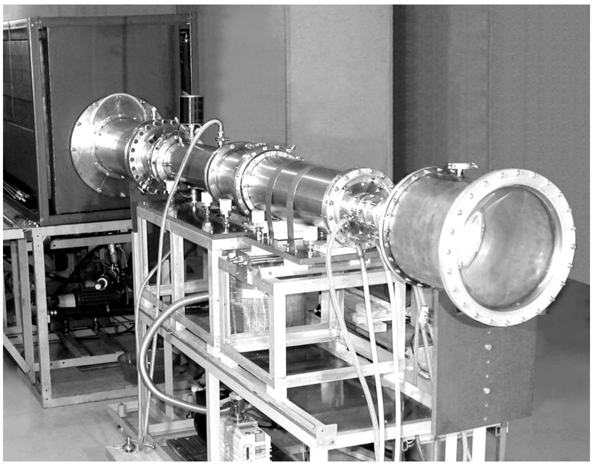

Fig. 2. Appearance of high power microwave source based on the accelerator employing inductive energy storage, a semiconductor opening switch and a peaking hydrogen-filled spark gap (the length is about 5 m)

2) Similarly to [2], a hybrid circuit of a high-voltage modulator was used for formation of more powerful accelerating pulses with a repetition frequency of up to 700 Hz. The modulator included a charging device (an S-5N driver [8]) with an all-solid-state switching system and an output stage comprising an inductive energy storage with a current interrupter based on SOS diodes [9]. A stable voltage pulse, which was formed by the driver, applied for charging of a coaxial forming line up to a voltage of 850–900 kV. A voltage pulse ~ 7 ns long with the rise time of ≤ 1 ns was formed after switching the peaking spark gap (filled with hydrogen under a pressure of 50 atm). Hydrogen was not circulated or cooled in the gas switch. Nevertheless, the full deviation of amplitudes did not exceed 5% in the case of commutation of pulses with energy of up to 30 J and a repetition frequency of up to 730 p.p.s. in bursts of 1 s long. The pulse amplitude at the accelerator cathode was as large as 600 kV. The beam current was 5.5 kA and the peak power was 3.3 GW.

4. Numerical Simulation

The numerical simulation of the generator by the particle-in-cell method (KARAT code) was used to test the slow-wave systems with the mean transverse dimension $2R \approx 1.4\lambda$ having a wide-band lumped reflectors. The shape of accelerating voltage pulses of electron injectors approached their real shapes as much as possible.

The following parameters were varied during the optimization procedure: the profile of the guiding magnetic field with decompression of the electron flow and the B-field magnitude; impedance of the vacuum diode; distribution of the coupling resistance of the electron flow with the incident wave E_{01} synchronous harmonic along SWS; and geometry and position of the reflector.

Geometries of the two variants of microwave sources were optimized independently taking the same degree of decompression of the electron flow. It is remarkable that the SWS lengths differed in the final configuration, but in each case the maximum conversion factors were nearly equal, $K \approx 0.7$. The magnetic field was $B_z \approx 0.75$ T near the cathode and $B_z \approx 0.55$ T in the SWS zone. Fig. 3 presents final results of the numerical simulation, which suggest that it is possible to obtain a peak radiation power of 2.5 GW (Fig. 2c) at a peak power of the electron beam equal to about 3.5 GW.

At the electron beam power of 1 GW the calculated power of a microwave pulse was about 0.7 GW. The SWS could be made shorter (about one-third) due to the decrease in the particle energy. It is for this circumstance that electron beams had different lengths.

It is known that a higher magnetic field is favorable for a more uniform distribution of explosive emission centers on the cathode edge. In the decompression section ~ 10 cm long, the average diameter of the emitted beam increased from 30 to 34 mm at the SWS inlet and then the beam widened smoothly up to 36 mm as it passed through the SWS (Fig. 3b). Therefore, the probability that electrons were ejected to the wall in the region of the resonance reflector, where the generated wave fields were the largest, was reduced. Notice that the numerical experiment yielded values of the conversion factor equal to or larger than unity if a strong magnetic field (~ 3 T) was used in simulation. Considering large transverse oscillations of electrons in the electromagnetic field of an incident pulse, the power conversion threshold of ~ 1 in small magnetic fields can be surmounted probably by increasing transverse dimensions of the slow-wave system.

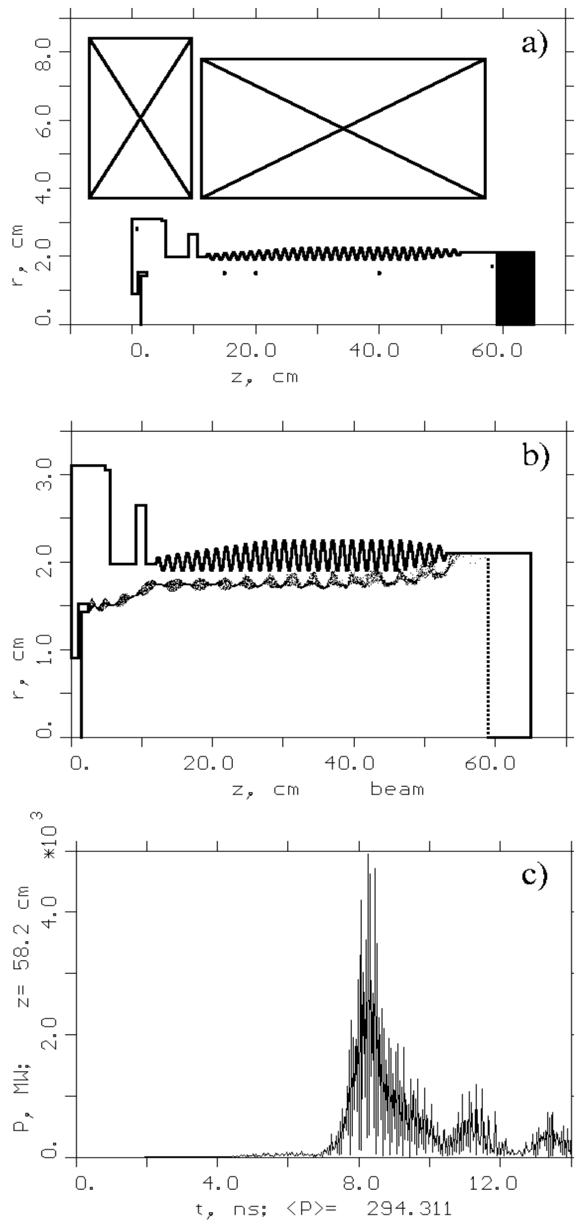

Fig. 3. Results of numerical simulation; a – the geometry of electron gun, solenoid and SWS; b – trajectory of the electron beam; c – non-averaged microwave power flow near the output of SWS

5. Experimental Realization

Geometries of the electron injector, the magnetic coil and the slow-wave system were exactly reproduced in experimental setups (Figs. 1 and 2). Explosive emission tubular graphite cathodes ~ 30 mm in diameter with the emitting edge 300 μm thick were installed in magnetically isolated vacuum diodes of electron accelerators.

Two-section DC magnetic coils with oil cooling were used in the experiments. A three-phase mains rectifier supplied a 120-A current to the windings in the variant shown in Fig. 1. A compact bank of molecular capacitors with an IGBT switch was used in the system in Fig. 2. In the latter case the charging device power and the capacitive storage energy provided 2–3 operations 1 second long per minute.

The microwave pulse energy was measured using vacuum calorimeters comprising glass tubes and an absorbing alcohol layer. Measurements were made by two ways: a capillary gauge (2.9 J/mm sensitivity) and a thermistor (the threshold sensitivity of about 0.1 J). The shape of the microwave pulse envelope was recorded using germanium hot-carrier microwave detectors and wideband oscilloscopes.

1. A maximum pulse energy of 0.6 J was obtained in the experiment with the SINUS-160 compact high-voltage generator (Fig. 1). This value corresponded to the pulse power of ≈ 0.6 GW at an efficient length of about 1 ns. The setup provided a pulse repetition frequency of 100 p.p.s. in bursts 1 to 10 s long. Fig. 4 presents a pulse burst from the detector, which illustrates high stability of the pulses.

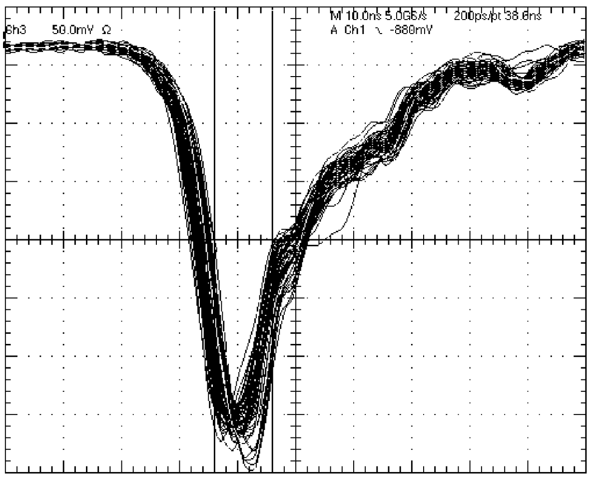

Fig. 4. Waveforms of germanium detector signals (Tektronix TDS 7404, 4 GHz). The distance between vertical cursors is equal to 1 ns

2. A train of consecutive operations in the experiment with a more powerful setup (Fig. 2) showed that the radiation energy of the microwave generator was 3.5 J per pulse and was reproduced to within 3%. Thus, at a pulse repetition frequency of 730 p.p.s. an average microwave power of 2.5 kW was achieved in bursts 1 s long. Detector signals were recorded using a Tektronix TDS820 digital sampling oscilloscope (6 GHz bandwidth), which formed one waveform over 512 consecutive samples. Processing of an averaged waveform (Fig. 5) gave FWHM equal to 800 ps.

Taking into account the full energy of a microwave pulse equal to 3.5 J, the peak radiation power was at least 2.2 GW.

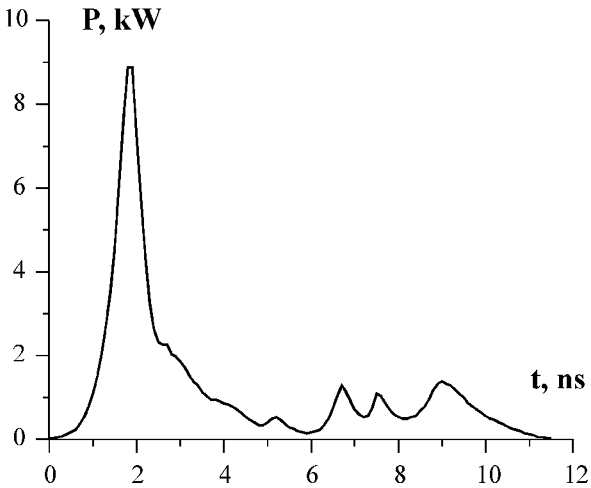

Fig. 5. Envelope curve of the microwave power obtained by reconstruction of the detector output pulsed signal and the Volt-Watt calibration characteristic

6. Conclusion

A pulsed periodic regime of generation of stable electromagnetic pulses having a width of 1 ns and a carrier frequency of 10 GHz was realized in a specially developed experimental setups with optimized electrodynamic and electron-optic systems. The mechanism of stimulated Cherenkov radiation in a spatially limited "wave–beam" system with a large single-pass amplification ensured for the first time generation of gigawatt-range X-band pulses having a high average power.

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