# High-Power Microwave Sources at the Institute of High Current Electronics

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**Abstract – The paper presents a review of pulsed high-power microwave sources recently developed at the Institute of High Current Electronics: a variety of relativistic BWOs, short-pulse generators of Ĉerenkov type, and vircators.**

## 1. Introduction

The studies of physical processes of conversion of intense pulsed electron beam's energy into energy of high-power microwave pulses at the Institute of High Current Electronics SB RAS have been conducted since its opening in 1977. Right in that year, a remarkable experiment was performed where, first in the world, a repetitively-pulsed relativistic high-power microwave (HPM) generator on the base of the backward-wave oscillator (BWO) was demonstrated producing 15-ns X-band pulses with peak power of 150 MW at pulse repetition rate of 100 Hz [1].

Since that time, a wide variety of microwave devices in the range of wavelengths 1 mm – 20 cm has been developed realizing almost all possible mechanisms of stimulated radiation by intense electron beams: Ĉerenkov and gyroresonant devices, the wave scattering ones, vircators, etc. [2, 3].

Custom-built HPM sources have found their application in nanosecond radio location, studies of electromagnetic compatibility, in biophysical experiments. This paper reviews a series of HPM sources developed at IHCE during the last few years.

## 2. High Current Nanosecond Electron Accelerators for HPM Production

For experimentation in the field of HPM production at IHCE, basically, repetitively-pulsed electron accelerators of the SINUS series are used [4, 5]. These machines have been developed at the Department of Physical Electronics. The design of the accelerators includes a Tesla transformer as a charging device, a long oil-insulated coaxial line playing the roles of a pulse-forming line as capacitive energy store switched using a two- or three-electrode gas gap high-voltage switch, and as a long nonuniform transmission line to match to a magnetically insulated coaxial vacuum diode with a cold explosive emission cathode.

On the basis of years of research and development, a series of high-current, repetitively-pulsed accelerators has been developed, having electron energy ranging from 0.2–2.0 MeV, beam current 0.2–20 kA, pulse width 4–130 ns (some of the recently developed long-pulse machines employ spiral type forming lines), pulse repetition rate up to 1000 Hz, and average power up to 200 kW. These accelerators are compact and reliable. The most powerful high-current electron accelerator of the series referred below, the SINUS-7, has maximum electron energy 2 MeV, beam current 20 kA, and pulse width 50 ns.

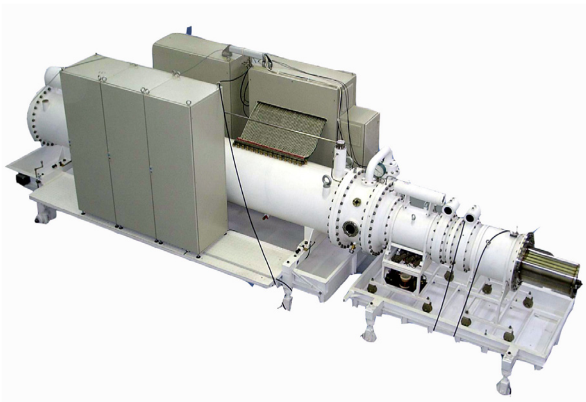

Fig. 1. The SINUS-130 repetitive electron accelerator with spiral forming line

Few other machines also used for HPM production were developed at the Department of Pulsed Power headed by Acad. B.M. Kovalchuk. These are the MARINA high-voltage generator with inductive energy storage and fuse opening switch and the STEND generator based on a Marx bank and a water forming line. These machines have sub-microsecond pulse duration and operate in single-pulse mode.

## 3. Resonant Relativistic BWO

The relativistic BWO (and its varieties) is apparently the device most frequently used in HPM experiments. An important result achieved at IHCE with the relativistic BWO was the production of 3-GW pulses in the X-band in 1997 [6]. Strong self-limitation of microwave pulse width was observed. Further, it was overcome by means of surface treatment of the BWO SWS and the pulse energy was increased from ~ 20 J up to 90 J [7].

Further studies of BWOs have been aimed at mastering of the decimeter wavelength band. Here, it was important to reduce the device electrodynamic system length and, respectively, to lower the energy spent on magnetic field production. Solving this problem resulted in the development of the resonant BWO [8–12].

Fig. 2. Electrodynamic system of the resonant BWO

Using intense interaction of the electron beam with non-synchronous – fundamental – harmonics of the operating wave (this was made by partially reflecting of the $TM_{01}$ wave from output edge of the electrodynamic system) enabled improved longitudinal distribution of the sum RF field (the $(-1)^{st}$ and the fundamental harmonics) in the beam trajectory, which gave a considerable increase in the generation power efficiency of the device comparing to the conventional relativistic BWO. The interaction space length was reduced to about 3λ, which allowed considerable energy saving on magnetic field production.

The device was realized in the S-band on the base of SINUS-7 accelerator. The strength of the guide magnetic field was 2–3 T. Single-mode emission at 3.6 GHz with peak power 5.3 GW and efficiency 30% was obtained. The microwave pulse width about 20 was limited by the current pulse width. The microwave pulse energy was up to 100 J.

Fig. 2. The SINUS-7 electron accelerator in high-power BWO experiments

The resonant relativistic BWO was demonstrated to be capable of broadband frequency tuning (up to 15% at half power level) achieved with constant electron beam parameters by varying the SWS period with simultaneous correction of the device full length.

Further studies of the resonant BWO were performed using the STEND high voltage generator with current pulse width of up to 300 ns, which is based on a Marx bank and a low-impedance water forming line. The main goal of this research was increasing the output microwave pulsewidth and energy and understanding qualitative regularities of the pulsewidth limitation. In these experiments, using low-energy, high-current electron beam (LEHCEB) surface treatment of electrodynamic structure in an S-band resonant BWO allowed an increase in the microwave pulse energy up to 250 J with the output power of ~ 3 GW [12].

## 4. Relativistic BWO with Resonant Reflector and Low Guide Magnetic Field

Efficient operation of the BWO in a low magnetic field range (below the cyclotron resonance) became possible primarily due to employment of a resonant reflector for the backward wave instead of a beyond cutoff-neck. This allowed using an electron beam and a slow-wave structure of increased cross size.

The device was originally realized in the X-band. Using the SINUS-6 electron accelerator (pulsewidth 25 ns) and a pulsed solenoid with magnetic field strength of ~ 0.6 T and a 600 keV, 5.5 kA electron beam, microwave pulses with peak power of 0.8 GW at λ ≈ 3 см were produced. This result allowed implementation of a repetitively-pulsed regime of BWO operation with peak output up to 500 MW at 150 Hz using a cooled DC solenoid with magnetic field induction of 0.6 T and power consumption of up to 20 kW [13, 14].

Studies of the generator have been continued using the SINUS-7 accelerator. In single-pulse experiments using low magnetic field (0.4–0.5 T), the following parameters of microwave emission were obtained: peak power ~ 4 GW, pulse width 10–20 ns, pulse energy up to 50 J.

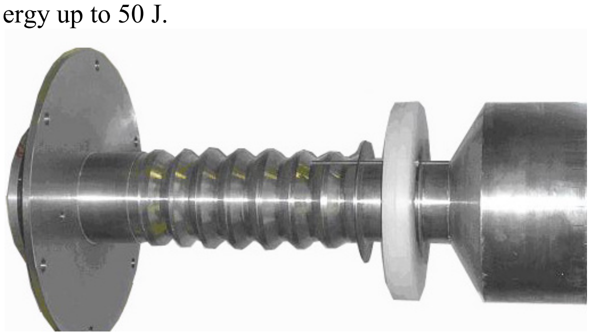

Fig. 3. Electrodynamic system of an S-band relativistic BWO with resonant reflector

In this generator, unlike the resonant BWO, it is possible to change the generation frequency without variation of the SWS period. This capability is due to the effect of preliminary modulation of the beam electrons by energy occurring in the region of the resonant reflector. The energy modulation causes modulation of electron velocity and their inertial bunching. Changing the drift distance between the reflector and the corrugated slow-wave structure allows variation of the phase of the beam RF current with respect to RF field of the synchronous harmonic at the SWS input. The value of this phase affects the device frequency. Using this method, frequency tuning in excess of 10% at half power was realized [15].

The relatively large cross size of the device electrodynamic system provides its higher electric strength and decreases the probability of spontaneous shortening of the microwave pulse. The low strength of the guide magnetic field radically simplifies its generation, which makes the device most promising for the use in the repetitive mode.

## 5. Vircators

Studies of two-sectional vircators have been conducted at IHCE since 1996 [16–21]. Using an electrodynamic system with two sections makes it possible, due to a more favorable RF field distribution along the electron trajectory, to achieve a much higher microwave efficiency than that in single-cavity vircators. Modulation of current by the virtual cathode resulting from electron energy premodulation provides efficient phase separation of particles in the RF field and allows its operation with slightly supercritical current (30–50%). Substantial width of the electron receptivity in the vicinity of the VC relaxation frequency resonance enables gradual frequency tuning by a corresponding adjustment of the electrodynamic system parameters. On the other hand, the resonator stabilizes the generation frequency during the pulse despite a variation of electron beam current inherent in high-current planar diodes.

The device was realized originally in the L-band on the base of SINUS-7 accelerator. Further studies were made by demand of customers mainly in the S-band. Single-mode, single-frequency microwave pulses with peak power of ~ 1 GW, 20–25 ns width (FWHM), and ~ 5% power efficiency were produced. By varying the resonator parameters, continuous tuning of the oscillation frequency within ~ 15% at half power was realized [18].

The studied of vircators were continued with the use of high-voltage generators with inductive energy store and fuse opening switch [19, 20]. A 2.1-GHz vircator was fed from the MARINA compact pulser. In these experiments, the peak diode voltage was ~ 1 MV, the electron diode ~ 20 kA, and the beam pulse width was ~ 150 ns. The microwave pulse peak power was ~ 1 GW with ~ 5% efficiency. The pulse width was ~ 50 ns at half power and the pulse energy was limited to 55 J [20]. The power gradually decreased during the pulse, which was largely due to the properties of the high-voltage generator, which behaved as a "source of current".

Next, a similar vircator was fed from the STEND high-voltage generator. Unlike the MARINA driver, the STEND generator behaves as a "voltage source". This allowed stabilizing the current of the electron beam working part mainly during the pulse, which changed from ~ 10 kA up to ~ 12 kA. The diode voltage of 700–800 kV was almost stable during 150 ns. This resulted in a longer microwave pulses (~ 70 ns) with larger energy (up to 70 J). The peak microwave power was in the range of ~ 1 GW, which, observing ~10 GW injected beam power, results in 10% "reduced" microwave efficiency.

After additionally smoothing some elements of the electrodynamic system to improve its electric strength, the microwave pulse width was increased to ~ 100 ns, with ~ 1 GW peak power (pulse energy ~ 100 J) [21].

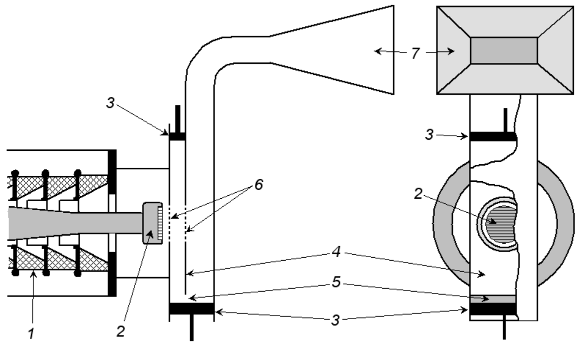


Fig. 4. Schematic of the two-sectional vircator: *1* – insulator, *2* – cold cathode, *3* – tuning plungers, *4* – partition wall, *5* – coupling window, *6* – foils or meshes, *7* – vacuum horn

Using the SINUS-7 electron accelerator, batch repetitive operation of an L-band vircator was demonstrated in the regime of reduced electron beam power. The peak power of pulses was about 100 MW and their width was 20–25 ns. The number of pulses in a batch was limited by destruction of the vircator intersectional grid and was about 50 at a pulse repetition rate of 50 Hz and about 400 at 20 Hz. Further, for an S-band vircator system equipped with Tungsten partition meshes and operating at 10 Hz, production of either 1000 pulses (200 MW) or 200 pulses (350 MW) was demonstrated, depending on the feeding beam power.

## 6. Sources of Ultrashort X-Band and Ka-Band Pulses

As a result of a series of theoretical and experimental studies performed in 2002–2003, first in the world the capability to produce extremely short (few RF periods) microwave pulses with peak power exceeding the power of the driving electron beam was demonstrated. The essence of the effect is the phenomenon of spatial accumulation of electromagnetic energy by a short microwave pulse running along an extended substantially nonuniform slow-wave structure of BWO-like Ĉerenkov type.

Several compact short-pulse microwave sources using this effect were developed, operating either in single pulse mode or repetitive mode [22–27].

In 2002, the world first experiment was performed at IHCE manifesting the possibility of overcoming the 100-% frontier in the power conversion efficiency of microwave generation [23]. The generator based on SINUS-150 compact accelerator (4 ns pulsewidth) produced 0.6-ns X-band pulses with peak power of 1.2 GW while the electron beam energy was 330 keV and the current was 2.6 kA. Thus, the power conversion coefficient notably exceeded unity (1.4). The source used strong magnetic field of 2.5 T produced by pulsed solenoid and operated in single-pulse mode (< 5 pulses/min).

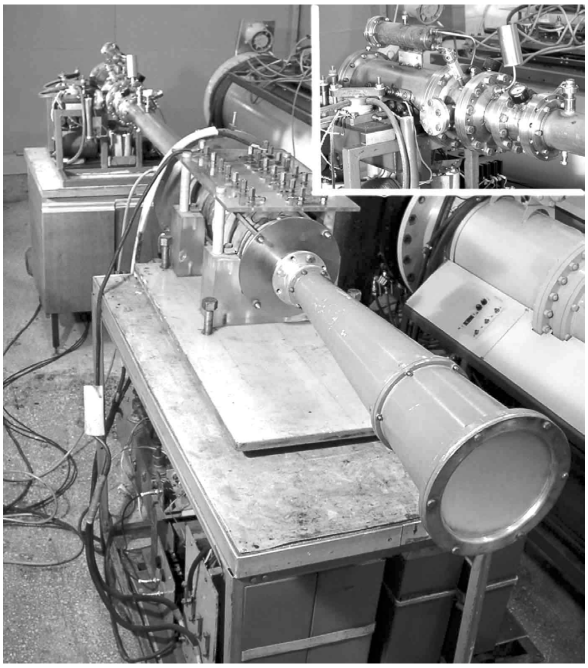

Fig. 5. The first X-band short-pulse source, which overcame the 100-% threshold of power conversion efficiency. Insert shows the SINUS-150 electron accelerator

In the demonstration experiment aimed at closer realization of conditions for spatial accumulation of microwave energy [23, 24], the SINUS-200 compact accelerator was used (pulsewidth 9 ns). A long SWS with strongly nonuniform corrugation depth but constant period was used. An annular cathode was immersed in a convergent magnetic field and injected into the SWS through a wire grid. The microwave pulse was generated in single-pass regime (excited at the collector edge of the SWS and radiated towards the beam injector). The strength of the magnetic field, generated by a pulsed solenoid, reached 1.7 T at the cathode and 5 T in the SWS. The high-voltage input was perpendicular to the axis of the microwave tube.

The source produced 0.6–0.7 ns wide (FWHM) pulses with central frequency 9.3 GHz, peak power ~ 3 GW and energy 2 to 2.4 J in single-pulse mode. The power conversion coefficient was up to 1.8. These parameters were obtained with a vacuum diode voltage of 300–330 kV and a beam current of 5.5–6 kA. Lengthening the SINUS-200 accelerator pulse to 16 ns (by including extra section in the forming line) allowed production of two sub-nanosecond microwave pulses in series.

After successful preliminary experiment on production of 300-MW sub-nanosecond Ka-band pulses in a low magnetic field (2 T) performed by IEP UB RAS and IHCE SB RAS, [26] a pulse source operating in high repetition rate mode was produced. The experimental device employed a hybrid modulator SM-3NS (1 ns, 270 kV, 1.8 kA) consisting of several energy compression stages with a SOS (Semiconductor Opening Switch) current interrupter and a hydrogen peaking switch (100 atm) at the output. A DC solenoid cooled by transformer oil circulation produced 1-s pulses with guide magnetic field of 2 T, which was stable within 2% during the pulse. The microwave pulse width was 250 ps. The microwave

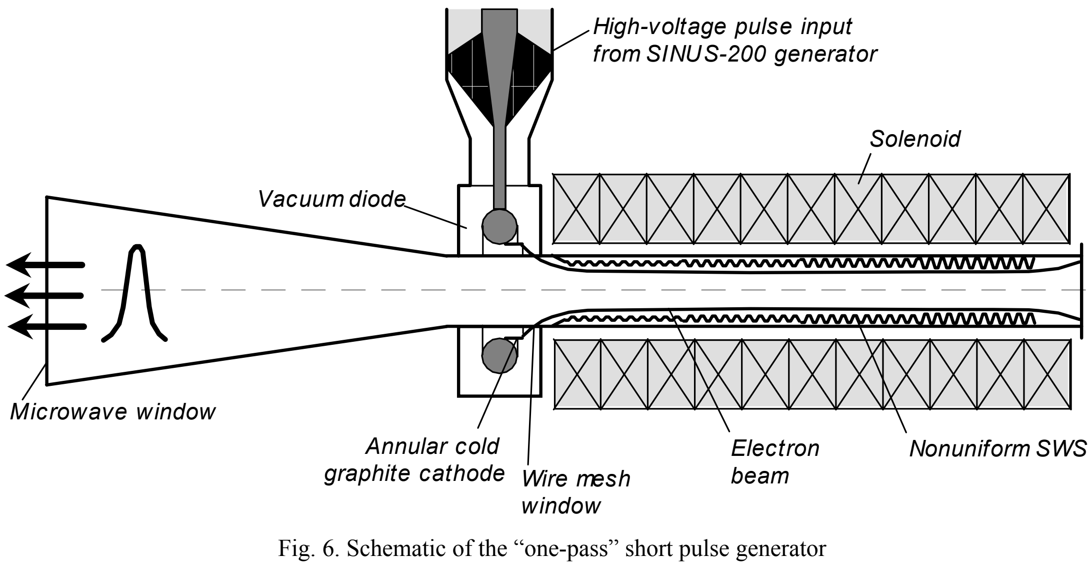


Fig. 6. Schematic of the “one-pass” short pulse generator

energy was reaching 80 mJ per pulse, which corresponds to a peak power of 300 MW. The average microwave power over the batch was 200 W at a PRF of 3,500 Hz [27].

In 2003, also in a joint work of IEP UB RAS and IHCE SB RAS a very compact source of sub–nanosecond (0.25 ns) 8-mm pulses with peak power 1 GW was developed. The power conversion coefficient was 1.5. The generator was based on RADAN-303BPM electron accelerator and operated in single-pulse mode with strong guide magnetic field (6.5 T) [28].

Another important result achieved jointly by IEP and IHCE in 2003 was the development of a compact source of sub-nanosecond X-band pulses with peak power in excess of 2 GW (power conversion coefficient ≈ 0.6 with guide magnetic field as low as 0.6 T) capable of operation at pulse repetition rate of up to 700 Hz [29]. The average microwave power of the source power reaches 2.5 kW. It is remarkable that this source is based on the generator employing inductive energy storage, a semiconductor opening switch and a peaking hydrogen-filled spark gap developed
at IEP.

Figure 7 shows one more repetitive short-pulse X-band source recently developed at IHCE on the base of small-size SINUS-160 accelerator with e-beam power of 1 GW [30]. The peak microwave power of pulses is 500–700 MW, the pulse width is about 1 ns. The $TM_{01}$ operating mode is converted to the Gaussian beam using a converter and special antenna. The source uses a cooled solenoid with oil circulation and is capable of continuous operation with pulse rep rate up to 150 Hz. The solenoid power consumption is about 20 kW. The weight of this compact (length ≈ 2 m) microwave source is 250 kg.

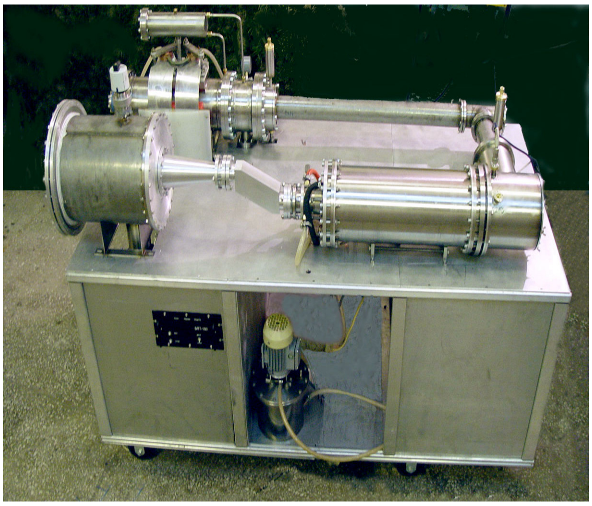

Fig. 7. Compact repetitive X-band short-pulse source

Thus, using the new mechanism for short microwave pulse production resulted in mastering of gigawatt powers of radiation using compact devices. It is expected that employment of larger, more powerful high-voltage pulse sources will allow getting in the microwave power range of over $10^{10}$ W.

## 7. Applications of High-Power Microwave Sources

Applications of HPM sources traditionally include plasma physics, particle acceleration technique, studies in the area of electromagnetic compatibility of electronic components, experiments in the field of high-resolution radio location, and biomedical researches.

For example, a nanosecond radar was developed on the base of sub-gigawatt relativistic BWO driven by repetitive high-current electron accelerator, having the location range of 100–200 km and distance resolution of ~ 1 m, capable of detecting small objects against a massive background [31, 32].

Compact pulsed microwave systems are expected to be demanded at airports and sea ports, by rescue in open sea, etc.

Promising potential applications of HPM sources arise in biology and medicine. Recent experiments demonstrated expressed repetition rate-dependent biological effect of the interruption of fruit-fly development by nanosecond microwave and X-ray pulses produced with high-current accelerators [33]. Application of nanosecond repetitive microwave pulses for the study of new inhibiting effects on tumor cells is intensively discussed [34].

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