Pulse Lengthenihg of S-Band Resonant Relativistic BWO

S.D. Polevin, S.D. Korovin, B.M. Kovalchuk, K.V. Karlik, I.K. Kurkan,
G.E. Ozur, I.V. Pegel, D.I. Proskurovsky, M.Yu. Sukhov, and S.N. Volkov

Institute of High Current Electronics, SB, RAS,
2/3 Akademichesky Ave., Tomsk, 634055, Russia,
Phone: (3822)492652, E-mail: polevin@lfe.hcei.tsc.ru

Abstract – Spontaneous pulse shortening occurring in an S-band resonant relativistic BWO at gigawatt power levels is studied. Termination of microwave output was caused mainly by emission of charged particles from the plasma forming at the slow-wave structure (SWS) surface under the action of the intense RF field. Treating the SWS surface by low-energy high-current electron beam (LEHCEB) allowed production of 3-GW, 90-ns microwave pulses with an energy of ~ 250 J.

1. Introduction

Improving the longitudinal distribution of RF field in the resonant BWO [1] due to reflection of the operating TM_{01} wave from the ends of the electrodynamic system and optimization of conditions for interaction between electron beam and both (-1^{st}) and fundamental harmonics allowed increasing the power efficiency of generation up to 30%. Significant advantage of the resonant BWO comparing to the conventional one is the shorter interaction space (~ 3λ), which allows energy saving on magnetic field production.

Experiments with the resonant relativistic BWO were made on the high-current electron accelerator SINUS-7 [2] (energy of electrons – up to 2 MeV, electron beam current – up to 20 kA, pulsewidth 50 ns). Single-mode S-band radiation with peak power 5.3 GW and efficiency 30% was obtained. The microwave pulse width about 20 ns was limited by the current pulse width.

This paper presents the results of further studies of the resonant BWO fed from the STEND high voltage generator [3] with current pulse width of up to 300 ns, which is based on a Marx bank and a water forming line. The main goal of this research was increasing the output microwave pulsewidth and energy, gathering quantitative data and understanding qualitative regularities of pulsewidth limitation.

2. Configuration of the Resonant BWO

Configuration of the resonant BWO is represented in Fig. 1. The electron beam is produced in a coaxial vacuum diode with magnetic insulation and is delivered to the tube via beyond cutoff-neck, which serves as a reflector for the backward wave. Slight narrowing of the SWS at its collector edge provides partial reflection of the wave and increased Q-factor of the tube. A piece of smooth cylindrical waveguide between the beyond cutoff-neck and the beginning of corrugation is used to adjust an integer number of oscillations of the fundamental standing wave along the tube. The ratio between amplitudes of fundamental harmonic of the forward wave and (-1^{st}) harmonic of the backward wave in the beam trajectory is determined by the corrugation depth of the SWS.

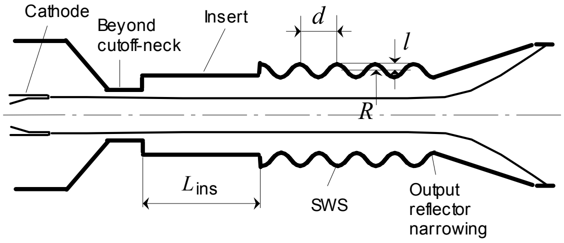

Fig. 1. Schematic of the resonant BWO

The generator was optimized numerically using the KARAT PIC-code [4].

Simulations evidenced that, with optimum geometry of the electrodynamic system ($l \approx \lambda/8$, $R \approx \lambda/2$, $L_{sws} \approx 2.5\lambda$, $L_{ins} \approx \lambda$, $Q \approx 100$, where L_{sws} and L_{ins} are lengths of the SWS and the insert, respectively and λ is the wavelength), the microwave power efficiency makes ~30% changing only slightly in a wide range of electron beam powers (from 5 up to 20 GW). The optimum vacuum diode impedance was about 100 Ω. The time for onset of microwave oscillation was ~ 20 ns.

3. Experimental Setup

The Marx high voltage generator (HVG) with output capacitance of 12 nF consists of 33 stages charged up to 45 kV each, and has output voltage up to 1.5 MV. The HVG is discharged via correcting inductance of 10 μH into a water forming line with the impedance 6 Ohm and electrical length 60 ns. In turn, the forming line is switched into the vacuum diode through a sharpening switch. The pulse length was controlled with a crowbar switch and could be varied in the range of 100–300 ns. Since the diode impedance was much greater than the forming line one, the generator, working as a “voltage source”, provided rather stable voltage in the diode during the pulse.

Explosive-emission hollow graphite cathode with the diameter of 5 cm was used to produce the electron beam. The electrodynamic system of the BWO was made of 12X18H10T stainless steel. The surface of the electrodynamic system was electrochemically polished in phosphoric acid after machining. The vacuum diode was evacuated by turbo-molecular pump up to 10^{-5} Torr. Liquid nitrogen traps were used to provide oil-less vacuum conditions.

The microwave radiation was outputted in air through horn antenna with the diameter of the output window ~ 8λ. The output microwave window was made of polyethylene with the thickness $\approx \lambda_w$, where λ_w is microwave wavelength in polyethylene. Measurement of the output power was carried out with calibrated dipole antennas, by means of integration over the radiation pattern, and with a 60-dB coupler built in the output waveguide of the microwave generator. The microwave pulse energy was measured using a wide-aperture calorimeter.

4. Experimental Results and Simulations

In experiments, the microwave generator was tuned to maximum output power and energy operating by varying the vacuum diode impedance and the position of electron beam dump. To eliminate the effect of cathode plasma expansion, the gap between the cathode and the anode narrowing was made big enough ($d_{a-c} \approx 6$ cm), so than $(d_{a-c} + L_{\text{cutof}}) > V_p \tau_b$, where L_{cutof} is the cutoff neck length, τ_b – current pulse width and $V_p \approx (0.6–2) \cdot 10^7$ cm/s – velocity of cathode plasma expansion along magnetic field [5]. In this situation, the vacuum diode impedance could be varied by changing the anode diameter.

In the optimum regime (cathode voltage ≈ 1 MV, diode current ≈ 12 kA) the microwave peak power was about 3 GW with efficiency of 25–30%. The oscillation frequency (3.6 GHz) was constant during the pulse. The dependence of microwave power on the position of electron beam dump (Fig. 2) had an oscillating shape due to interaction of electrons with the fundamental harmonic of traveling wave [6]. The microwave pulse width for an electrically polished SWS was limited to 50–60 ns and the pulse energy was 150–180 J. The pulsewidth dramatically dropped when decreasing the SWS – to beam dump distance to less than 10–12 cm, which could result from collector plasma expansion [7].

As shown in the earlier studies [8], termination of microwave pulse in a gigawatt relativistic BWO may result from the development of explosive emission on the SWS surface under the action of intense RF field and absorption of the operating wave power by electrons flowing between SWS ripples. The direct reason of termination of generation is the increase in the critical (starting) current of the BWO. Positive ions emitted from the surface plasma, which remove space-charge limitation of electron emission current, play the key role in the wave absorption. Thus, the width of the microwave pulse is limited by the summary time of development of explosive emission and accumulation of ions in the SWS volume.

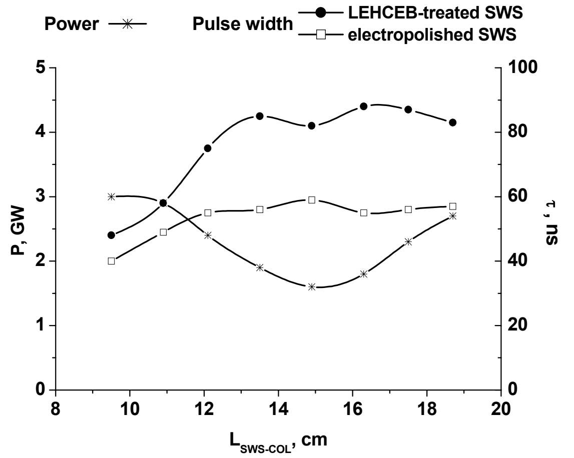

Fig. 2. Dependences of microwave power and pulsewidth on SWS – to beam dump distance for different methods of SWS surface treatment

Figure 3 presents the results of numerical simulations with the KARAT PIC-code for a resonant BWO with particles emission from the SWS surface. Parameters of microwave generator used in the simulation are close to the experimental ones. Emission of different species of particles – electrons and ions (protons) – was switched separately in time to demonstrate essential influence of ions on the process of oscillation suppression.

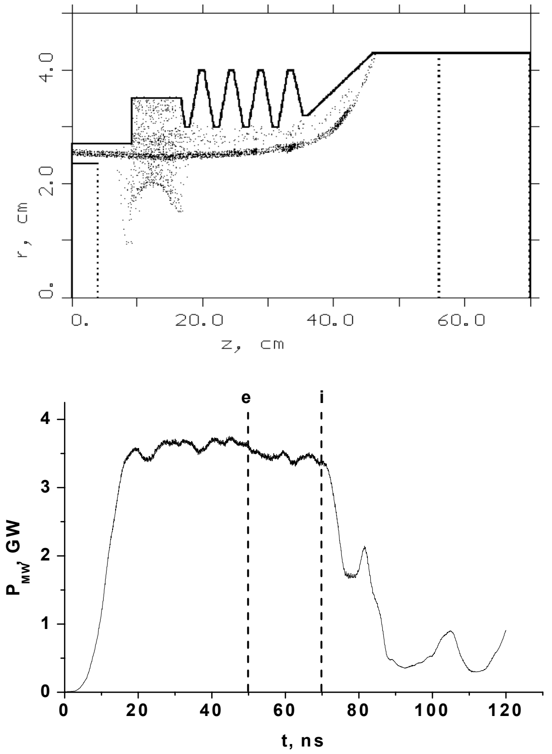

Fig. 3. Simulated BWO configuration and the output power waveform. Particle emission from the SWS surface starts: electrons at $t = 50$ ns, protons at $t = 70$ ns

The emission current densities for electrons and protons were $j^e_{\text{em}} = 1.5$ kA/cm^2 and $j^p_{\text{em}} = 30$ A/cm^2 so that $j^e_{\text{em}} \big/ j^p_{\text{em}} \approx (m_p/m_e)^{1/2}$. The simulation demonstrated that the microwave generation process is most substantially perturbed in the situation where particle emission occurs from the area adjacent to the cutoff neck and beginning of the SWS. As estimation shows, if the microwave output power is about 3 GW, then the electric RF fields strength near the cutoff neck and at the beginning of SWS makes ~ 1 MV/cm.

5. Pulse Lengthening Experimentation

Following the explosive-emission scenario of pulse shortening, solution of the problem of pulse lengthening of the BWO requires improvement of electric strength of its slow-wave structure by way of suppression or sufficient delay of explosive emission processes.

A new method to improve the electric strength of vacuum insulation was developed at IHCE [9, 10]. It is based on pre-treatment of electrode surface with low-energy high current electron beam (LEHCEB) of microsecond duration. High energy density (10–20 J/cm^2) and small pulsewidth of the electron beam allow material surface layer treatment in the regime of melting as well as in the regime of initial evaporation. Effectively removing dielectric impurities and dopes, outgasing and smoothing the metal surface, such a treatment suppresses the developing of explosive emission. Experiments have shown that LEHCEB treatment substantially reduces the intensity of pre-breakdown currents and enhances the electric strength of the vacuum insulation.

For instance, after LEHCEB treatment of stainless-steel electrodes and subsequent conditioning of the vacuum gap with high voltage pulses (250 kV, 40 ns, 100 pulses), the breakdown electric field achieved was as high as 2.2 MV/cm.

An LEHCEB source was produced for the treatment of the electrodynamic system surface. It is based on an electron gun where plasma is generated in a pulsed reflected (Penning) discharge in inert gas (Ar) [11]. The source differs from the earlier ones based on vacuum sparks [12] by severe decreasing of erosions products generated during its operation, which is essential requirement. Parameters of the LEHCEB source are as follows: electrons energy 20–30 keV, pulse duration 2–4 μs, electron beam energy density 2–20 J/cm^2, beam diameter up to 8 cm.

Surface treatment was made consequently in two regimes: the first one with energy density 8–10 J/cm^2 causing evaporation of ~ 0.4 μm surface layer and melting of ~ 4 μm layer, the second one with energy density 5–6 J/cm^2 causing melting of ~ 3 μm surface layer without evaporation. Thus, the first regime removed surface contaminations and gas and the second one provided smoothing of the micro relief.

In BWO experiments with LEHCEB–treated electrodynamic structure, as comparing to electro–polished one, microwave pulse lengthening was observed (Fig. 2). As well as earlier [8], “training” effect for electrodynamic structure of BWO in the intense RF field was observed. Duration of the first pulses was 70–75 ns with 3 GW output power, and during the next 5–10 pulses (produced without opening the system to air) the pulsewidth reached about 90 ns. In the next 10–20 pulses, there were no visible changes of the pulse duration; the pulse-to pulse spread of the pulsewidth was not over 10% (RMS). The microwave energy measured by calorimeter was about 250 J. Typical waveforms of cathode voltage, diode current and microwave power are depicted in Fig. 4.

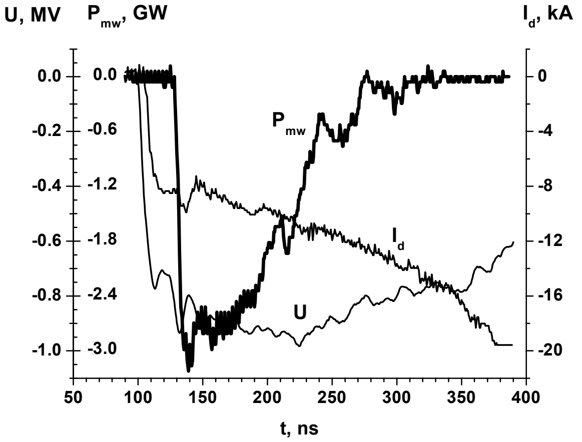

Fig. 4. Typical waveforms of cathode voltage, diode current and microwave power (LEHCEB-treated SWS)

It should be mentioned that noticeable erosion was observed on the surface of the BWO electrodynamic system at the points of electric fields maxima (near the cutoff-neck and first ripple) but the number of craters per square unit was 2–3 times less than that one without LEHCEB treatment.

6. Conclusion

Using the LEHCEB surface treatment of electrodynamic structure in S-band resonant BWO allowed an increase in the microwave pulse energy up to 250 J with the output power of ~3 GW.

This result gives additional support to the hypothesis about the explosive-emission nature of spontaneous pulse shortening in nanosecond high-power microwave devices.

References

[1] S.A. Kitsanov, A.I. Klimov, S.D. Korovin, I. K. Kurkan, I. V. Pegel, S. D. Polevin, *in: Proc. 14th Int. Conf. on High Power Particle Beams*, Albuquerque, 2002, pp. 255–258.

[2] S.D. Korovin, V.V. Rostov, Izvestiya vuzov. Fizika (Rus) **12**, 21 (1996).

[3] M.I. Vorobjushko, B.M. Kovalchuk, B.A. Kokshenev, V.V. Kremnev, V.I. Manilov, A.A. Novikov, V.P. Yakovlev, *in: Proc. 1st Conf. po ingenernim problemam termoyadernih reaktorov, Leningrad,* 1977, **3**, p. 160.

[4] V.P. Tarakanov, *User Manual for Code KARAT,* Springfield, VA: BRA, 1992, 176 pp.

[5] S.P. Bugaev, V.P. Ilyin, V.I. Koshelev, G.A. Mesyats et al., *in: Relativistic High Frequency Electronics (Rus),* Gorky, 1979, pp. 5–75.

[6] S.D. Korovin, S.D. Polevin, V.V. Rostov and A.V. Roitman, *in: Proc. of the 9th Int. Conf. on High Power Particle Beams*, Washington, 1992, **3**, pp. 1580–1585.

[7] J. Benford and G. Benford, IEEE Trans. Plasma Sci. **26**, 311 (1997).

[8] S.D. Korovin, G.A. Mesyats, I.V. Pegel, S.D. Polevin, and V.P. Tarakanov, IEEE Trans. Plasma. Sci. **28** (3), 485 (2000).

[9] A.V. Batrakov, A.B. Markov, G.E. Ozur et al., IEEE Trans. Diel. and Electr. Insul. **2** (2), 237 (1995).

[10] A.V. Batrakov, D.S. Nazarov, G.E. Ozur et al., IEEE Trans. Diel. and Electr. Insul. **4** (6), 857 (1997).

[11] G.E. Ozur, D.I. Proskurovsky, D.S. Nazarov, and K.V. Karlik, J. Tech. Phys. Lett. (Rus) **23** (10), 42 (1997).

[12] D.S. Nazarov, G.E. Ozur, D.I. Proskurovsky, Izvestiya vuzov. Fizika (Rus) **3**, 100 (1994).