A Possibility of Pulsed Power Increasing of X-Band Relativistic Backward Wave Oscillator[1]

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Abstract – Using the PIC-code KARAT, the geometry of a relativistic backward-wave oscillator (BWO) with a resonant reflector was calculated for an 18 kA beam current, an 850 kV diode voltage, and a 5 T guide magnetic field. For the mean diameter of the slow-wave structure (SWS) 1.6 times greater than the radiation wavelength, the predicted microwave power at ≈ 9.2 GHz was 5.7 GW with 37% power efficiency. The estimation was made of the maximum RF electric field at the SWS surface for the set limit of the microwave power. It was shown that the threshold of the explosive electron emission responsible for the electron-ion plasma appearance and the oscillation suppression is reached at the collector end of the device. Experimental studies of the relativistic BWO demonstrated efficient oscillation with a peak power of 4.3–5.3 GW, an efficiency of 31–22% and a microwave pulsewidth of ~ 20 ns in a 4.5 T guide magnetic field. The oscillation frequency was 9.4 GHz. In all operating modes, no effect of pulse shortening was observed.

1. Introduction

It is known [1, 2] that an obstacle to increasing the microwave power and energy in a relativistic backward-wave oscillator (BWO) is the explosive electron emission that develops at the surface of the slow-wave structure (SWS) in ~ 10^6 V/cm RF electric fields. With these fields, the resulting electron-ion plasma may suppress the oscillation and shortens the microwave pulsewidth to a few nanoseconds [2]. For example in experiment [3], a microwave peak power of ~ 3 GW with a power efficiency of ≈ 20% was obtained in the 3-cm range using a conventional BWO circuit with a beyond cutoff-neck and a SWS of mean diameter ≈ 0.9 λ (λ is the radiation wavelength). Estimates show that taking into account the standing wave, the maximum RF electric field at the corrugation surface is ~ 2.5 MV/cm. Note that in the experiment, special treatment of the SWS surface was used to increase the microwave pulsewidth from 6 to 30 ns. However even with this treatment, the electric strength of the SWS and, hence, the microwave pulsewidth gradually decreased from pulse to pulse. Another mechanism for decreasing the RF electric field at the corrugation surface, which is to increase the SWS cross section ($D/\lambda > 1$, where D is the mean diameter of the SWS), was limited due to excitation of competitive modes.

Earlier theoretical and experimental studies of the relativistic BOW with a resonant reflector demonstrate the feasibility to selectively excite the operating wave for $D/\lambda \approx 1.5$ [4, 5, 6]. In this oscillator design, the electron beam premodulation in the reflector region provides a decrease in oscillator starting current for the operating TM_{01} wave and creates a necessary condition for mode selection. Moreover, it is shown [5] that with efficient energy premodulation of the electron beam, the device operates as a twystron for which the maximum predicted efficiency reaches 60%.

2. Theoretical analysis

The BWO electrodynamic system is shown schematically in Fig. 1. In this oscillator circuit, the incident TM01 wave is reflected from the resonant reflector in the idle mode due to excitation of the locked symmetric TM_{02} mode. The amplitude of the electric field z component at the beam radius in the reflector region can be several times greater than that in the waveguide [5]. Thus, in the confined space region, conditions are provided for efficient energy premodulation of the electron beam.

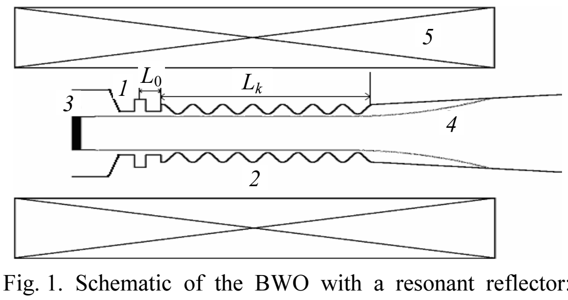

Fig. 1. Schematic of the BWO with a resonant reflector: resonant reflector (*1*); SWS (*2*); cathode (*3*); electron beam (*4*); solenoid (*5*)

The basic mechanisms of the energy exchange between the electron beam and the electromagnetic wave can be derived in solving a system of equations [5, 7] descriptive of the electron motion in RF fields and of the backward wave excitation in the ultrarelativistic energy range (γ >> 1). In numerical analysis, the elec-

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tron beam premodulation is described by the complex modulation parameter $\alpha = |\alpha|\exp(i\arg(\alpha))$ [5] whose modulus characterizes the depth of electron energy modulation in the reflector region, and argument (modulation phase) determines the position of the forming bunch relative to the phase of the synchronous wave field at the SWS inlet. (For arg(α) = π/2, the maximum RF current is at the center of the region of decelerating field phases). The modulation phase parameter is determined self-consistently by solving the boundary problem:

$$\arg(\alpha) \approx -\frac{\pi}{2} - 2\pi\Lambda - \Lambda(1-\delta)\,kd\big/2\gamma_0^2,$$

where $\Lambda = L_0/d$, L_0 is the drift space length, d is the corrugation period, $k = 2\pi/\lambda$, λ is the radiation wavelength, γ_0 is the relativistic factor, $\delta = 2\gamma_0^2(h_{-1}/k - 1)$ is the synchronism mismatch, and h_{-1} is the longitudinal wave number of the synchronous (–1)st space harmonics.

The solution of the linearized system of equations [5] is the oscillation starting conditions (Fig. 2): the dimensionless oscillator starting length

$$\zeta_{l,st} = \left(2\pi I\right)^{1/3} kL_{k,st}\big/2\gamma_0^2$$

and synchronism mismatch

$$\delta_{l,st} = 2\gamma_0^2(h_{-1}/k - 1)/(2\pi I)^{1/3},$$

where $I = 2\gamma_0^3 e Z_{-1} J_b/(\pi m c^2)$ is the parameter of reduced current, Z_{-1} is the beam – synchronous harmonic coupling resistance, J_b is the beam current, $L_{k,st}$ is the SWS starting length, and e and m are the electron charge and mass, respectively.

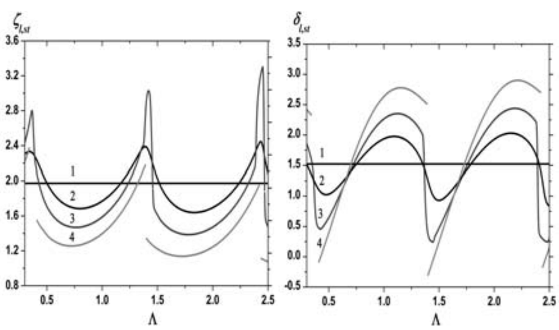

Fig. 2. Oscillator starting parameters versus the parameter Λ for different modulation depths $(2\pi I)^{1/3}|\alpha|$: 1 – 0.0; 2 – 0.3; 3 – 0.6; 4 – 0.9

The numerical analysis suggests that with the SWS length fixed, the oscillator starting current decreases with increasing premodulation depth in a wide range of the parameter Λ. Thus, the possibility exists of realizing selective excitation of the operating mode in the cross-sectionally increased SWS ($D/\lambda > 1$).

The efficiency of energy exchange $\eta = \hat{\eta}\gamma_0/(\gamma_0 - 1)$, where $\hat{\eta}$ is the reduced efficiency [5], is determined from solving a nonlinear boundary problem. Modes with high efficiency up to 60% (Fig. 3) are realized provided the condition of optimum energy exchange $|\alpha|_{\mathrm{opt}} \approx (4\pi I)^{-1/2}$ [5], which relates the modulation depth to the reduced current, is satisfied.

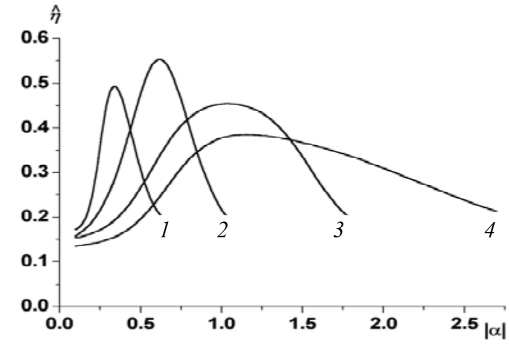

Fig. 3. Reduced efficiency optimized with respect to the SWS length (L_k) and modulation phase arg(α) versus the parameter $|\alpha|$ for several values of I: *1* – 1.0; *2* – 0.3; *3* – 0.1; *4* – 0.05 at $\left|\Lambda(1-\delta)kd/2\gamma_0^2\right| << 1$

3. Numerical experiment

The oscillator geometry and the electron beam parameters were optimized in numerical simulation using the PIC-code KARAT [8]. The final calculations were performed for an electron beam of current 18 kA accelerated by a pulsed voltage of amplitude 850 kV and transported along the oscillator electrodynamic system by a 5 T guide magnetic field. The mean diameter of the SWS was 1.6 times greater then the radiation wavelength. The SWS was nonuniform in corrugation amplitude (l = 0.95÷1.95 mm) and period (d = 15.2÷14.1 mm) to preclude the excitation of competitive oscillations. For the optimum position of the resonant reflector relative to the SWS L_0 = 23.5 mm (Fig. 1), the maximum predicted efficiency of the oscillator was 37% at ≈ 9.2 GHz with a steady-state microwave power of 5.7 GW (Fig. 4). The maximum RF electric field at the corrugation surface was determined using a program based on the scattering matrix method [9]. For the predicted 5.7 GW power, the

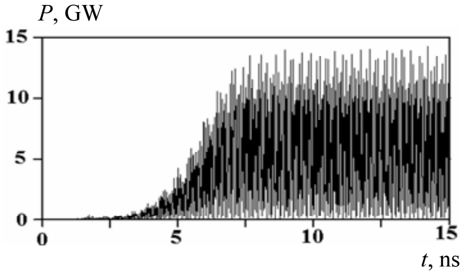

Fig. 4. Unaveraged power immediately outside the calculation region

maximum RF electric field was ~ 2.5 MV/cm and fell on the ripples nearest to the electron collector (Fig. 5). It seems unlikely that the explosive-emission plasma produced near the SWS outlet may suppress the oscillation [2].

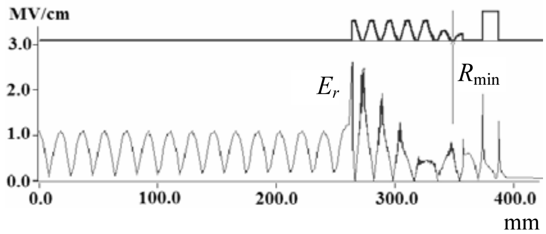

Fig. 5. Longitudinal distribution of the radial component of the RF electric field at the radius R_{min}

4. Experimental results

Experiment was performed on the SINUS-7 nanosecond high-current electron accelerator [10] in the single pulse mode. The voltage pulsewidth was ~ 50 ns. The electron beam was emitted from a graphite cathode of diameter 44 mm. All elements of the oscillator electrodynamic system were made of stainless steel and were held together by studs. Microwave signals were detected by a receiving antenna (an open end of a rectangular waveguide of geometrical cross section 23 mm × 10 mm) with absorbers on its outside to decrease the effective antenna section and make it less dependent on frequency. The measurement error for the effective cross section was ± 13%. The receiving antenna was located 4.5 m away from an emitting horn antenna. The emitting and receiving antennas were placed in a volume filled with SF_6 gas. The microwave signal was detected by 6D16D thermionic tube diode detector connected to the receiving antenna via a directional coupler with a coupling coefficient of ~ 19 dB and was recorded by a TDS 754C oscilloscope. The detector calibration error was ± 15%. The microwave energy was measured with an aperture calorimeter located immediately upstream of the emitting horn such that it covered the entire horn aperture (the space between the emitting horn and the calorimeter was filled with SF_6). The microwave pulsewidth was controlled with a receiving antenna located directly downstream of the calorimeter through which some power was transmitted. The radiation spectrum was measured with a heterodyne frequency meter and a TDS 7404 oscilloscope in which the intermediate frequency signal was processed with a built-in fast-Furrier transform function.

For the optimum e-beam parameters (diode voltage ≈ 950 kV and diode current ≈ 14.7 kA), reflector position relative to SWS L0 ≈ 23.5 mm, and 4.5 T magnetic field, stable oscillation at ≈ 9.4 GHz was realized The microwave power measured by integrating the radiation pattern (corresponding the TM_{01} wave) was 4.3 ± 1.1 GW with a power efficiency of 31 ± 8% (Fig. 6). The FWHM was about 22 ns. In this mode, the peak-to-average standard deviation of microwave pulses was no greater than ± 2%. The microwave energy measured by the calorimeter was about 70 J and corresponded to a peak power of ≈ 3.4 GW.

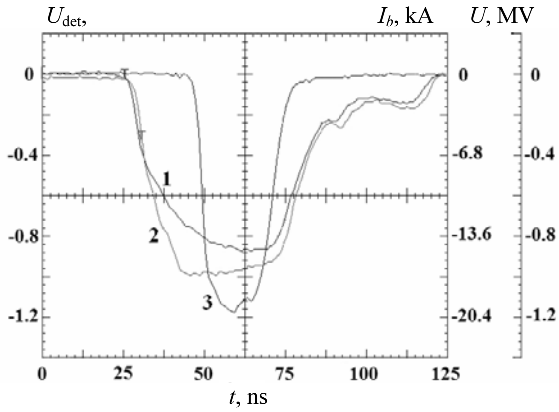

Fig. 6. Oscillograms of the diode current (1), diode voltage (2), and signal from the thermionic tube diode detector (3)

As the electron beam power was increased, the microwave power increased from 4.3 to 5 GW, the oscillator efficiency decreased from 31 to 22% (Fig. 7), and the microwave pulsewidth slightly decreased to ≈ 20 ns. The microwave energy measured with the aperture calorimeter was about 80 J, which corresponded to a peak power of ≈ 4.4 GW.

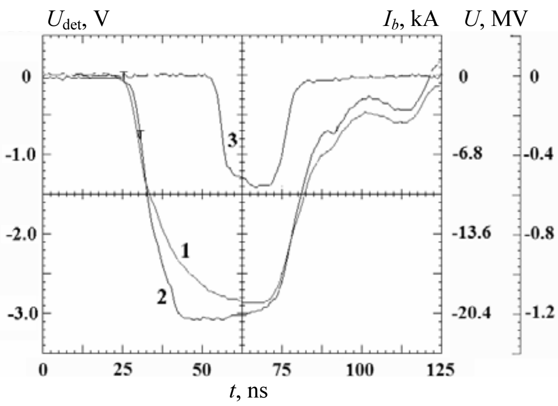

Fig. 7. Oscillograms of the diode current (1), diode voltage (2) and signal from the thermionic tube diode detector (3)

5. Conclusion

Thus, an oscillation mode of the RBWO with a power efficiency of ~ 31%, a peak power of ≈ 4.3 GW and microwave pulsewidth of ~ 22 ns was realized in experiment without taking special measures to increase the SWS electric strength. The increase in microwave power to 5 GW did not involve any considerable shortening of the pulsewidth. The further increase in output power and energy in the RBWO can be attained through specially treating the SWS surface as well as through further increasing the mean diameter of the SWS on retention of the selective properties of the oscillator.

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References

[1] A.S. Elchaninov, F.Ya. Zagulov, S.D. Korovin et al., Pis'ma Zh. Tekh. Fiz. **7**, 1168–1171 (1981).
[2] S.D. Korovin, G.A. Mesyats, I.V. Pegel et. al., Pis'ma Zh. Tekh. Fiz. **25**, 217–220 (1999).
[3] A.V. Batrakov, K.V. Karlik, S.A. Kitsanov et. al., Pis'ma Zh. Tekh. Fiz. **27**, 150–152 (2001).
[4] I.K. Kurkan, V.V. Rostov, and E.M. Totmeninov, Pis'ma Zh. Tekh. Fiz. **24**, 388–389 (1998).
[5] S.D. Korovin, I.K. Kurkan, V.V. Rostov et. al., Radiotekhn. Kvant. Elektron. **42**, 1047–1054 (1999).
[6] S.D. Korovin, V.V. Rostov, and E.M. Totmeninov, Pis'ma Zh. Tekh. Fiz. **31**, 411–413 (2005).
[7] N.F. Kovalev, V.I. Petrukhina, and A.V. Smorgonsky, Radiotekhnika i Electronika **2**0, 1547–1550 (1975).
[8] V.P. Tarakanov, *User's Manual for Code KARAT*. Springfield, BRA, 1992.
[9] G.G. Denisov, D.A. Lukovnikov, and S.V. Samsonov, Int. J. Infrared and Millimeter Waves **1**6, 745–752 (1995).
[10] S.D. Korovin and V.V. Rostov, Rus. Phys. Zh. **12**, 21–30 (1996).