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Efficiency of moderately relativistic resonant S-band BWO

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Abstract. The scheme of a resonant relativistic backward wave oscillator (BWO) was proposed by the group of researchers from IHCE SB RAS for efficient generation of high-power microwave radiation in the S-band while maintaining relatively small structure length about 2.5 λ. As far as can being found from publications, the scheme proposed uses high-current relativistic electron beams with energies of 0.7–1.5 MeV and a strong guiding magnetic field (at least 1.5 T, typically 2–3 T). In this paper, we propose a variant of a resonant relativistic backward wave oscillator that operates at moderately relativistic beam energies (450–550 keV) and at guiding magnetic field values starting from 1.3 T. Compared to the original resonant BWO geometry, in the current investigated scheme, the length of the periodic structure is increased by 1 period. For optimization using particle-in-cell code XOOPIC, the length of the insert between the cutoff-neck and the periodic structure, as well as the profiles of two terminal corrugations (defining the reflections from boundaries of periodic structure) are varied. It is shown in the numerical simulation that for a beam energy of 500–550 keV the average radiation power in proposed RBWO reaches level of 1 GW and efficiency is up to 27–28%.

Keywords: backward wave oscillator, electron beams, high power microwaves.

1. Introduction

In the last decade, there has been an increasing interest in the creation of powerful multi-gigawatt sources of high power microwaves based on a relativistic backward oscillator (BWO). Representative examples of such generators are a BWO with a maximum power of 4.3 GW in the X-band frequency range [1] and more than 5 GW in the 8-cm wavelength range (S-band) [2], a relativistic klystron-like BWO with an output radiation power of 6.5 GW [3]. Such studies are of considerable interest and have applied applications in various fields of science and technology, such as relativistic microwave electronics, high energy density physics, plasma and electron beam physics, communication and radar systems, etc.

The resonant relativistic backward oscillator (RBWO), developed by a group of researchers from IHCE SB RAS for efficient generation of high-power microwave radiation in the S-band in 2002, is hitherto the one of the most promising pulsed microwave sources of gigawatt power level. Single-mode generation at a frequency of 3.6 GHz with a maximum pulse power of 5.3 GW was produced in experiments [2, 4]. Based on the resonant oscillator scheme the possibility of generating high-power microwave pulses with an efficiency of 14% with a power supply system based on explosive magnetocumulative generators has been demonstrated [5]. A stable repetition rate mode of BWO's generation with an output power of 1 GW at a microwave pulses duration of 100 ns and a repetition rate of 10 Hz has been successfully implemented [6]. A characteristic feature of the resonant BWO is the interaction of the electron beam with both backward and forward waves of slow-wave structure. It is implemented by optimizing reflections from ends of slow-wave structure and by improving the longitudinal distribution of the RF field of the fundamental harmonic of the forward wave and (-1st) harmonic of the backward wave. This results in increased generation efficiency up to 30% in the range of electron beam power from 5 up to 20 GW.

Further development in research field of high power microwaves radiation in various wavelength ranges is accompanied by an increase of the requirements for the parameters and the quality of high-current electron beams [7, 8]. Essentially important are the problems of generating high-voltage "quasi-rectangular" power supply pulses with stable parameters, providing a flat top pulse duration and fast rise time of the pulse in a few ns [9, 10], repetitively pulsed HPM generation, optimizing the profile of the guiding magnetic field to obtain electron beams with a low transverse velocity electrons $\beta_{\perp}$ with respect to their longitudinal velocity (so that $\beta_{\perp}^2 \ll 1/\gamma^2$) etc. There is also the task of achieving high-efficiency generation in a BWO at a level of 1 GW at a more moderate, practically convenient electron beam energy in the range of 450–600 keV and at an electron beam power of less than 5 GW.

In this paper on the basis of numerical simulations, we propose a variant of a resonant BWO that operates at more lower, moderately relativistic beam energies (450–550 keV) than original prototype of RBWO [2, 4] and generates a high power microwave level of 1 GW at beam power of less than 5 GW.

2. Resonant BWO model in XOOPIC

The configuration of the electrodynamics structure of proposed RBWO is shown in Fig.1 (the interface view inside of particle-in-cell code XOOPIC). As in the original RBWO prototype, there is an insert of cylindrical waveguide between the cutoff neck and the periodic slow-wave structure (SWS), by choosing the length of which can be selected the optimal phase shift between the fundamental harmonic and (-1st) harmonics of the forward and backward electromagnetic waves can be selected. To implement the optimal conditions for the interaction of the electron beam with the (-1st) harmonic of the backward wave and the fundamental harmonic of the forward wave, the partial reflection of the operating TM_{01} mode from the ends of the SWS is used, and the amplitudes of the terminal corrugations are varied in the numerical simulations. To improve BWO performance at moderately relativistic beam energies, the number of corrugation periods was increased (structure is composed of 5 periods).

Simulation and optimization of the proposed RBWO were carried out in 2.5D particle-in-cell code XOOPIC [11]. An electron beam with set values of current, energy, and velocity spread was injected into the computational domain from the left side (before the cutoff neck, see Fig.1). A uniform magnetic field was established inside the RBWO structure; at the boundary of the SWS the field dropped to ensure the beam ejection at a given location directly behind the horn.

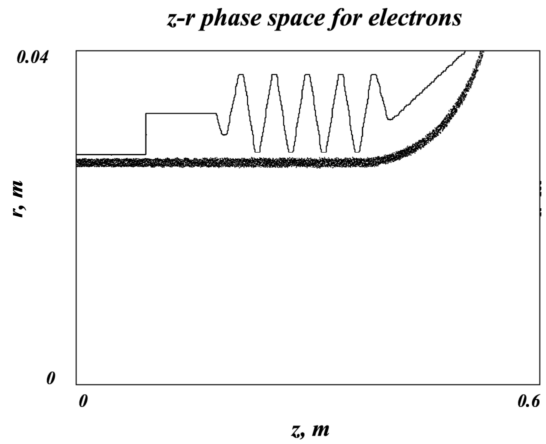

Fig.1. Geometry of the proposed resonant BWO in XOOPIC.

On the right edge of the computational domain, boundary conditions of the impedance type (PML – perfectly matched layer) were set, corresponding to the propagation of a wave into free space without additional back reflections. The microwave power is determined by integrating the flow of the Umov-Poynting vector over the cross section of the output horn. The Fourier transforms of the *r*- and *z*-components of the electric field at several points near the boundary are used to calculate the radiation spectrum.

The length of the cylindrical waveguide insert, the period and amplitude of the SWS corrugations, the inner radius of the terminal corrugations, which determine the partial reflection of waves from the edges of the electrodynamics structure, are the main parameters studied and varied in the numerical simulations of the operation of the relativistic RBWO.

The calculations are carried out for various beam energy and current values (beam energy range from 400 up to 700 keV, vacuum diode impedance from 60 to 150 Ω). The dependence of the microwave generation power on the amplitude of the guiding magnetic field are also studied.

3. Results of numerical studies RBWO

As a result of the research, the optimal parameters for the configuration of the electrodynamics structure of the RBWO are found:

• Trapezoidal corrugation profile, structure period $D \approx 0.37 \cdot \lambda_g$, average SWS radius $r \approx 0.29 \cdot \lambda_g$, corrugation depth $h \approx \lambda_g/12$, where λ_g is the wavelength of the TM_{01} radiation mode of the circular waveguide containing the RBWO structure;

• Two RBWO configurations are determined, optimized for electron beam energies of 400–500 keV and for energies of 500–700 keV, realizing in a numerical experiment a generation efficiency level of 27–28% similar to the original prototype of RBWO experiments [2, 4]. The optimal beam impedance in the calculations is 80 Ω. The rise time of microwave generation defines 22–23 ns;

• Generation of radiation power of the level of 1 GW is obtained at an electron beam energy of 550 keV.

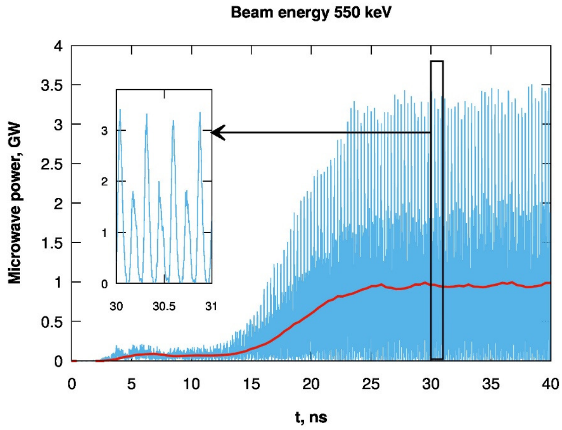

Fig.2. Microwave power: instantaneous (impulse) and averaged radiation powers of RBWO with beam energy of 550 keV.

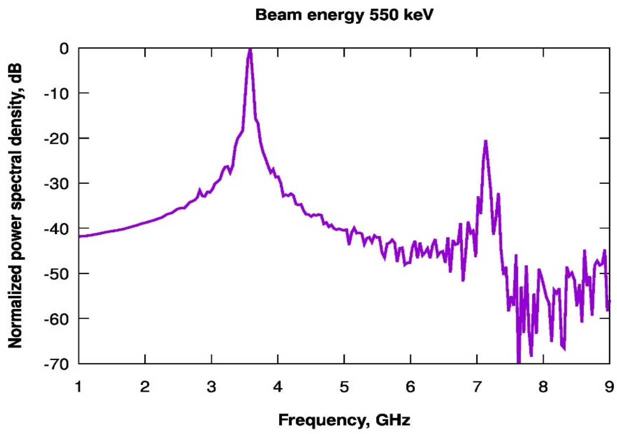

Fig.3. Spectrum of the resonant BWO with a beam energy of 550 keV.

The graphs of Fig.2 and 3 present the results of calculating the microwave power and the output spectrum of the RBWO radiation at a beam energy of 550 keV. The beam impedance is 80 Ω (current 6.9 kA), the guiding magnetic field amplitude establishes 2.5 T. Under these parameters, the average microwave generation power reaches level of 1 GW, which corresponds to an efficiency of ~26%. We note that the instantaneous radiation power in this case exceeds 3 GW due to the inherent "resonance" mechanism of the RBWO generation (see inset in Fig.2). The radiation spectrum is shown in Fig.3. The main frequency of RBWO radiation is 3.55 GHz, the second harmonic at a frequency of 7.1 GHz is strongly suppressed.

Typical calculated dependencies of the average power and frequency of RBWO radiation on the impedance of the electron beam and on the magnitude of the guiding magnetic field are shown in figures 4–5. It can be concluded that, in the case of stable single mode operation, the generation frequency depends weakly on these parameters. The optimal beam impedance is 80 Ohm. The dependence of the radiation power on the magnetic field amplitude has a downturn in the field range below 0.5 T, stable single-frequency generation begins at magnetic field values from 1.1–1.3 T and above.

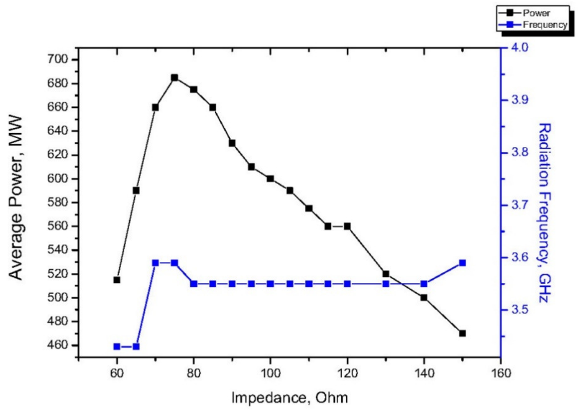

Fig.4. Dependencies of the average microwave power and radiation frequency on the impedance of the vacuum electron diode (voltage at the cathode 450 kV).

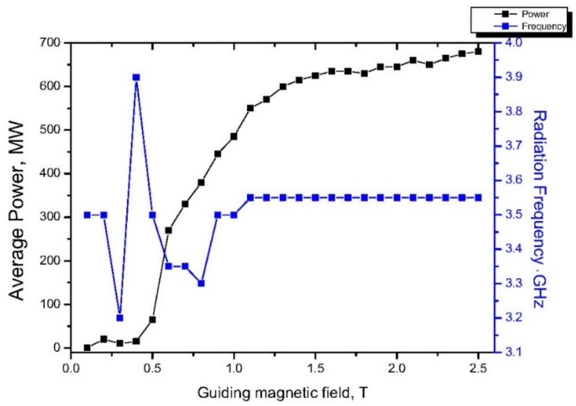

Fig.5. Dependencies of the microwave radiation power and frequency on the magnitude of the guiding magnetic field (voltage at the cathode 450 kV, beam current 5.6 kA).

The calculated dependence of the average radiation power on the length of the cylindrical waveguide insert (L_{ins}) for the variant of RBWO configuration at a beam energy of 450 keV and a guiding magnetic field of 2.5 T is shown in Fig.6. We can conclude while considering and analyzing the presented dependence, that the optimization of the insert length with other identical oscillator parameters makes it possible to double the output radiation power.

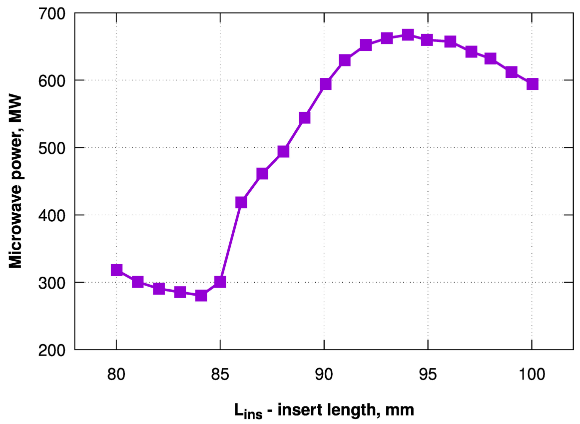

Fig.6. Dependence of the RBWO radiation power on the length of the insert L_{ins} between the cutoff neck and the periodic SWS.

4. Optimization of RBWO generation efficiency with different beam energy

Significant advantages of a resonant BWO over traditional schemes of a relativistic BWO are the shorter length of the interaction region ~3λ, the "resonant" regime of generation of high level oscillations of impulse radiation power, and the mechanism for improving the interaction of an electron beam with both backward and forward waves. On the basis of this principle, this paper presents the results of optimizing the proposed variant of the RBWO with different beam energy. Two RBWO configurations have been developed, optimized for electron beam energies of 400–500 keV and for energies of 500–700 keV indicated below in Fig.7 and Fig.8 as No.1 and No.2, respectively.

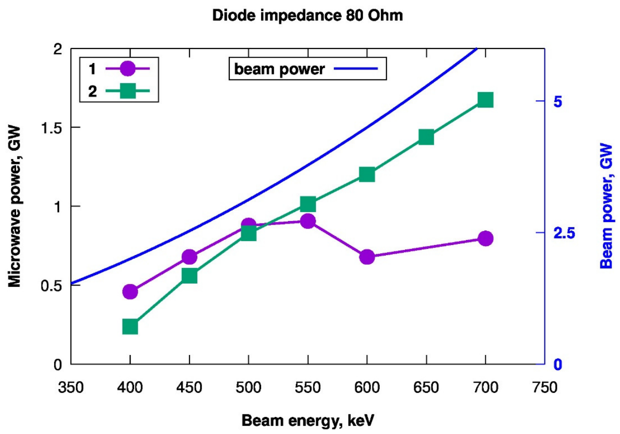

Fig.7. Dependencies of the averaged radiation power for two configurations of the RBWO for the beam energy range of 400–700 keV, the curve of the total beam power is shown above the graphs.

In the course of calculations based on the particle-in-cell code simulation of the BWO, the profiles of the two terminal SWS corrugations, determining the level of partial wave reflection from the edges of the structure, as well as the length of the cylindrical insert have being varied. Other parameters of the SWS specified in section 2 remain the same. In accordance with the graph in Fig.6 the optimal value of L_{ins} for RBWO of configuration No. 1 is 94 mm and for RBWO of configuration No.2 determined optimal length of L_{ins} is amount 70 mm.

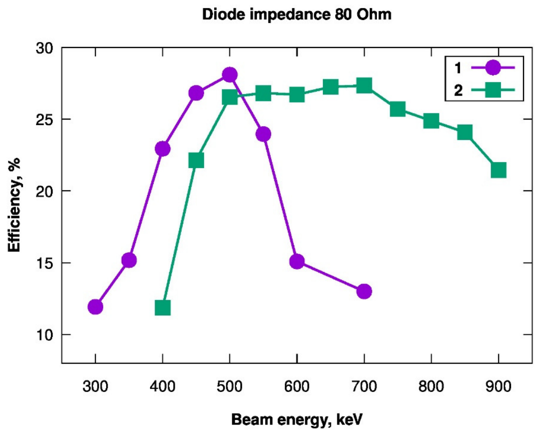

Fig.8. Generation efficiency dependencies for two RBWO configurations.

The results of optimizations the generation of RBWO with different beam energy are shown in the graphs of Fig.7 and Fig.8, which represent the achieved levels of radiation power and the efficiencies of RBWO generation.

5. Conclusion

In this paper the results of research of the generation and optimization of a resonant BWO for the electron beam energy range of 400–700 keV are presented. The variant of a resonant BWO that operates at moderately relativistic beam energies (400–550 keV) and at values of the guiding magnetic field starting from 1.3 T, is presented. Compared to the original BWO geometry, in the current investigation scheme, the length of the periodic structure is increased and composed of 5 periods. It is shown in the numerical simulation that for a beam energy of 550 keV the average radiation power reaches level of 1 GW. High generation efficiency is achieved in magnetic field of 2.5 T. The main generation wavelength is about 8 cm. Thus we have demonstrated efficient approach to the design of the resonant BWO.

6. References

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