S-band Superradiant BWO[1]

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Abstract – Investigation is accomplished of superradiation regime of generation of electromagnetic 3.7 GHz pulses in the relativistic BWO with a long slow wave system at the magnetic field induction of 0.2 Tesla that is lower than the level of cyclotron absorption of the electromagnetic wave by an electron flow. Decompression of the hollow electron beam is used in order to reduce the transversal electron velocity. The decompression as well as the sharp leading edge of 460 kV pulse at explosive emission cathode is used in order to increase the beam azimuthal homogeneity and the cathode life time as well. As a result, a peak power as high as 800 MW of 2.5 ns microwave pulses is obtained at the repetition rate of 100 p. p. s. The time of the continuous pulse periodical operation is increased up to 10^5 – 10^6 pulses. The conversion efficiency of the electron beam power into the electromagnetic wave power increases up to 50 %. Fixation of the phase of electromagnetic oscillations from pulse to pulse by the sharp leading edge of the cathode high voltage was found. That was observed for the fist time in the relativistic oscillator.

It is known, that in a relativistic backward wave oscillator, a short pulse with a duration of a few high-frequency field cicles can be formed whose power considerable exceeds the stationary level. This mode has been actively investigated over the last years theoretically and experimentally [1,2].

The microwave pulse duration is inversely proportional to the absolute instability increment in the beam–backward wave system [1]. It can be about 10 periods of the RF field for typical high-current beam parameters.

$$\tau \cong \left|\mathrm{Im}\,\omega\right|^{-1} \cong \frac{1+V_0/V_{gr}}{C\omega},$$

$$C=\left(\frac{eI_bZ}{2mc^2\gamma_0^3}\right)^{1/3}, \quad Z=\frac{2\,|E_{z,-1}|^2}{k^2\,|N_s|}$$

where C is the generalized Pierce parameter , Z is the coupling impedance, ω is the the wave frequency, e and m are the electron charge and mass, respectively; c is the velocity of light, V_0 is the velocity of electrons at the input of the slow wave structure (SWS), γ_0 is the corresponding relativistic factor, V_{gr} is the wave group velocity, $k = 2\pi/\lambda$ is the wave number, λ is the wavelength in free space I_b is the beam current, N_s is the wave norm, $E_{z,-1}$ is the amplitude of the longitudinal component of the electric field of the synchronous harmonic.

If the SWS length is much greater than the threshold of excitation, a short electromagnetic pulse is formed at the collector end of the device and begins to move towards the beam. The interaction time of an electromagnetic pulse with a beam can exceed its own duration. It allows otaining an output microwave power wich exeeds serveral times the power of the electron beam. [2].

High power conversion is realized by means rather strong magnetic fields and usually in a single pulse regime. For practical applications it is more expedient to use solenoids with a weak magnetic field cooled by a heat-carrier at a room temperature. The level of the magnetic field is about half the value of H_r corresponding to the resonant cyclotron absorption under the condition of

$$\frac{eH_r}{mc\gamma}=\omega+hV_{//}.$$

Here $V_{//}$ is the longitudinal velocity of electrons, h is the longitudinal wave number.

As the first experiments have shown, for such conditions, when generated in a superradiation mode, the microwave power was 2–3 times less than in strong magnetic fields, and the pulse duration was approximately 1.5 times longer. The presence of transversal velocities during electron beam formation leads to dispersion of the longitudinal velocities, which essentially reduces the time of coherence relaxation in a stream.

To estimate the influence of the electron longitudinal speed dispersion on the superradiance generator output parameters one-dimensional PIC-code simulations have been performed.

Fig. 1 shows the dependence of the conversion factor on the generalized nonlinearity parameter ν

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($\nu=2\gamma_0^2C$) at various relative values of the electron longitudinal velocity dispersion: a – $\Delta\gamma/\gamma_0$ = 0, b – $\Delta\gamma/\gamma_0$ = 0.1, c – $\Delta\gamma/\gamma_0$ = 0.2, d – $\Delta\gamma/\gamma_0$ = 0.4.

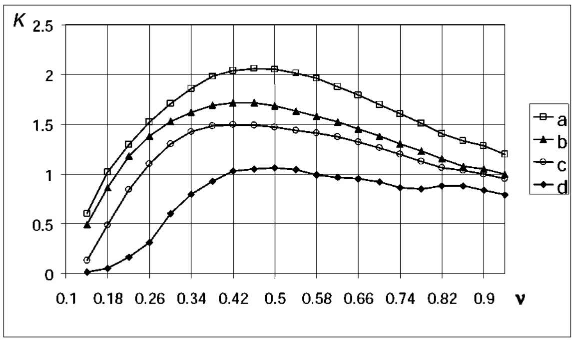

Fig. 1. Dependence of the conversion factor on the nonlinearity parameter.

The parameters of calculation: beam current I_b = 3 kA, γ_0 = 1.6, dimensionless length of the system ξ_k = 6 ($\xi_k = \omega CL/V_0$). Fig. 2 shows the dependence of the relation of energy in the main part of a superradiating microwave pulse to the electron beam energy from the parameter of nonlinearity under the same conditions.

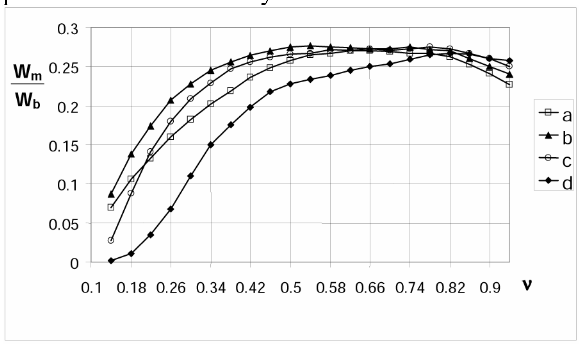

Fig. 2. Energy efficiency as a function of the nonlinearity parameter.

The conversion factor noticeably falls with an increase in the electron longitudinal velocity dispersion $\Delta\gamma/\gamma_0$. However, the energy in the main part of the pulse remains almost constant, and at a moderate level of dispersion, due to the growth of the pulse duration, it can even increase. At greater dispersion an insignificant drop of the energy efficiency occurs at high values of coupling impedance. An additional positive factor of increase in the coupling impedance is a reduction of the SWS length, which allows reducing the magnetic field volume. Besides, reduction of the electron beam length allows one to limit the development of the convective beam instabilities. It contributes to a decrease in the electron longitudinal velocity dispersion, reduction of the beam thickness and improvement of its azimuthal uniformity.

However, realization of such modes is complicated, as at lowered magnetic field the electron beam has a significant thickness, and in the SWS with a high value of the coupling impedance the electric field of the synchronous harmonic has a greater radial inhomogeneity.

Because of the low Larmor frequency electrons have no time to redistribute on the beam thickness during interaction with a short pulse, so some part of the particles is excluded from effective interaction that it is equivalent to a decrease in the current of the beam.

Beam instability development was modelled using a 3-D version of the KARAT code. As the factors influencing the BWO operation, the beam thickness and the growth of the longitudinal electron speed dispersion were considered.

In the real device the rising edge of a vacuum diode voltage pulse has finit duration. It leads to the fact that a part of the electrons moving in the drift space has a speed less than the other particles. Modelling has shown that the instability at the beam front considerably exceeds the stationary level and develops more quickly. This effect can be the reason for a decrease in the superradiance BWO output power with increasing duration of the voltage rising.

At a lowered magnetic field the instability develops more quickly. Besides, the formation of the final number of the emission centers on the cathode edge and the shielding of the surface by space charge fields increase the azimuthal heterogeneity of an electron beam.

In X-band microwave pulse generation research it was revealed that at degradation of the explosive-emission cathode the output power fell, the stability worsened and the delay of the microwave impulse from the leading edge of the vacuum diode voltage pulse increased.

The present work deals with generation of short microwave pulses with the central frequency f_0 = 3.7 GHz in a superradiance mode. Besides, the possibility of increasing the life of the cathode in the long pulse-periodic regime is investigated. The authors suggest raising the decompression degree of an electron beam. So the magnetic field in the cathode area has been strengthened more than 2 times in comparison with the field in the SWS. Stronger field on the cathode allows to increase quantity of the explosive-emission centers and to improve the azimuthal uniformity of an electron beam. It is known [3], that beam decompression reduces the electron transverse velocities, which increases the output power of a generator.

A generator of the type SINUS-350 was used as a source of a voltage pulse. It had the following parameters: the diameter of the coaxial forming line of 350 mm, a wave resistance of 36 Ohm, a charging voltage of 650 kV and a pulse width about 13 ns (Fig. 3).
For correction of the high-voltage pulse shape we used athe circuit made of a "buffer" transmitting line with an electric length of 0.5 nanoseconds and a wave resistance 15 Ohm, as well as a sharpening switch. Part

of the high-voltage pulse rising edge, reflected from the main gas gap swich, after breakdown of the sharpening switch, added to the main part of the pulse and led to increasing the amplitude of its initial site up to 30 %.

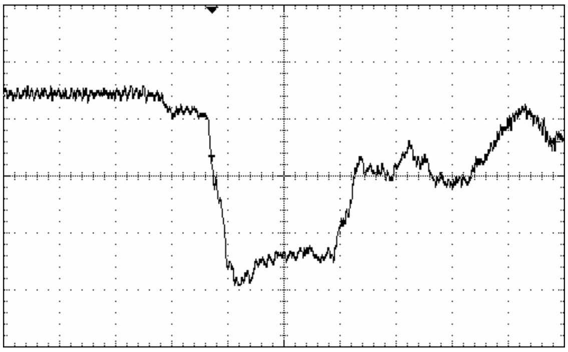

Fig. 3. Cathode voltage pulse. The scale is 5 ns/div.

The electron beam was formed in the coaxial vacuum diode with an impedance about 100 Ohm. The voltage on the cathode was 460 kV. The cathode material was foiled fiberglass laminate. Use of the voltage pulse with an abrupt rising improved the emission ability of the cathode due to an increase in the number of explosive-emission centers and contributed to the improvement of the azimuthal symmetry of an electron beam. For guiding the beam a solenoid with two sections was used which included a cathode and a drift section of drift with the lengths of 370 mm and 920 mm. The solenoid fed from a pulse-width modulator with independent adjustment of a current in the sections.

The parameters of the slow-wave structure were optimized using an axisymmetric version of the KARAT program. The corrugation period of the slow-wave structure was 36 mm, the internal diameter was 113 mm, and the corrugation amplitude was variable. A wideband resonance reflector ensured reflection of the electromagnetic back wave. The space between the SWS wall and the inner tube of the solenoid was cooled by running water.

Improvement of the emission conditions and the uniformity of an electronic beam allowed achieving a resource of continuous operation of the cathode over 10^5 pulses at 100 p.p.s. within 20 minutes batches without appreciable fall of the output microwave power.

Microwave radiation was received by the short symmetric electric vibrator antenna. Besides, a waveguide-to-strip line coupler on the output of the SWS was also used. Further a microwave signal was transferred via a coaxial cable to a shielded room and when passing through a set of coaxial attenuators, it was measured with a semiconductor diode detector. The detected signal was registered by a digital real time oscilloscope TDS 7704B with a 4 GHz band. Also the microwave signal was registered directly. The microwave pulse batch was measured with a coaxial vacuum calorimeter. The calorimeter included a thermoresistor located in a glass tube with ethyl alcohol.

In the experiment generation at a frequency of 3.7 GHz was observed. The spectrum width was about 400 MHz at a –10 dB level. Direct registration of a radio pulse allowed finding out the effect of synchronization of the phase of high-frequency oscillations with the rising edge of the feeding voltage pulse.

Fig. 4 shows the result of overlay of a series of 30 microwave pulse waveforms. The oscilloscope was triggered by the leading edge of the voltage pulse (Fig. 3).

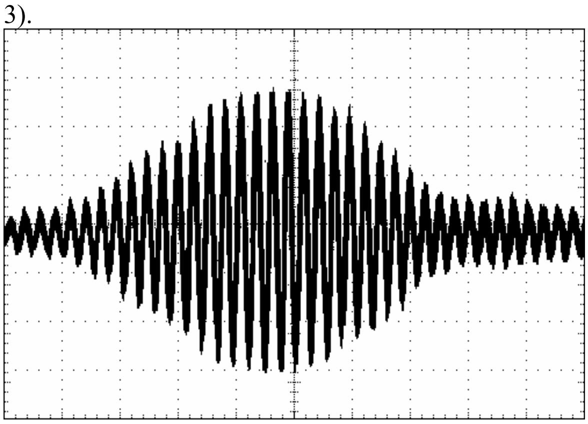

Fig. 4. Microwave pulse waveform. The scale is 1 ns/div.

This result can be explained by the fact that that excitation of generation occurs due to the harmonics of short rising of an electron beam current.

The energy of the microwave pulse was as high as 2 J. the peak output power at 100 p.p.s. was up to 800 MW. Its instability did not exceed 5 %, it was caused, mainly, by instability of the output voltage of the high-voltage generator. Change the ratio of currents in cathode and the drift sections of the solenoid enabled changing the diameter of an electron beam in the SWS without replacement of the cathode. An increase in the current in the drift section reduced the diameter of the beam and the coupling impedance. Accordingly, the instability increment also decreased. So, with an increase in the current of the drift section by 10 % duration of a pulse increased from 2.2 up to 2.8 ns.

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