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Power self-modulation search in terahertz Cherenkov generators with single-section slow-wave structure

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Abstract. The interaction of an electron beam and the electromagnetic field of an oversized slow-wave structure in the terahertz (>300 GHz) frequency range was studied using a 2.5D hybrid electromagnetic code. In numerical experiments, a tubular electron beam with a current of 0.2–25 kA was injected into a single-section slow-wave structure with and without a diffraction reflector. Regular self-modulation of power in a single-section structure without a diffraction reflector was detected at a beam current of 20 kA, electron energy of 415–445 keV, and a magnetic field of 3.5–4 T. This corresponded to a ratio of the beam current to the starting generation current of 66.6. The power modulation depth reached 50–60%. When using a diffraction reflector, the range of beam parameters at which self-power modulation was detected reduced. It was found at a beam current of 20 kA, electron energy of 430 keV and a magnetic field of 4 T. At the same time, the power modulation depth decreased to 16.7%.

Keywords: vacuum electron devices, Cherenkov radiation, terahertz waves, self-modulation mode.

1. Introduction

Vacuum electronic devices are promising for creating powerful compact radiation sources in the terahertz (0.3–3 THz) frequency range [1]. Megawatt radiation pulses in the frequency range 319–349 GHz were obtained in a Cherenkov surface wave oscillator [2, 3]. In these experiments, a single-section slow-wave structure with a ratio of diameter to radiation wavelength $D/\lambda = 6.8$ without a reflector [2] and with a resonant reflector [3] was used.

In theoretical studies [4] of a surface wave oscillator in the X-band, it was shown that at $D/\lambda = 7$ and beam current $I_b = 7.5$ kA, the output radiation is multi-frequency and contains a mixture of symmetrical TM_{01} and asymmetrical TM_{11} modes with a pulse duration of 20 ns or more. With a pulse duration of more than 60 ns, the asymmetric TM_{11} mode prevails. However, experimental studies [5] on the SINUS-7M accelerator with a voltage pulse duration of 40 ns, $D/\lambda = 13.7$ ($D = 118$ mm, $\lambda = 8.6$ mm) and beam current $I_b = 9.5$ kA showed that the asymmetric mode in a single-section structure does not was excited with an average beam diameter of 108 mm. With an average beam diameter of 109 mm, the power of axially symmetric radiation was 93% of the total output power. The wavelength of axially symmetric radiation increased to 8.8 mm. In these experiments, the beam was asymmetrical due to the asymmetrical magnetic field of the solenoid. The difference between the large and small diameters did not exceed 1 mm. The width of the output radiation spectrum did not exceed 1%. The share of the radiation power of the asymmetric mode was more than 95% when the difference between the small and large beam diameters increased to 3 mm. Thus, by controlling the beam geometry and the length of the slow-wave structure, it is possible to obtain axially symmetric radiation with an oversize parameter $D/\lambda >> 10$.

In our numerical experiments on the generation of terahertz (> 300 GHz) radiation, we used a single-section slow-wave structure with a length of 40 diaphragms and an oversize parameter $D/\lambda = 49$ [6, 7]. The studies were carried out in the absence [6] and use of a diffraction reflector [7]. The calculations took into account longitudinal electromagnetic resonances of the axially symmetric mode TM_{01} near the π-type oscillations. At a tubular beam current of up to 10 kA, we did not detect self-modulation of the radiation power. In theoretical studies [8], it was shown that the ratio of the beam current at which the self-modulation regime occurs to the starting current in the generator near the upper boundary of the TM_{01} mode transmission band is much greater than for a backward wave oscillator. In this regard, to detect the self-modulation mode in generators [6, 7], we increased the beam current in numerical experiments to 25 kA.

2. Numerical simulation results

Initially, a Cherenkov generator was studied, which, similar to [6], had a homogeneous slow-wave structure with a diameter of 40 mm. The structure contained 40 rectangular diaphragms with length $w = 0.17$ mm, height $h = 0.17$ mm, and period $d = 0.34$ mm. In the second Cherenkov generator, a diffraction reflector containing 6 diaphragms with a period of 0.4 mm was installed in front of a similar slow-wave structure at a distance of 0.6 mm. The number of diaphragms in the diffraction reflector and the distance between it and the slow-wave structure were chosen based on the results of previous studies [7].

For numerical simulation of Cherenkov generators, a 2.5D hybrid electromagnetic PIC code was used without taking into account ohmic power losses [6, 7]. A tubular beam with electron energy $W_e = 405$–465 keV, current $I_b = 0.2$–25 kA, average radius $r_b = 19.7$–19.75 mm, and thickness 0.3 mm was injected into an electrodynamic system with pre-calculated fields of longitudinal electromagnetic resonances. The duration of the leading front of the beam current pulse I_b and, accordingly, the voltage on the diode U_d was 0.5 ns. The magnetic field varied within the range $B = 2$–4.5 T.

The calculations took into account the first three longitudinal resonances, measured from the frequency of π-type oscillations of the TM_{01} mode (368.47 GHz) of an infinite periodic ($d = 0.34$ mm) waveguide, which corresponds to an electron energy near 420 keV. Resonances are characterized by frequency F, quality factor Q, norm N_e and field structure. The calculations assessed the power forward (P^+), backward (P^-) and total power ($P^- + P^+$) of radiation. To analyze the process of interaction between the beam and the field, the amplitudes of the resonances, the synchronization frequency f_s of the instantaneous resonance frequencies f_i, the spectra S_i, and the frequency of the maximum of the radiation spectrum f_0 were estimated. The parameters of the radiation power are given after generation reaches a stationary regime. The main numerical experiments were carried out at $W_e = 420$ keV, $r_b = 19.75$ mm, $B = 4$ T. The starting current I_{st} for both Cherenkov generators is 0.3 kA.

Initially, we will consider the results of research on the Cherenkov generator without a diffraction reflector. The geometry of an electrodynamic system with an electron beam ($W_e = 420$ keV, $I_b = 20$ kA, $B = 4$ T, $r_b = 19.75$ mm) for the time $t = 3$ ns is shown in Fig. 1.

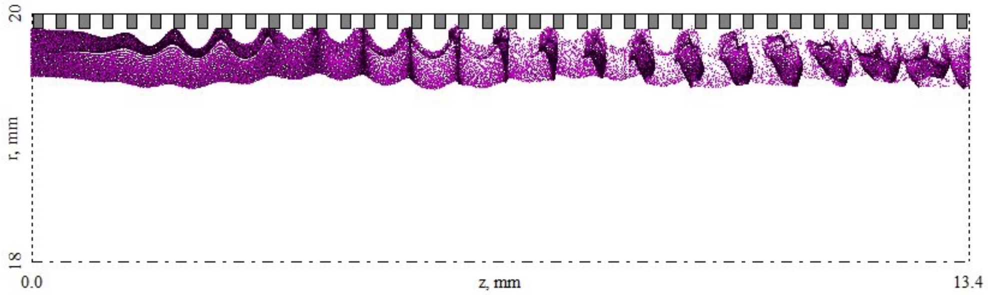

Fig. 1. Geometry of a homogeneous slow-wave structure with a beam ($W_e = 420$ keV, $I_b = 20$ kA, $r_b = 19.75$ mm, $B = 4$ T) at time 3 ns.

Regular self-modulation of the radiation power was detected in the generator with the electron energy range $W_e = 415$–445 keV at $r_b = 19.75$ mm, $B = 3.5$–4 T and current $I_b = 20$ kA. The ratio of the beam current to the starting current is $I_b/I_{st} = 66.6$. The power of self-modulation with a frequency of 2.1 GHz is equal to 130 MW in a stationary regime with an efficiency of forward radiation power output of 15–25% (Fig. 2*a*, 2*b*). The depth of power self-modulation was 50–60%. The spectrum contains the main frequency and two symmetrical satellites (365.3±2.1 GHz). Power self-modulation decay within 4–7 ns when the beam radius decreases to 17.25–17 mm, the beam current to 10–15 kA, the magnetic field to 3 T, or the magnetic field increases to 4.5 T.

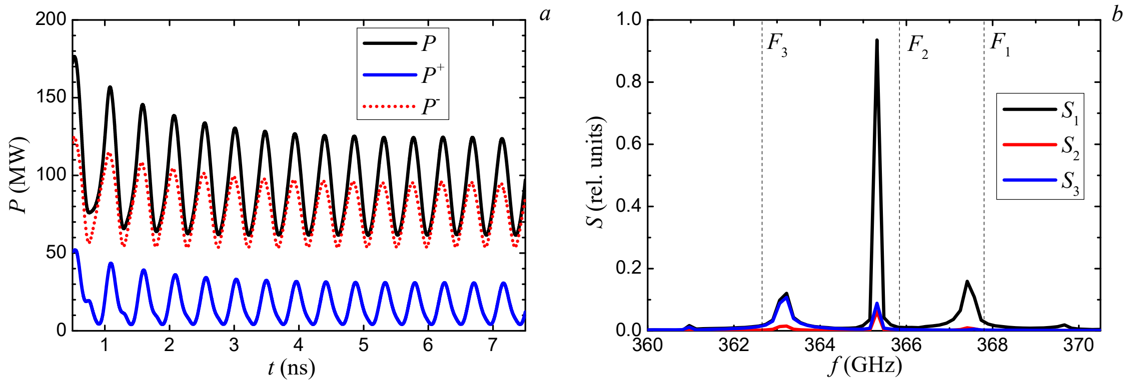

Fig. 2. Self-modulating power (*a*) and spectra of resonances (*b*) for homogeneous slow-wave structure with beam (420 keV, 20 kA, 19.75 mm, 4 T).

As the beam current increases to 25 kA, power fluctuations become irregular (chaotic) (Fig. 3*a*). The spectrum expands and contains many frequency bands (Fig. 3*b*). As the electron energy increases to 430 keV, with other beam parameters being the same, the power increases (Fig. 4*a*), and three main peaks stand out in the spectrum on the pedestal (Fig. 4*b*).

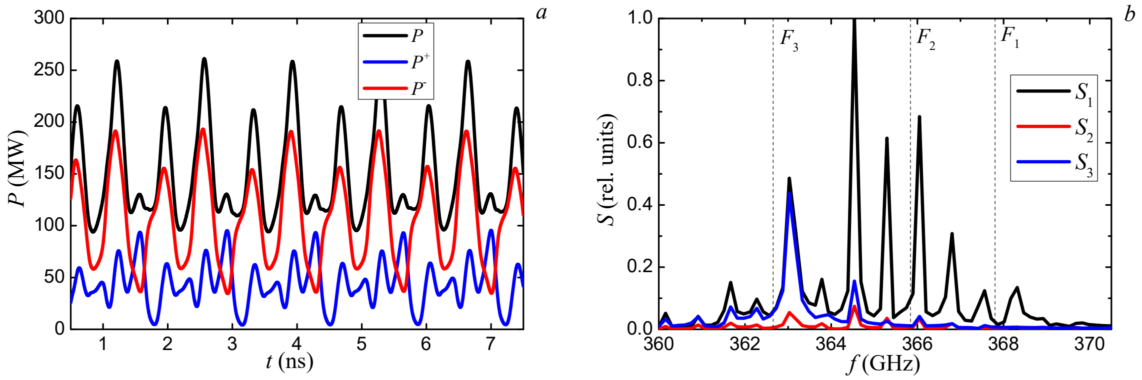

Fig. 3. Self-modulating power (*a*) and spectra of resonances (*b*) for homogeneous slow-wave structure with beam (420 keV, 25 kA, 19.75 mm, 4 T).

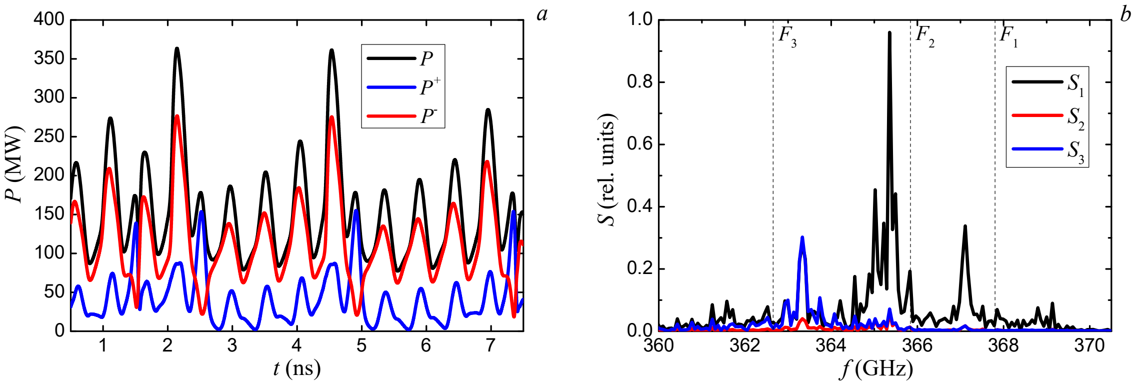

Fig. 4. Self-modulating power (*a*) and spectra of resonances (*b*) for homogeneous slow-wave structure with beam (430 keV, 25 kA, 19.75 mm, 4 T).

Detailed numerical studies of a Cherenkov generator with a diffraction reflector (Fig. 5) were performed.

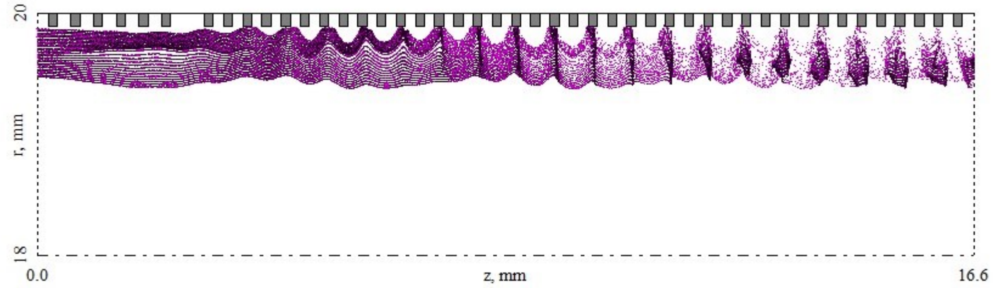

Fig. 5. Geometry of the diffraction reflector and slow-wave structure with the beam (420 keV, 20 kA, 19.75 mm, 4 T) at time 3 ns.

Regular self-modulation of power was detected at energy W_e = 430 keV, I_b = 20 kA r_b = 19.75 mm, B = 4 T. The modulation depth of full power and forward power was low at 16.7% (Fig. 6*a*). Self-modulation of backward power was practically absent. The spectrum contained a central frequency of 365.9 GHz and symmetrical low-amplitude satellites (Fig. 6*b*).

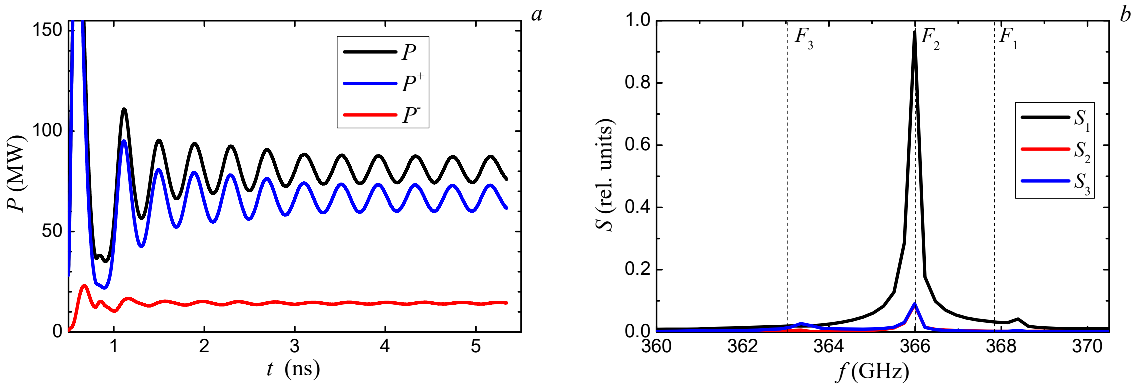

Fig. 6. Self-modulation power (*a*) and spectra of resonances (*b*) for a slow-wave structure with a diffraction reflector and a beam (430 keV, 20 kA, 19.75 mm, 4 T).

The total power of stationary radiation is 80 MW with an efficiency of forward radiation power output of 82%. Outside the specified parameters of the electron beam, damped power oscillations were observed at the beginning of the pulse for 1.5–3 ns before synchronization of the instantaneous resonance frequencies. The corresponding research results are presented for the energy W_e = 420 keV (Fig. 7*a*, 7*b*) and W_e = 410 keV (Fig. 8*a*, 8*b*) with other identical beam parameters.

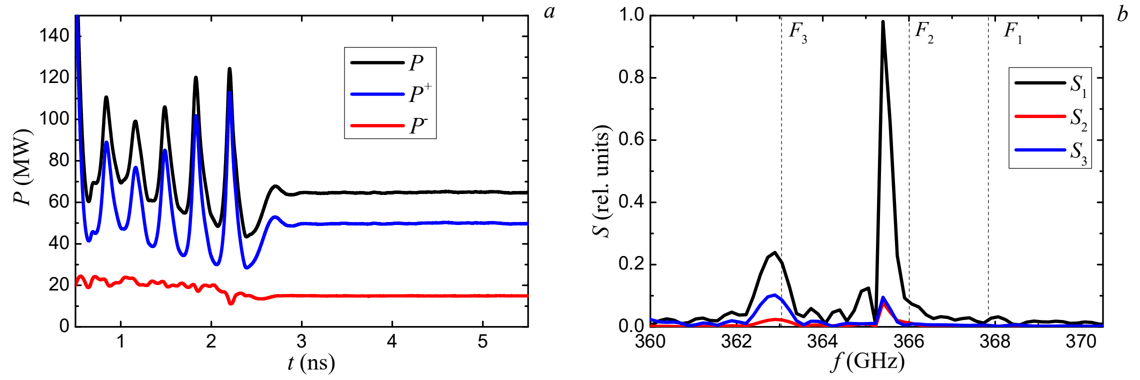

Fig. 7. Damped self-modulation of power (*a*) and spectra of resonances (*b*) for a slow-wave structure with a diffraction reflector and a beam (420 keV, 20 kA, 19.75 mm, 4 T).

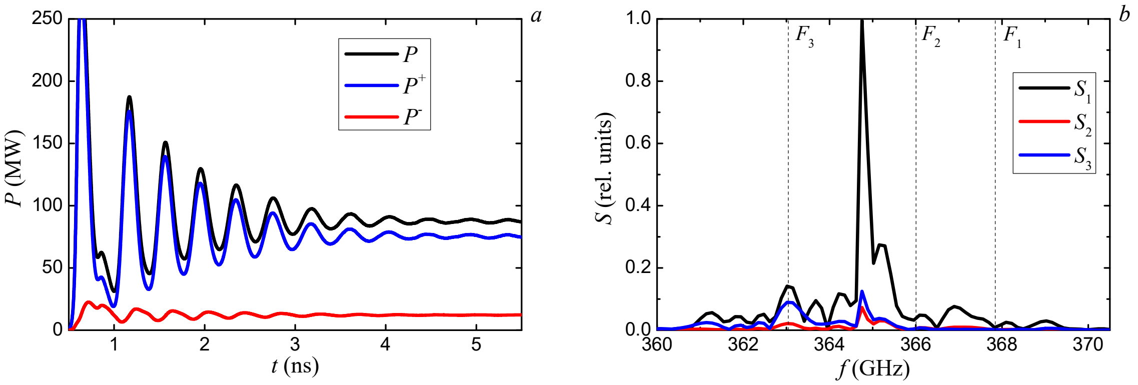

Fig. 8. Damped self-modulation of power (a) and spectra of resonances (b) for a slow-wave structure with a diffraction reflector and a beam (410 keV, 20 kA, 19.75 mm, 4 T).

The self-modulation mode was discovered earlier in a multiwave Cherenkov generator (MWCG) with a diffraction reflector at W_e = 420 keV, I_b = 5 kA, B = 3 T, r_b = 19.75 mm [9]. A similar slow-wave structure with 40 diaphragms was divided into two sections. The length of the drift tube between sections was 2.4 mm at a radiation wavelength λ = 0.82 mm. The total radiation power reached 190 MW with a modulation depth of 97% and a subnanosecond pulse repetition rate of 1.7 GHz. Power ratio was equal to P^+/P = 73%.

3. Conclusion

From the obtained results of numerical simulation of the interaction of the electron beam and the electromagnetic field in a single-section slow wave structure with D/λ = 49 near the upper boundary of the TM_{01} mode transmission band, it follows that the self-modulation regime of the radiation power is realized at a beam current of 20 kA, which corresponds to the ratio I_b/I_{st} = 66.6. The I_b/I_{st} ratio is approximately 20 times greater than for a standard backward wave oscillator. The use of a diffraction reflector made it possible, at I_b = 20 kA, to reduce the range of electron beam parameters in terms of energy and magnetic field for unstable generation of radiation, as well as to reduce the depth of power modulation by 3–4 times. At the same time, the proportion of forward radiation power relative to the total power has increased significantly, which increases the energy efficiency of the generator.

From a comparison of the obtained results of numerical simulation of a Cherenkov generator with a diffraction reflector and a MWCG [9], it follows that the MWCG is a promising device for producing subnanosecond pulses with a gigahertz repetition rate in the terahertz frequency range. Sectioning the slow-wave structure in the MWCG made it possible in the self-modulation mode to reduce the beam current from 20 kA to 5 kA, the magnetic field from 4 T to 3 T, to increase the total radiation power from 80 MW to 190 MW and the self-modulation depth from 16.7% to 97% at similar values efficiency of forward radiation power output.

Acknowledgement

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4. References

[1] J.H. Booske, R.J. Dobbs, C.D. Joye, C.L. Kory, G.R. Neil, G.S. Park, J. Park, and R.J. Temkin, Vacuum electronic high power terahertz sources, *IEEE Trans. Terahertz Science and Technology*, vol. **1**, 54, 2011, doi: 10.1109/TTHZ.2011.2151610

[2] J. Wang, G. Wang, D. Wang, S. Li, and P. Zeng, A megawatt-level surface wave oscillator in Y-band with large oversized structure driven by annular relativistic electron beam, *Scientific Reports*, vol. **8**, 6978, 2018, doi: 10.1038/s41598-018-25466-w

[3] S. Li, J. Wang, and D. Wang, Relativistic surface wave oscillator in Y-band with large oversized structures modulated by dual reflectors, *Scientific Reports*, vol. **10**, 336, 2020, doi: 10.1038/s41598-019-55525-9

[4] N.S. Ginzburg, V.Yu. Zaslavskii, A.M. Malkin, and A.S. Sergeev, Quasi-optical theory of coaxial and cylindrical surface-wave oscillators, *Technical Physics*, vol. **58**, 267, 2013, doi: 10.1134/S1063784213020102

[5] V.I. Koshelev, V.A. Popov, Relativistic multiwave Cerenkov generators of millimeter wavelength range, *Proc. SPIE*, vol. **4031**, 270, 2000, doi: 10.1117/12.391808

[6] M.P. Deichuly, V.I. Koshelev, A.A. Petkun, V.A. Chazov, Synchronization of electromagnetic resonances in terahertz Cherenkov generator, *Izvestiya vuzov. Fizika*, vol. **66**, 92, 2023, doi: 10.17223/00213411/66/6/11

[7] M.P. Deichuly, V.I. Koshelev, A.A. Petkun, and V.A. Chazov, Interaction of a relativistic electron beam and electromagnetic field in a terahertz Cherenkov generator with a Bragg reflector, *Journal of Commun. Technol. Electronics*, vol. **68**, 1430, 2023, doi: 10.1134/S1064226923120057

[8] L.V. Bulgakova, S.P. Kuznetsov, Unsteady-state nonlinear processes accompanying the interaction of an electron beam with an electromagnetic field near the boundary of a transmission band. 1. The high-frequency boundary, *Radiophysics and Quantum Electronics*, vol. **31**, 155, 1988, doi: 10.1007/BF01039179

[9] V.A. Chazov, M.P. Deichuly, V.I. Koshelev, and A.A. Petkun, Interaction between electron beam and electromagnetic field in terahertz multiwave Cherenkov generator with diffraction reflector, *Russian Physics Journal*, vol. **66**, 567, 2023, doi: 10.1007/s11182-023-02976-3