doi: 10.56761/EFRE2022.S3-O-020502

High-power terahertz Cherenkov radiation in oversized slow-wave structure

V. Chazov, M. Deichuly, V. Koshelev, and A. Petkun*

Institute of High Current Electronics SB RAS, Tomsk, Russia
koshelev@lhfe.hcei.tsc.ru

Abstract. The paper presents the results of numerical simulation of the interaction of a relativistic electron beam and an electromagnetic field in an oversized slow-wave structure near π-type oscillations of the TM_{01} mode in the terahertz (>300 GHz) frequency range. The calculations used the developed 2.5D hybrid electromagnetic model. A tubular electron beam with a current of 5 kA and energy of 400–490 keV was injected into a 40-mm diameter slow-wave structure. In the calculations, radiation with a power of 250 MW was obtained.

Keywords: numerical simulation, relativistic electron beam, Cherenkov radiation, terahertz.

1. Introduction

It seems promising to use electronic vacuum devices of the Cherenkov type to generate high-power terahertz (0.3–3 THz) radiation. To create small-sized sources of high-power radiation on a mobile platform, it is necessary to use high-current electron beams with an electron energy of up to 500 keV. Currently, 2.1 MW radiation pulses in the frequency range of 0.319–0.349 THz have been obtained in the Cherenkov surface wave oscillator [1] in a slow-wave structure with an oversize parameter (the ratio of the diameter to the wavelength of the radiation) equal to 6.8. An electron beam with a current I_b = 2.3–3.6 kA generated in a diode at a voltage U_d = 350–480 kV in a magnetic field B = 3.1 T was used in the experiments.

For numerical simulation of various types of Cherenkov devices with axial symmetry, we have developed a 2.5D hybrid electromagnetic code consisting of two parts. The electrodynamic part of the scattering matrix-based code is used to study the resonant properties of oversized sectioned slow-wave structures. Examples of using the electrodynamic part of the code, including in the sub-terahertz frequency range, can be found in papers [2, 3] The second part of the code is developed on the basis of the PIC method and is used to simulate the interaction of a relativistic tubular electron beam with an electromagnetic field of pre-calculated resonant modes with high Q-factor, the amplitudes of which are determined by the changing beam current.

The paper presents the first results of numerical simulation of the Cherenkov device of the terahertz range using the developed hybrid code. The interaction of a tubular electron beam and an electromagnetic field near the π-type oscillations of the TM_{01} mode was investigated. The model used the condition of ideal conductivity of the slow-wave structure surface, that is, ohmic power losses [1] were not taken into account.

2. Geometry of the problem

The geometry of the slow-wave structure with an electron beam is shown in Fig.1. The calculations used a section of a periodic (d = 0.34 mm) waveguide of the radius R_w = 20 mm with rectangular diaphragm of the width w = 0.17 mm and height h = 0.09 mm. The number of diaphragms in the section is 40. The length of the section L = 13.43 mm. Note that in the device under study, the oversize parameter is 49, and the ratio $L/2R_w$ is 0.3, while usually this ratio is much greater than the one for surface wave oscillators.

A tubular electron beam with a current I_b = 5 kA was injected into the slow-wave structure. The duration of the leading edge of the beam current pulse varied in the range τ = 0.25–2.5 ns. The thickness of the electron beam $\Delta R_b = R_2 - R_1$ with a uniform distribution of current density varied within 0.2–0.6 mm. The average radius of the electron beam R_b varied in the limits of 19.35–19.8 mm. The uniform magnetic field B = 1–5.5 T. The electron energy of the beam varied in the range of $W_e = 400–490$ keV. At the same time, the estimated voltage on the diode U_d did not exceed 500 kV.

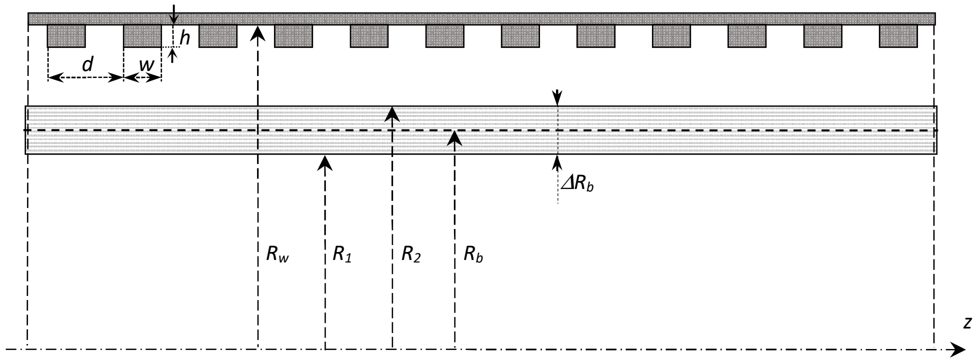

Fig.1. Parameters of the geometry of the calculated area (arbitrary scale).

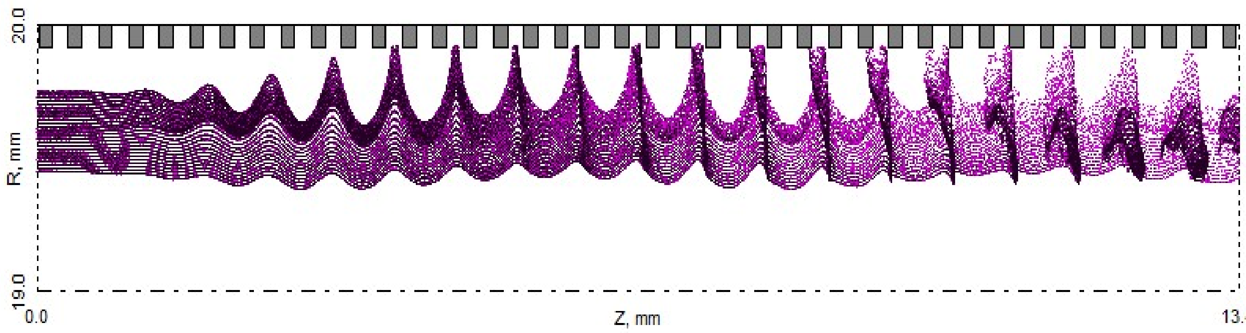

Fig.2. Portrait of the beam (*r*-*z*) in the process of bunching when interacting with the field. The beam radius is 19.6 mm, the thickness is 0.3 mm, the energy is 490 keV, and the magnetic field is 1 T. The time point 1.1 ns corresponds approximately to the middle of the radiation power front for this variant.

The computation 2.5D model based on the PIC method used a grid $N_r \times N_z = 2000 \times 1344$ (a sampling step is 0.01 mm). The number of large particles averages 110 000–140 000 (4–8 particles per cell). At each time step $\Delta t = 0.03$ ps, particles enter the calculated region on the left at $z = 0$, and leave on the right at $z = L$ (Fig.2). The finite-difference $(r - z)$ Poisson equation determines the Coulomb field, and the vortex electromagnetic field is calculated using the equations of excitation of resonant modes of the slow-wave structure by an electron beam. The total field is used in 3D equations of particle motion. During the front, the particles gradually fill the area with an increase in the voltage on the diode and a matched rise in the current and energy of the particles. The temporal dynamics of the beam-field interaction was studied within 3–20 ns and depended on the parameters of the problem.

3. Results of numerical simulation

In electrodynamic calculations, two main longitudinal resonances were found corresponding to the modes TM_{011} and TM_{012} with the frequencies of 0.3678 and 0.3658 THz and *Q*-values of 2464 and 622, respectively. The frequency of the π-type oscillations of the TM_{01} mode of an infinite periodic waveguide is 0.3685 THz. After preliminary discussion, a set of parameters was selected for the first calculations of the interaction of the electromagnetic field of resonances with an electron beam of the current $I_b = 5$ kA. They are the following: $W_e = 422$ keV ($U_d = 430$ kV), $\Delta R_b = 0.3$ mm, $\tau = 0.5$ ns, and $B = 3$ T.

It follows from the calculations that as a result of the interaction of the two resonances with the beam, they are synchronized at a frequency different from the original ones. The dependence of the backward radiation power on time for different beam radii is shown in Fig.3.

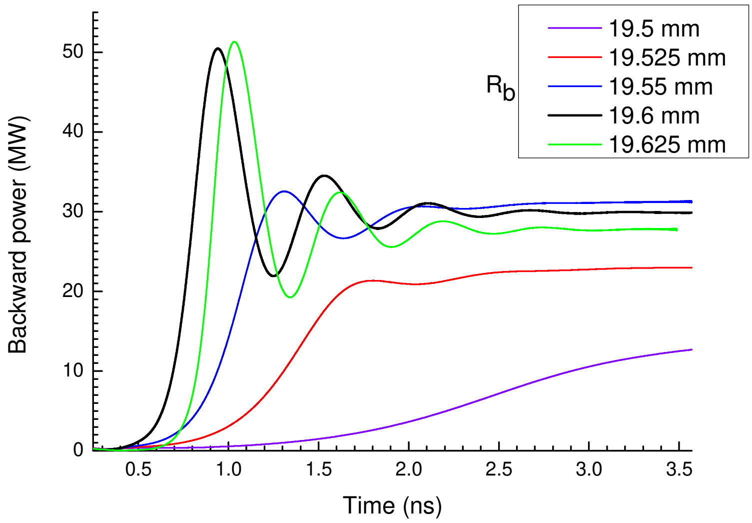

Fig.3. Backward power versus time at different beam radii and the same electron energy of 422 keV.

After setting the mode-locked regime, the radiation power and the frequency are constant. The values of the forward (P^+) and backward (P^-) radiation power and the total power ($P = P^+ + P^-$) will be given only for a stationary generation mode. Figs.4a,b shows the dependences of the power and frequency of radiation on the electron beam radius. The basic part of the power goes backward. The forward and backward power ratio $P^+/P^- \approx 0.1$. The frequency of the maximum of the radiation spectrum f_c and instantaneous frequency f_i decreases with an increase in the beam radius in the range of 0.3675–0.3662 THz.

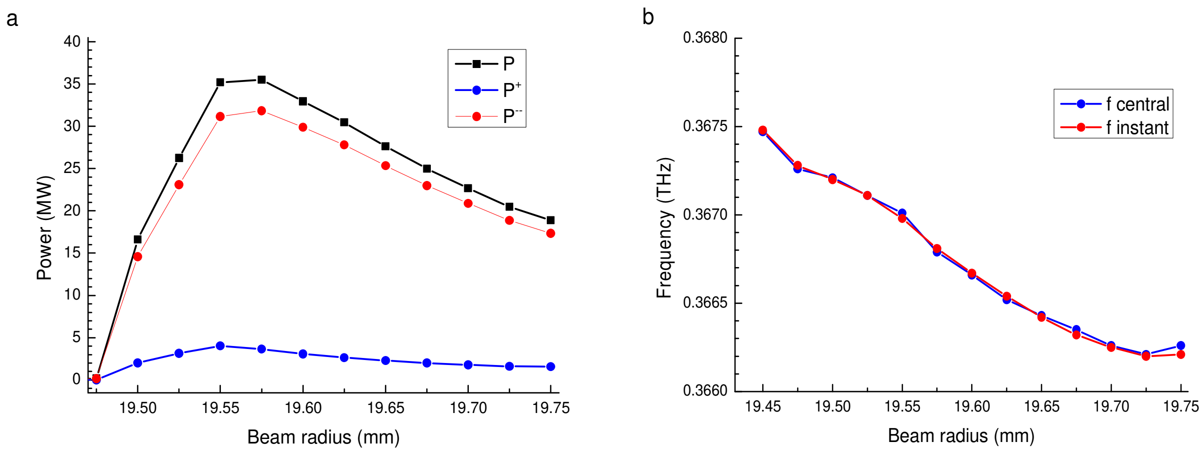

Fig.4. The power (a) and the frequency (b) of radiation versus the radius of a 0.3-mm thick beam.

To find out the influence of the beam thickness on the radiation power, two series of calculations were performed. In the first series, the outer radius of the beam $R_2 = 19.9$ mm was constant, and the thickness of the beam (0.2–0.6 mm) changed by decreasing the inner radius R_1. The radiation power increased up to $\Delta R_b = 0.4$ mm, and then decreased. At the same time, the average beam radius also changed. It follows from the calculations that at the same $R_b = 19.7$ mm, the radiation power at $\Delta R_b = 0.3$ mm was 11 % greater than at $\Delta R_b = 0.4$ mm. In the second series of calculations, the beam thickness varied in the range ΔR_b = 0.2–0.6 mm with constant R_b = 19.6 mm. The main part of the power (P^-) decreased from 40 MW at ΔR_b = 0.2 mm to 30 MW at ΔR_b = 0.3 mm, and to 14 MW at ΔR_b = 0.6 mm therewith. As it follows from the calculations, bunches are formed over the entire thickness of the beam at ΔR_b = 0.2–0.3 mm (see also Fig.2). With further increase, the bunches are formed only in the upper part of the beam. Note that the field decreases radially by *e* times at a distance Δr = 0.2 mm. From our point of view, the optimal is ΔR_b = 0.3 mm, taking into account the difficulties of forming a thin high-current beam.

In subsequent calculations, the basic beam radius R_b = 19.6 mm was added to the above set of parameters. Calculations showed that the change in the beam front (τ = 0.25–2.5 ns) did not result in a change in the power and frequency of radiation, but increased the calculation time. Therefore, the calculations continued at τ = 0.5 ns.

An important parameter is the magnetic field. Figs. 5a,b shows the results of calculations of the dependences of the power and frequency (instantaneous f_i and central f_c) of radiation on the magnetic field B = 1–5.5 T. The total power increases with growth of B and reaches a maximum at B = 4 T, then drops slightly and reaches saturation. It should be noted that at B > 4 T, the beam electrons do not touch the surface of the diaphragms. The instantaneous frequency was estimated using the analytical signal (Hilbert transform). With B growth, it gradually reaches saturation. The frequency of the radiation spectrum maximum differs from the instantaneous frequency within the limits of the calculation accuracy due to the choice of the time window during the Fourier transform. A small dip in frequency at B = 1.5 T should be noted.

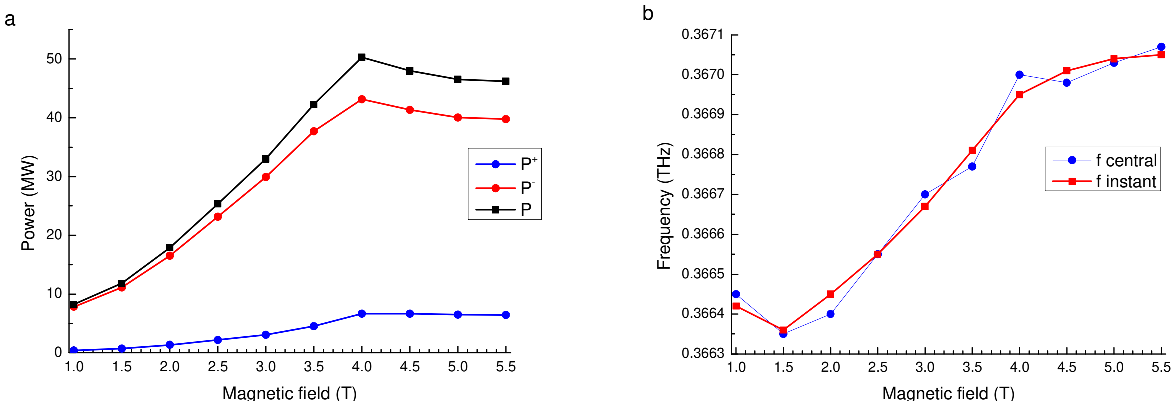

Fig.5. The power (a) and the frequency (b) of radiation versus the magnetic field.

The results of numerical simulation of the influence of electron energy (W_e = 400–490 keV) on the power and frequency of radiation are shown in Figs. 6a,b. One can see that the growth of W_e results in the increase of the ratio P^+/P^- from 0.13 to 0.71 and the total power reaches 78.85 MW. A small dip in power at W_e = 422 keV should be noted. The frequency gradually increases within 0.3662–0.3674 THz therewith. This tendency is consistent with the results of calculations of a surface wave oscillator with an oversize parameter 3 in the frequency range of 264–273 GHz using an analytical model [4].

An attempt was made to search for a higher radiation power when the beam radius changes. Indeed, as the electron energy increases, the optimal beam radius with maximum power decreases. At a radius R_b = 19.425 mm and electron energy W_e = 490 keV, radiation with a power of 171 MW was obtained. At the same time, the ratio P^+/P^- = 0.65. Magnetic field increase up to 4 T resulted in the increase of the radiation power up to 238 MW; the ratio P^+/P^- = 0.72. Decrease of the beam thickness to 0.2 mm under the same conditions resulted in the radiation power increase up to 252 MW; the ratio P^+/P^- = 0.73. The generation efficiency is 10 %.

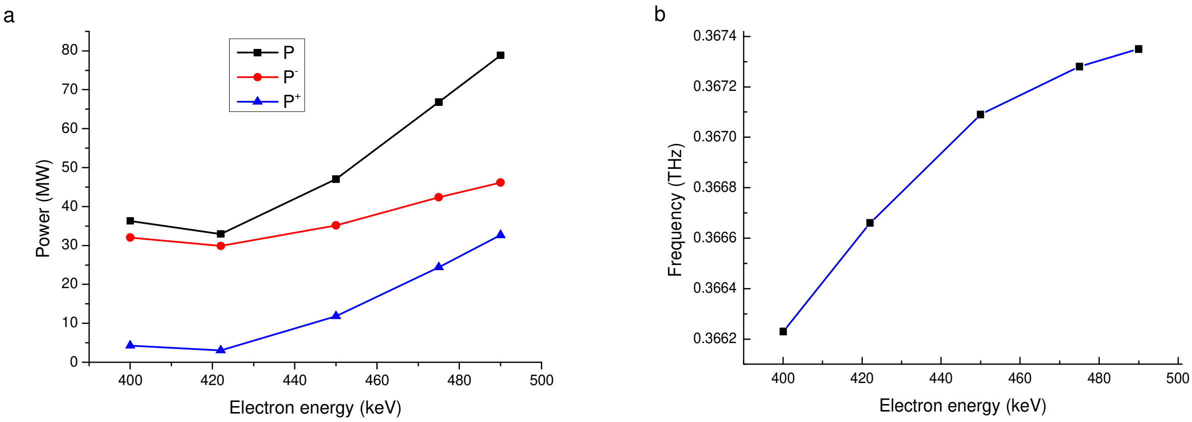

Fig.6. The power (a) and the central frequency of the radiation spectrum (b) versus the energy of the beam electrons at a beam radius of 19.6 mm.

After synchronization of the resonances, the interaction of the beam and the field is carried out at the same frequency. The forward and backward radiation power is the sum of the power modes TM_{0m} (m = 1–49) of a smooth waveguide (multiwave radiation). Figure 7 shows the forward and backward power distribution by modes for the calculation variant with the power of 171 MW. The main part of the power is radiated by the modes with m = 1–20.

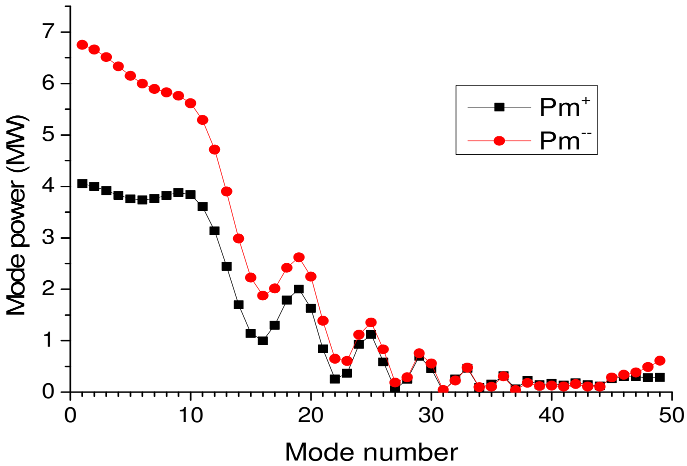

Fig.7. Distribution of radiation power over the modes of a smooth waveguide.

4. Conclusion

A hybrid 2.5D electromagnetic model of vacuum Cherenkov devices based on oversized slow-wave structures has been developed. Numerical simulation of the interaction of a relativistic electron beam and an electromagnetic field in a wide range of beam parameters was performed. In the terahertz frequency range, radiation with a power of up to 250 MW was obtained in the approximation of the absence of ohmic losses. To increase the total power and especially the forward radiation power, it is assumed to use a sectioned slow-wave structure and a diffraction reflector, as in a multiwave Cherenkov generator [3]. In the calculations, it is also necessary to take into account ohmic power losses.

Acknowledgements

This work was financially supported by the Russian Science Foundation (project No. 22-29-00063).

5. References

[1] Wang J., Wang G., Wang D., Li S., Zheng P., *Scientific Reports*, **8**, 6978, 2018; doi: 10.1038/s41598-018-25466-w
[2] Chazov V.A., Deichuly M.P., Koshelev V.I., *Rus. Phys. J.*, **63**(2), 221, 2020; doi: 10.10007/s11182-020-02024-4
[3] Chazov V., Deichuly M., Koshelev V., 7*th International Congress on Energy Fluxes and Radiation Effects (EFRE)*, 23, Tomsk, 2020, doi: 10.1109/EFRE47760.2020.9241973
[4] Malkin A., Ginzburg N., Zaslavsky V., Zheleznov I., Sergeev A., *Electronics*, **11**, 1197, 2022; doi: 10.3390/electronics11081197