MWCG Efficiency Versus Beam Current at Electron Energy Less 500 keV

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Abstract – The paper generalizes investigation results of multiwave Cherenkov generator (MWCG) efficiency versus 3–15 kA beam current at the electron energy up to 500 keV.

1. Introduction

Investigations on optimizaton of a three-cm wavelength range MWCG were carried out earlier [1, 2] at the dode voltage of 1–2 MV. In these experiments, multigigawatt power levels were obtained at high generation efficiency. At the first attemp to decrease the diode voltage U_d to 500 kV [3], radiation power decreased to до 200 MW at the efficiency of ~ 10%. The beam current was of ~ 3 kA. Later, more detailed MWCG investigations [4] were carried out aiming to increase radiation power and efficiency at relatively low electron energy ($U_d \leq 500$ kV). At $U_d = 470$ kV and beam current $I_b = 9.8$ kA gigawatt-power level radiation pulses were obtained, the generation efficiency being of 30%.

This paper presents results of both previously fulfilled MWCG investigations at $U_d \leq 500$ kV and new ones in which the beam current varied from 7 to 17 kA.

MWCG investigations were carried out both experimentally and by means of a particle-in-cell code describing excitation of eigen axial-symmetric fields of a sectionalized resonator [5] in the approximation of an infine magnetic field.

2. Results of Experimental Investigations

The experiments were carried out at the accelerator Sinus-7M The scheme of the experimental setup is presented in Fig. 1. A hollow beam with the mean diameter $D_b = 2r_b = 100$–116 mm and the width of 1.5–3 mm was formed at the diode voltage $U_d = 300÷500$ kV. The current pulse had the length $\tau_p \approx 40$ ns. The waveguide magnetic field varied in the limits of $B = 3$–15 kG. The slow-wave structure (SWS) diameter was $D = 130$ mm ($D/\lambda \approx 4$, where λ is the radiation wavelength). Radiation power was determined by two measured patterns for two polarizations. Radiation pattern was measured with the probes placed three meters apart the generator. Generation efficiency was determined relative to the beam power in the accelerator $U_d I_b$.

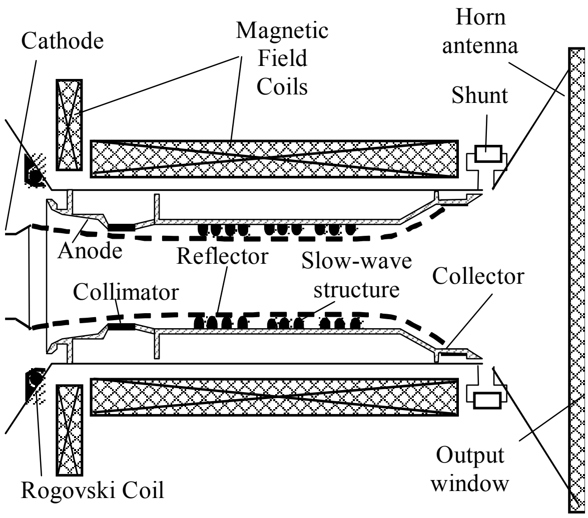

Fig. 1. Scheme of the experimental setup

During optimization of the generator by efficiency, the diaphragm heights and the slow-wave structure period as well as the distance between two sections and their lengths varied. The beam current I_b was changed from 7 to 17 kA at $U_d \sim 500$ kV by means of changing the gap between the cathode and anode. The diode impedance was changed, correspondingly, from 70 to 27 Ω. At the diode impedance of < 27 Ω the current obtained the limiting value in the region of the operating beam radii (Fig. 2).

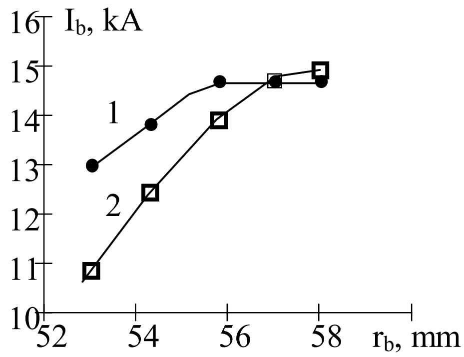

Fig. 2. Beam current versus radius at $U_d = 390$ kV, $B = 14$ kG (1), $B = 6$ kG (2)

Investigations have shown the following characteristic features of the generator operation at $U_d \leq 500$ kV and $I_b \geq 7$ kA. Fulfilment of starting conditions for several longitudinal symmetric and non-symmetric modes results in the broken shape of the radiation signal and instability of spatial and temporal radiation parameters. Moreover, the portion of the nonsymmetric component in the pattern increases apreciably (from 30 to 50% by power).

Application of a diffraction reflector in front of the slow-wave structure similarly to [4] allowed improving essentially such characteristics of microwave radiation as stability from pulse to pulse, signal envelope shape, spectrum width and increasing the power as well. Fig. 3 presents the waveform of the output radiation envelopes for MWCG with a diffraction reflector and without the one. Application of the diffraction reflector allowed selecting symmetric and nonsymmetric modes (more detailed investigations are presented in [6]). Investigation results of the generators with the portion of symmetric modes in the output radiation being the main (more than 80% of the total radiation power) are presented below.

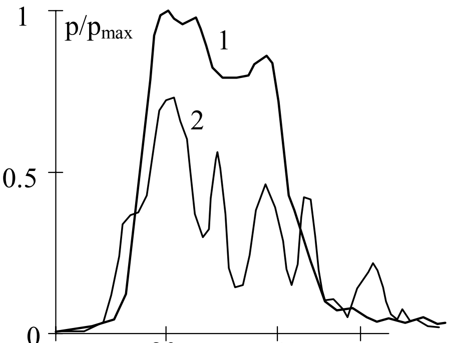

Fig. 3. Waveforms of the radiation pulse envelopes for MWCG with diffraction reflector (1) and without reflector (2)

Investigation of MWCG radiation power dependence on magnetic field at $U_d \leq 500$ kV and $I_b \geq 7$ kA have shown that microwave radiation power in the first maximum region ($B \approx 6$ kG) is 2÷4 times less than in the second one ($B \approx 13$ kG) (Fig. 4).

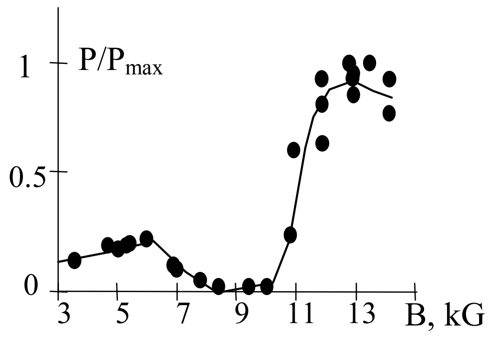

Fig. 4. Output radiation power versus waveguide magnetic field value at U_d = 440 kV, I_b = 9.3 kA

Results of experimental measurements of the total MWCG efficiency with different SWS at the beam current of 3–15 kA (using previously obtained data [3, 4]) are shown in Fig. 5 by black squares. Optimum values of the beam current by the total power of the output radiation (1.1–1.4 GW) and generation efficiency (≈ 30%) at the diode voltage of 420–470 kV made up 9.3–9.8 kA (diode impedance R_d = 45–50 Ω). Magnetic field value was 13–15 kG. Ratio of the beam current to the limiting transport current for the first two generators was 0.5–0.7. Radiation power for the third generator practically had no changes (1.1–1.3 GW) but generator efficiency reduced to 20% at the beam current of 14.5 kA and U_d = 440 kV (R_d = 30 Ω). Further decrease of Rd results in rapid decrease of both power and efficiency of the generator. Beam current reduces by ~ 10% during a pulse.

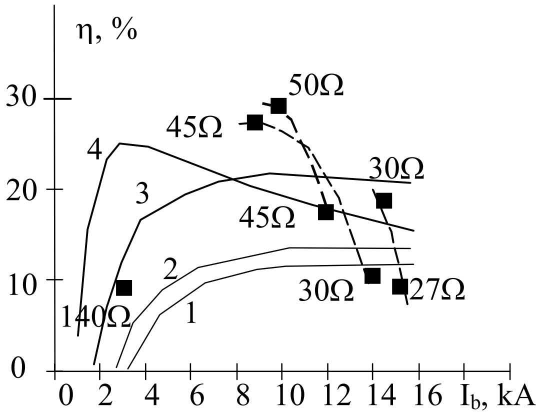

Fig. 5. Calculated MWCG peak efficiency by output radiation versus electron beam current at the diode voltage of 440 kV. Curves 1–4 correspond to 5, 6, 8 and 11 diaphragms in each SWS section. Experimental results are shown by black squares

The slow-wave structure of the first generator [4] containing two sections with 6 diaphragms in each and a diffraction reflector was most optimum at $R_d \approx 50$ Ω. The output section was biperiodic. Decrease of R_d to 45 Ω results in decrease of generation efficiency with this SWS to 17%. Use of SWS with less slowing-down and section length (5 diaphragms) in the second generator allowed increasing efficiency up to 27% at $R_d \approx 45$ Ω. At $R_d \approx 27$–30 Ω, the efficiency of this generator decreased to 10%. In the third generator the effiiency was doubled at $R_d \approx 30$ Ω due to increase of the SWS mean radius in comparison with the smooth waveguide radius at the SWS input and output. That allowed approaching the beam to the waveguide walls retaining an optimum gap between SWS and the beam. Hence, optimum SWS geometry of generators was changed with the diode impedance change.

Results of MWCG investigations at R_d = 140 Ω (Fig. 5) are presented in [3]. No diffraction reflector was used in this generator. Number of diaphragms in each section was 11.

Data of experimental investigations of optimum MWCG structures with a diffraction reflector at R_d =45 Ω (U_d = 415 kV, I_b = 9.3 kA) and R_d =30 Ω (U_d = 440 kV, I_b = 14.5 kA) are presented below.

Figs. 6 and 7 present the output radiation patterns. In case of $R_d = 30\ \Omega$, more than 50% of power is radiated at the angle more than 180.

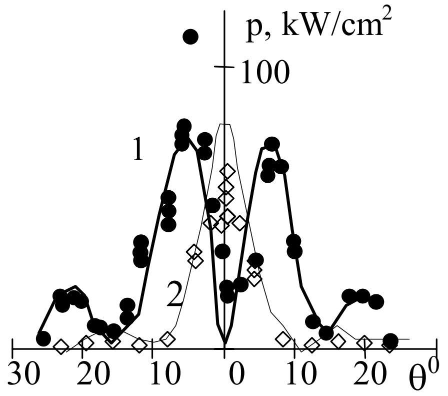

Fig. 6. Patterns of radial (1) and cross-polarized (2) radiation components at $R_d = 45\ \Omega$

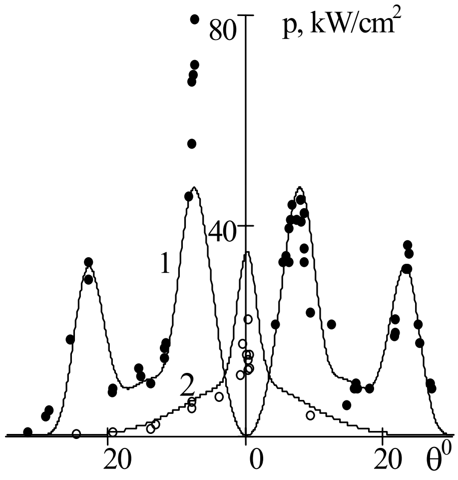

Fig. 7. Patterns of radial (1) and cross-polarized (2) radiation components at $R_d = 30\ \Omega$

Output radiation spectra are shown in Fig. 8. Central wavelengths of radiation spectra are equal to 3.36 and 3.34 cm, respectively. The optimum mean radius of the beam current $r_b \approx 57$ mm. The pulse of the microwave radiation envelope breaks simultaneously with the electron beam current in case $R_d = 45\ \Omega$, and at $R_d = 30\ \Omega$ the power begins to drop somewhat earlier (Fig. 9).

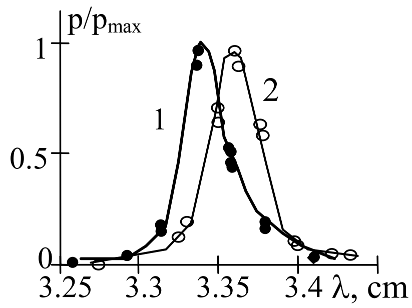

Fig. 8. Radiation spectra at $R_d = 45\ \Omega$ (1), $R_d = 30\ \Omega$ (2)

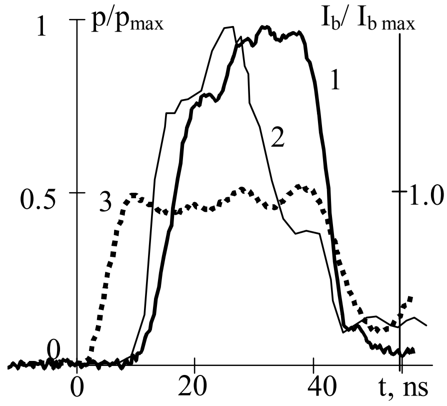

Fig. 9. Waveforms of radiation pulse envelopes at $R_d = 45\ \Omega$ (1), $R_d = 30\ \Omega$ (2) and electron beam current (3)

Dependence of generation effciency of radially polarized radiation on the diode voltage at the invariable gap between the cathode and anode for the generator having optimum at $U_d = 415$ kV and $I_b = 9.3$ kA has a resonance mode (Fig. 10). At $U_d > 450$ kV generation stability decreases and microwave radiation signal gets broken shape (Fig. 11).

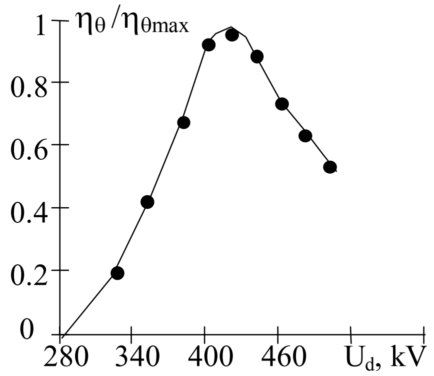

Fig. 10. Generation efficiency of radially polarized radiation versus diode voltage at $B = 14$ kG

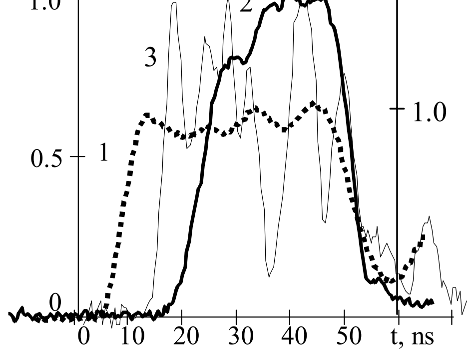

Fig. 11. Waveforms of electron beam current (1) and radiation pulse envelopes at $U_d = 415$ kV (2) and $U_d = 500$ kV (3)

Detailed investigations of radiation power dependence on the diode voltage for MWCG with optimum $R_d = 30\ \Omega$ were not carried out.

3. Results of Numerical Simulations

In the numerical code [5], the slow-wave structure geometry was specified to be the same as in the experimental investigations for optimum generator at $R_d = 45\ \Omega$ but without reflector. Resulting from numerical simulations, MWCG efficiency by peak forward radiation power was plotted versus electron beam current (2–16 kA) at $U_d = 440$ kV and $r_b = 57$ mm for two-sectional SWS containing $N_s = 5$, 6, 8 and 11 diaphragms in each section (Fig. 5, curves 1, 2, 3 and 4, respectively).

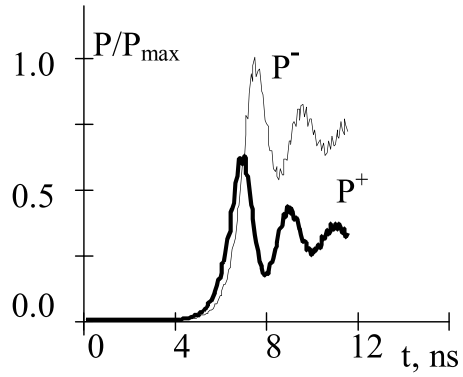

Fig. 12. Forward and backward radiation power for $N_s = 6$, $I_b = 3$ kA

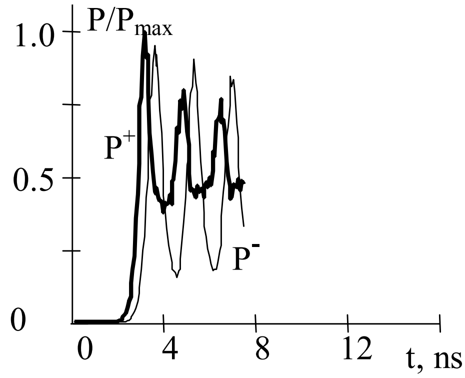

Fig. 13. Forward and backward radiation power for $N_s = 6$, $I_b = 10$ kA

When the beam current exceeds the starting one by 2-times, generation presents an oscillating process near the stationary solution (Fig. 12). Increase of the number of diaphragms in sections and the beam current results in increase of oscillation amplitude of the forward P^+ and backward P^- power (Fig. 13) relative to the electron beam motion direction.

Backward power $P^- > P^+$ for all SWS at $I_b < 7$ kA and $P^- < P^+$ at $I_b > 12$ kA. An approximate equality of $P^- \approx P^+$ was observed at $I_b = 8$–12 kA. Note that in this interval of beam current values in the exerimental investigations of MWCG with a reflector, generation of radiation was the most efficient and stable.

4. Conclusion

Experimental investigations of MWCG at the electron energy lower than 500 keV have shown that generation efficiency of radiation essentially depends on the beam current. The optimum beam current value is 9–10 kA at the diode voltage of 420–470 kV and the waveguide magnetic field of ≥ 13 kG. At the optimum diode impedance of 45–50 Ω and ratio of the beam current to the limiting one of 0.5–0.7 radiation pulses with the peak power of ~1 GW have been obtained at the generation efficiency up to 30%.

References

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