LA-UR--83-2602

CONF-830911--27

DE84 001346

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: MICROWAVE GENERATORS: OSCILLATING VIRTUAL CATHODES AND REFLEXING ELECTRONS

AUTHOR(S): Thomas J. T. Kwan and Lester E. Thode

SUBMITTED TO: Fifth International Topical Conference on High-Power Electron and Ion-Beam Research and Technology

September 12-14, 1983
San Francisco, CA

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

MICROWAVE GENERATORS: OSCILLATING VIRTUAL CATHODES AND REFLEXING ELECTRONS

Thomas J. T. Kwan and Lester E. Thode
Advanced Concepts and Plasma Physics Group
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Abstract

Simulation of the generation of a relativistic electron beam in a foil diode configuration and of the subsequent intense microwave generation resulting from the formation of the virtual cathode is presented. The oscillating virtual cathode and the trapped beam electrons between the real and the virtual cathodes were found to generate microwaves. Generation of high-power microwaves with about 10% efficiency might be reasonably expected from such a virtual-cathode configuration.

Introduction

In this article we report on our investigation of a microwave generator based on trapped beam electrons reflexing in the potential well formed between the real and the virtual cathodes of a relativistic electron beam. Several groups have studied this process experimentally [1-3], and two of them have observed a microwave power level of 100 MW. The frequency of the microwave can be tuned by varying the density or energy of the electron beam and the spacing between the real and the virtual cathodes. Furthermore, unlike other microwave devices [4-6] in which efficient operation requires electron beams of high quality, the efficiency of microwave production due to reflexing electrons was experimentally observed to be <u>not</u> sensitive to the quality of the electron beams [1].

Computer Simulation Results

In our study the two-dimensional particle-in-cell plasma simulation code CEMIT was used to simulate the generation of the electron beam from the Anomalous Intense Driver (AID) relativistic electron beam facility [7-9] and the subsequent generation of microwaves by the electrons reflexing in the potential well. Figure 1 has a real-space diagram (r versus z) showing the configuration of the simulations. A 3.0-MV transverse electromagnetic wave was launched at the left-hand boundary into the coaxial line, causing the field emission of electrons. Then, the electrons emitted from the cathode were accelerated to the anode foil to form an approximately 1-mm-thick annular electron beam. (Because of a small mismatch between the driving and the diode impedances, the beam energy was 3.10 MeV [10]. The electron beam current in the simulation was 75 kA.) The anode foil was modeled as an infinitesimally thin perfect conductor, and the electrons did not lose energy or suffer velocity scatter as they traversed through the anode foil. This is a reasonable model for a very thin foil (~μm). Transmitting boundary conditions for the electromagnetic fields were used in both ends of the waveguide, and a perfectly conducting boundary condition was used in the radial direction. Finally, since azimuthal symmetry was assumed, the proper boundary condition for the lower boundary in the radial direction was chosen to be reflecting for electromagnetic fields and electrons, but electrons were absorbed when they reached the other three boundaries.

As indicated in Fig. 1, the radius of the waveguide beyond the anode foil was increased to 3.0 cm to facilitate the virtual cathode formation. The space-charge limiting current of the waveguide for an annular electron beam of infinitesimal thickness is given by [11]

$$I_{SCL} = 17(\gamma^{2/3} - 1)^{3/2}/2 \ln(r_W/r_b) \text{ kA} \quad , \qquad (1)$$

where γ is the relativistic factor of the electron beam, r_W is the radius of the waveguide, and r_b is the electron beam outer radius. With $\gamma = 7.07$ and $r_b = 1.0$ cm, Eq. (1) gives $I_{SCL} = 34.01$ kA. Since the current carried by the electron beam was 75 kA, a virtual cathode was formed beyond the metallic foil.

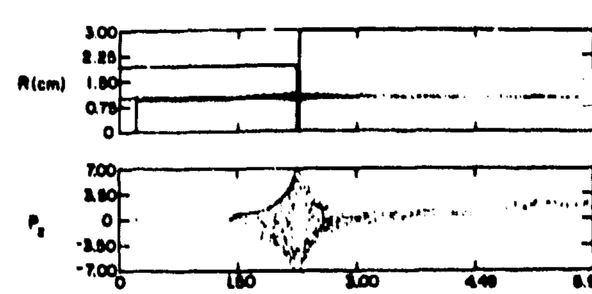

Fig. 1. Real-space (r-z) and phase-space (p_z-z) diagrams of the electron beam, showing the formation of the virtual cathode and the reflexing system in the case with an axial magnetic field of 90 kG.

The phase-space diagram (P_z versus r) in Fig. 1 shows the process of acceleration of the electrons to about 3.10 MeV toward the anode foil and the deceleration of the electron beam because of the buildup of the space-charge potential once it entered the waveguide. The formation of a virtual cathode by the electron beam occurred at a distance of about 1.4 cm away from the cathode. In the simulation a constant axial magnetic field of 90 kG was present and, therefore, the motion of the electrons was primarily along the magnetic field lines (Fig. 1). With the presence of the strong magnetic field, the quality of the electron beam was very good [9]. Consequently, one would expect microwave production by the oscillating virtual cathode [4] in addition to the electrons reflexing inside the potential well formed between the real and the virtual cathodes. However, the frequencies of the microwaves produced by these two mechanisms are, in general, different. On the one hand, the microwave frequency due to an oscillating virtual cathode varies from $\omega_\perp$ to $\sqrt{2\pi}\ \omega_\perp$ as the ratio of the beam current to the space-charge limiting current increases [12]. Here, the transverse plasma frequency is given by $\omega_\perp = (4\pi n_0 e^2/\gamma m e)^{1/2}$. On the other hand, the frequency of the microwaves due to the reflexing electrons is determined by the transit time of the electrons in the potential well [3].

The time history of the azimuthal component of the magnetic field at a position near the left-hand boundary and its Fourier transform were obtained from the simulation shown in Fig. 2. The oscillatory behavior shown in the figure is indicative of the excitation of electromagnetic waves; furthermore, the Fourier transform of the time history clearly shows that electromagnetic waves were excited at two distinct frequencies of 10.65 and 25.74 GHz.

The density of the electron beam as determined in the simulation was $n_0 = 4.0 \times 10^{13}/cm^3$ and the transverse plasma frequency, $\omega_\perp = (4\pi n_0 e^2/\gamma m_e)^{1/2}$, was 21.4 GHz. The fact that the frequency of the microwaves generated by oscillating virtual cathodes ranges from $\omega_\perp$ to $\sqrt{2\pi}\ \omega_\perp$ leads us to conclude that the high-frequency component (25.74 GHz) of the electromagnetic waves observed in the simulation was excited by the oscillating virtual cathode. The transit time of the electrons reflexing in the potential well can be estimated by assuming the electrons making round trips between the real and the virtual cathodes with a velocity near the speed of light. The distance between the cathodes (measured in the simulation to be about 1.4 cm) yielded an electron

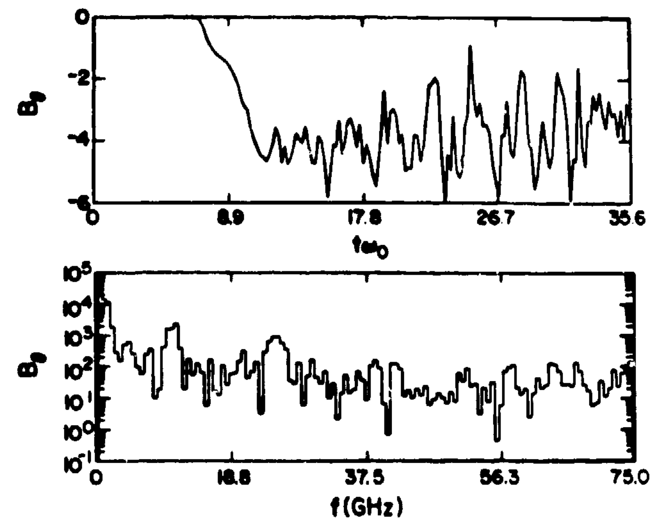

Fig. 2. Time history and Fourier transform of electromagnetic waves.

transit frequency of 10.71 GHz, confirming that the low-frequency component (10.65 GHz) of the electromagnetic waves was generated by the trapped electrons as they phase-bunched in the potential well [1]. It is evident from Fig. 2 that the radiation power was more concentrated at the low-frequency component of the microwaves. In addition, note that the large dc level of the magnetic field was due to the self-field of the electron beam.

Simulations of the same geometry and parameters were done without the constant axial magnetic field. The results indicated that the dominant mechanism in microwave generation was the oscillating virtual cathode and not the reflexing electrons [13]. In the absence of the axial magnetic field, the reflexing electrons tend to oscillate along the z-axis where the potential is at a minimum. The frequency of electron oscillations were substantially higher than the case with the axial magnetic field where electrons were confined by the magnetic field lines. Furthermore, heating and scattering of the incoming beam by the reflexing electrons are more likely to occur with the presence of the axial magnetic field. This is consistent with our observations in our simulations.

The mode structures of the electromagnetic waves could not be clearly identified in the simulation because the waveguide was quite over-moded. The efficiency of microwave production was difficult to calculate because the approximation of the excitation of a single mode electromagnetic wave in the waveguide was not valid in the simulations [4]. However, one may obtain an estimate of the output of the microwaves by using the amplitude of the electromagnetic radiation as shown in Fig. 2 and averaging it over the cross section of the waveguide. This procedure yielded an estimated total microwave power output of 21 GW and an efficiency of 10.5%.

Conclusion

In conclusion, we have shown that high-power microwave generation with about 10% efficiency might be reasonably expected from trapped electrons reflexing in the potential well found between the real and the virtual cathodes of a relativistic electron beam. In our configuration with a magnetic field present, both the reflexing electrons and the oscillating virtual cathode generate microwaves at two distinct frequencies.

Acknowledgments

The authors are grateful to B. DeVolder, M. Mostrom, and M. Jones for valuable discussions, and they also wish to acknowledge J. Lunsford and C. Snell for their efforts in developing and maintaining CEMIT. This work is supported by the U.S. Department of Energy.

References

1. R. A. Mahaffey, P. Sprangle, J. Golden, and C. A. Kapetanakos, Phys. Rev. Lett. 39, 843 (1977).

2. H. E. Brandt, A. Bromborsky, H. B. Burns, and R. A. Kehs, Proc. of the Second Intl. Top. Conf. on High Power Electron and Ion Beam Research and Technology, (Cornell University, Ithaca, New York, 1977).

3. A. N. Didenko, Ya E. Krasik, S. F. Perelygin, and G. P. Fomenko, Sov. Tech. Phys. Lett. 5, 128 (1979).

4. Thomas J. T. Kwan, submitted to Phys. Fluids.

5. Thomas J. T. Kwan and Charles M. Snell, Phys. Fluids 26, 835 (1983).

6. R. J. Jackson, S. H. Gold, R. K. Parker, H. P. Freund, P. C. Efthimion, V. L. Granatstein, M. Herndon, A. K. Kinkead, J. E. Kosakowski, and T. J. T. Kwan, IEEE J. Quantum Electron QE-19, 346 (1983).

7. M. D. Montgomery, J. V. Parker, K. B. Riepe, and R. L. Sheffield, Appl. Phys. Lett. 39, 217 (1981).

8. R. L. Scheffield, M. D. Montgomery, J. V. Parker, K. B. Riepe, and S. Singer, J. Appl. Phys. 53, 5408 (1982).

9. Michael E. Jones, Michael A. Mostrom, and Lester E. Thode, J. Appl. Phys. 52, 4942 (1981).

10. Michael E. Jones and Lester E. Thode, J. Appl. Phys. 51, 5212 (1980).

11. L. S. Bogdankevich and A. A. Rukhadze, Sov. Phys. Usp. 14, 163 (1971).

12. M. A. Mostrom, T. J. T. Kwan, and C. M. Snell, Bull. Am. Phys. Soc. 27, 1075 (1982).

13. Thomas J. T. Kwan and Lester E. Thode, submitted to Phys. Fluids.