High-Efficiency, Magnetized, Virtual-Cathode Microwave Generator

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Microwave generation by electron beams in virtual-cathode configurations can achieve signficant power levels. However, most designs inherently have two competing mechanisms generating microwaves: the oscillating virtual cathode and the reflexing electrons. These mechanisms interfere destructively with each other. This paper reports investigation of a novel idea of using an external axial magnetic field and a thick anode with an appropriate collimating slot to extract the electron beam and to suppress the reflexing electrons. It was found that high-power, narrow-band, monochromatic microwaves could be generated with efficiency of 10% to 20%.

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Microwave generation resulting from the formation of a virtual cathode of a relativistic electron beam has been demonstrated in a number of experiments.[1–6] With the possible exception of the experiments of Didenko *et al.*,[3] this new class of microwave tube generates radiation with multiple frequencies and modes at low efficiency. Also, recent work shows that the output occurs in random subnanosecond bursts.[7] Although most virtual-cathode tubes have a simple geometry, they exhibit complex nonlinear behavior that has resulted in the slow development of a narrow-bandwidth virtual-cathode tube.

The complex, nonlinear character of the virtual-cathode device necessitates particle-in-cell plasma-simulation techniques, which have been used extensively to understand the microwave generation process. These investigations[8–10] indicate two sources of the radiation: (i) the trapped electrons reflexing between the real and virtual cathodes and (ii) the oscillation of the virtual cathode. In the conventional design, the two mechanisms coexist and interfere with each other destructively, causing degradation of the efficiency of microwave generation. I have investigated a novel configuration which can effectively eliminate the reflexing electrons. I have confirmed via two-dimensional particle-in-cell simulations that this configuration exploits the oscillations of the virtual cathode exclusively and it generates nonbursting, single-mode, narrow-bandwidth, high-power electromagnetic radiation. The efficiency of microwave production can be as high as 38% in the most optimized case.

Microwave generation by the oscillating virtual cathode of a relativistic electron beam suffers from rapidly decreasing efficiency as the energy spread or angular scattering increases.[11] In the configurations considered to date, the quality of the incoming electron beam can be adversely affected by the electrons reflexing between the virtual cathode and the real cathode of the diode. Specifically, the reflexing electrons subject the electron beam to the two-stream instability, causing considerable heating of the electron beam. Further, the space charge of the reflexing electrons can cause the diode impedance to fluctuate, resulting in oscillations of the electron beam energy. These effects which have been observed in the present computer simulation greatly degrade the efficiency of microwave production by oscillating virtual cathodes. A typical microwave spectrum generated by a virtual-cathode oscillator where no special precaution is taken to eliminate the reflexing electrons consists of multiple modes and is generally broad band. Moreover, the efficiency is limited to 1% or 2%.

To eliminate these undesirable effects, I have developed a concept that prevents electrons from reflexing into the diode region. (Similar concepts were pointed out by Sullivan.[12]) The idea considered here is to use a thick anode with appropriate slits in combination with an axial magnetic field of suitable strength. The thickness of the anode has to be at least an electron range. The electron beam generated by field emission is guided through the anode slit by the magnetic field, and many of the reflected electrons from the virtual cathode are absorbed by the anode because of the transverse momentum induced by the self-fields. Properly matching the magnetic field strength with the slit width so that few electrons can get back to the diode will maximize microwave production efficiency. Such a design is shown in Fig. 1, where the anode is made up of a high-Z material (for example, tungsten). Numerical modeling of such a design requires self-consistent treatment of the electromagnetic fields and accurate treatment of electron transport through the anode via Monte Carlo methods. I have successfully incorporated the Monte Carlo charged-particle transport method developed by Moliere and Bethe into the two-dimensional, fully electromagnetic, relativistic, particle-in-cell plasma simulation codes, ISIS and CCUBE,[13] to treat the physics of microwave generation by virtual cathodes correctly.

The two-dimensional particle simulations confirm the basic idea of such a virtual-cathode microwave generator. In the study of efficiency scaling with the axial magnetic field, a simplification was made by

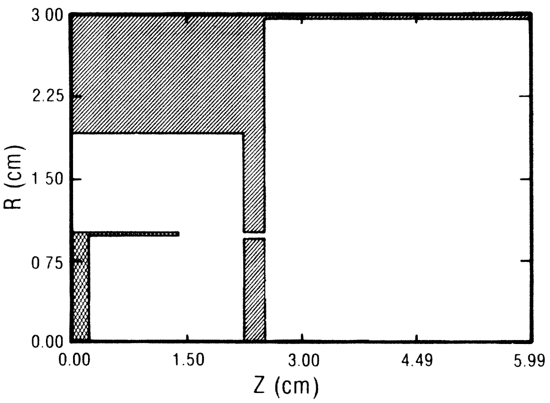

FIG. 1. Configuration of a highly efficient, single-mode, monochromatic virtual-cathode microwave generator.

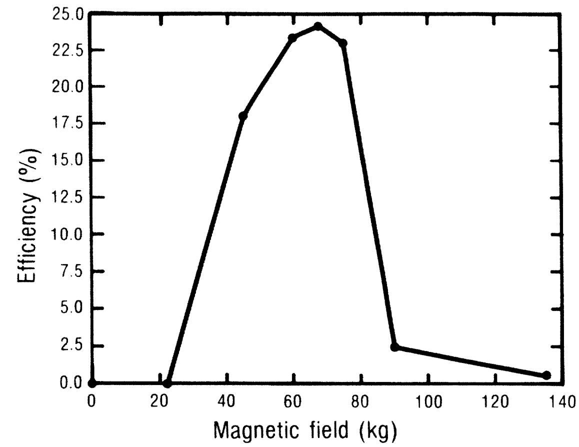

FIG. 2. Efficiency of microwave generation maximized at a particular value of axial magnetic field for a given configuration.

treating the anode as perfectly absorptive to discriminate the reflected electrons. As soon as the reflected electrons get in contact with the anode surface, they are absorbed without transporting them in the anode via the rather computer-time–consuming Monte Carlo method. The results are shown in Fig. 2 which shows the dependence of the efficiency on the axial magnetic field. For the configuration shown in Fig. 1, the optimal magnitude was found to be 67.5 kG. In the simulations, a TEM wave of 3.45 MV was launched from the left-hand boundary into the coaxial waveguide. Electron emission at the cathode was treated according to space-charge limitation model. A hollow electron beam was generated in the simulations. For magnetic field less than 22 kG, the electron beam was not adequately guided through the slit. Consequently, there were no microwaves generated in the waveguide. When the magnetic field was increased beyond 80 kG, the efficiency dropped off rapidly because the reflected electrons streamed back to the diode region along the strong magnetic field lines and caused adverse effects on the electron beam. It was also evident that the efficiency depends not only on the magnetic field but also on the width of the slit as well as the energy of the electron beam.

After the optimal value of the magnetic field was found, I proceeded to simulate self-consistently the case including electron transport in the anode. Electron transport in the anode was modeled according to the Moliere multiple-scattering theory[14] of electrons and Bethe's formula of electron stopping power.[15] The

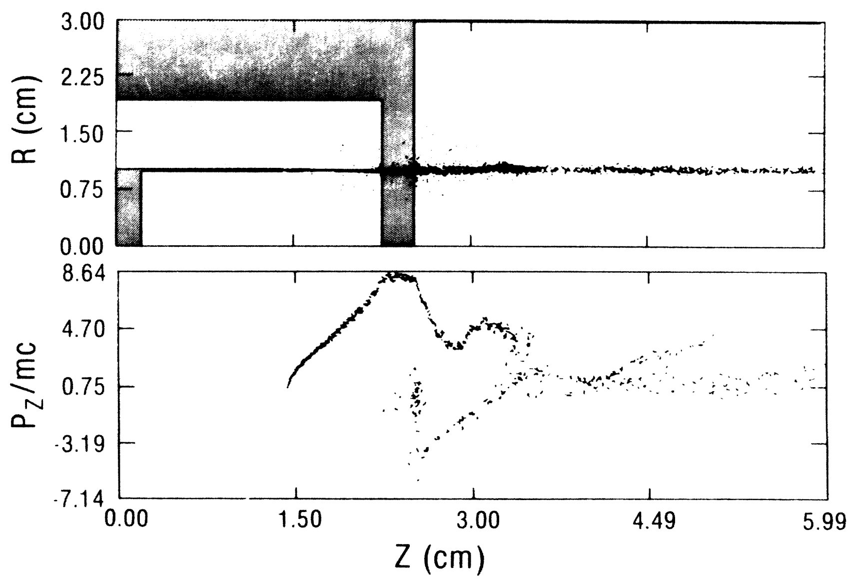

FIG. 3. Configuration- and phase-space diagrams of the electron beam showing the effect of the thick anode and strong modulation by the oscillating virtual cathode which is indicative of strong excitation of microwaves.

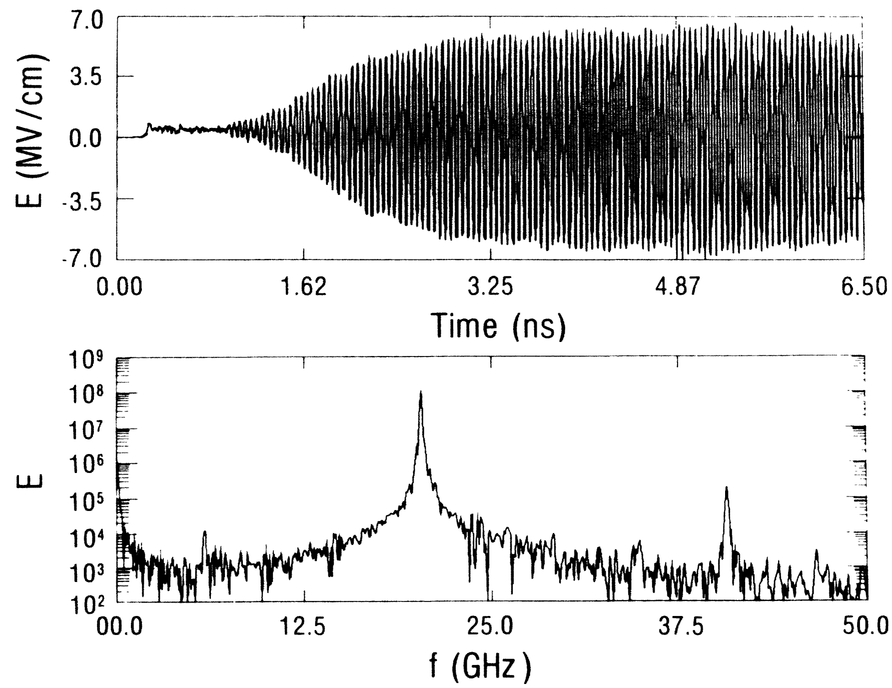

FIG. 4. Time history of the axial electric field and its Fourier transform showing the coherent generation of electromagnetic radiation.

configuration-space diagram of the electron beam in Fig. 3 shows that there were a few electrons that leaked through the slit into the diode. With more optimized shaping of the anode foil, one might be able to further reduce the reflexing electrons in the diode. The electron beam was 3.8 MV and had a current of 79.8 kA. The space-charge limiting current of the waveguide was 36.4 kA. The phase-space diagram is also shown in Fig. 3 where the formation and oscillation of the virtual cathode are clearly demonstrated. Further, the electron phase space shows strong modulation of the electron beam beyond the virtual cathode, a characteristic of strong excitation of coherent radiation. The electromagnetic radiation field was monitored in time at a fixed location near the right-hand boundary and away from the electron beam. The time history of the axial component of the electric field (E_Z) is shown in Fig. 4. The envelope of the field shows the growth and saturation of the transverse magnetic modes. The Fourier transform in Fig. 4 shows that the frequency spectrum of the microwaves peaks at 20.25 GHz with a bandwidth ($\Delta\omega/\omega$) less than 3%. The frequency of the microwaves can be tuned by variation of the geometry of the device and/or the electron beam parameters (that is, voltage and current density).[16] The power distribution among the transverse magnetic modes is shown in Fig. 5. The microwave power was almost entirely concentrated in $TM_{0,4}$. Note that this single mode had a power level of 29 GW which is at least several times higher than the power level in any mode in a conventional virtual-cathode configuration. In fact, this single-mode characteristic has never been achieved in any virtual-cathode device.

The efficiency of the microwave production was monitored during the course of the simulation. The microwave power was obtained by summation of the power in all waveguide modes. The efficiency (primarily in TM modes) is shown as a function of time in Fig. 6. It rose during the rise time of the electron beam and saturated at a level of about 12%. For comparison, I simulated the same configuration with a thin anode (10 μm). The microwaves were broad band and

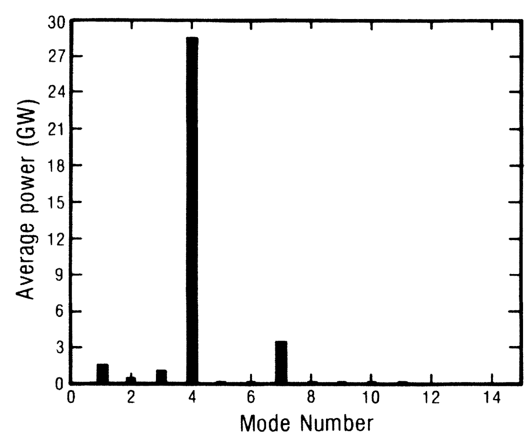

FIG. 5. Distribution of microwave power showing that the virtual-cathode design is capable of generating high-power microwaves (TM modes) at a single mode.

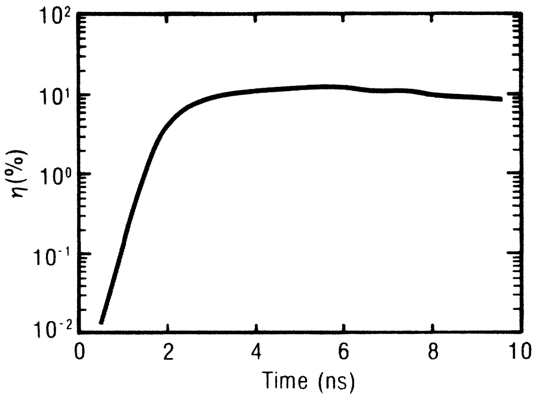

FIG. 6. Efficiency of generation of TM modes vs time showing the growth and saturation of microwave power.

the efficiency was only 0.25%.

I have demonstrated via computer simulations that high-power, single-mode, and monochromatic microwaves can be generated by oscillating virtual cathodes in a configuration where reflexing electrons can be effectively eliminated. The monochromatic and single-mode characteristics of the microwave output are extremely desirable for microwave generators. On the other hand, they also represent important advances toward the development of single modules of high-power, phase-locked microwave sources. Further enhancement and selection of modal purity and monochromaticity may be achieved by the use of a cavity resonator in conjunction with a straight waveguide placed downstream from the anode foil.

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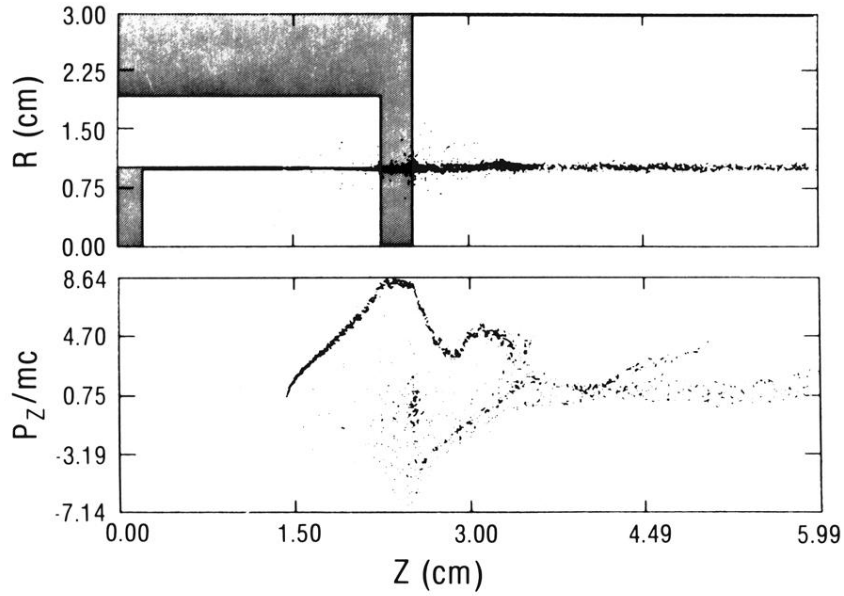

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