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AN EFFICIENT, MONOCHROMATIC, HIGH-POWER MICROWAVE GENERATOR

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ABSTRACT

Microwave generation by electron beams in virtual cathode configurations can achieve significant power levels. However, most designs inherently have two competing mechanisms generating microwaves; namely the oscillating virtual cathode and the reflexing electrons. These two mechanisms tend to interfere destructively with each other. Specifically, the reflexing electrons subject the electron beam to two-stream instability, causing considerable heating of the electron beam. In addition, the space-charge of the reflexing electrons can cause the diode impedance to fluctuate, resulting in oscillations of the electron beam energy. We have investigated a novel idea to remove these undesirable effects and we found that high-power, narrow-band, and monochromatic microwaves could be generated with efficiency of 10 to 20%.

INTRODUCTION

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 Didenko et al. experiments [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; therefore, the efficiency of microwave generation suffers. These two mechanisms interfere with each other destructively, so it is essential to select a dominant mechanism by design of the device. We have investigated a novel configuration which can effectively eliminate the reflexing electrons. We 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. The virtual cathode microwave generator has a large operation frequency range, about 100 MHz to 40 GHz. Further, it can generate significant power (tens of gigawatts) concentrated in a single waveguide mode. This configuration is therefore, ideal for development of single modules of the extremely high-power phase-array microwave generator.

A NARROW-BANDWIDTH, EFFICIENT MICROWAVE GENERATOR

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 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 our computer simulation greatly degrade the efficiency of microwave production by oscillating virtual cathodes. A typical microwave spectrum generated by a virtual cathode 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 broadband. Moreover, the efficiency is limited to 1 or 2%. The broadband characteristic and low efficiency are undesirable in the further development of system of phase-locked virtual cathode oscillators.

To eliminate these undesirable effects, we have developed a concept that prevents electrons from reflexing into the diode region. (Similar concepts were pointed out by D. 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 transvere 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. We 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 code, ISIS and CCUBE [13], to treat the physics of microwave generation by virtual cathodes correctly.

Our 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 treating the anode perfectly absorptive to discriminate the reflected electrons. As soon as the reflected electrons get in contact with the anode surface, they are absorbed immediately without transporting them in the anode via the rather computer-time consuming Monte Carlo method. The results are shown in Fig. 2 which show the dependence of

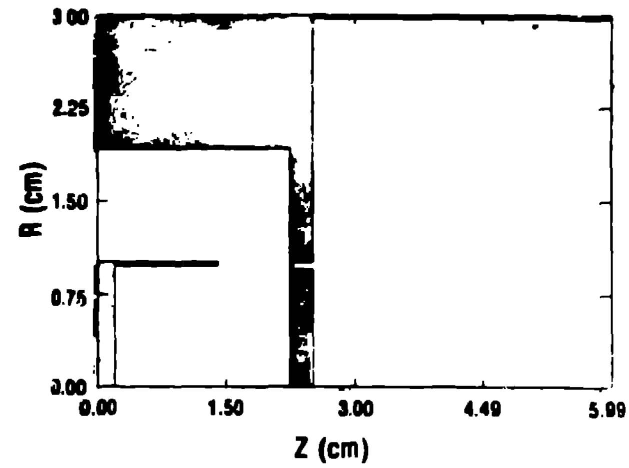

Fig. 1. Configuration of a highly efficient, single-mode, monochromatic virtual cathode microwave generator.

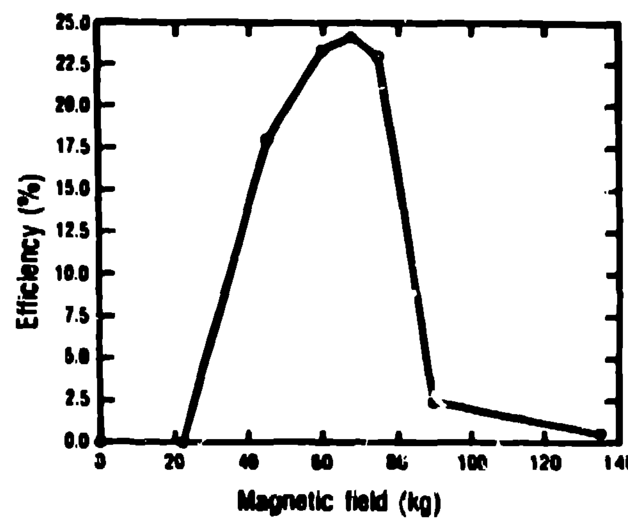

Fig. 2. Efficiency of microwave generation maximized at a particular value of axial magnetic field for a given configuration.

the efficiency on the axial magnetic field. In the configuration shown in Fig. 1, the optimal magnitude is 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. Electrons 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 the adverse effects on the electron beam. It was also evident that the optimal value depends not only on the magnetic field but also the width of the slit as well as the energy of the electron beam.

After the optimal value of the magnetic field is found, we proceeded to simulate self-consistently the case including the 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 configuration space diagram of the electron beam in Fig. 3 shows that there were a few electrons 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 phase-space diagram is also shown in Fig. 3 where the formation and oscillation of 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 varying 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 concentrate in $TM_{0,4}$. Note that this single mode had power of 29 GW which is at least several times higher than the power level in any mode in a conventional virtual cathode configurations. In fact, this single-mode characteristic has never been achieved in any virtual cathode device.

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

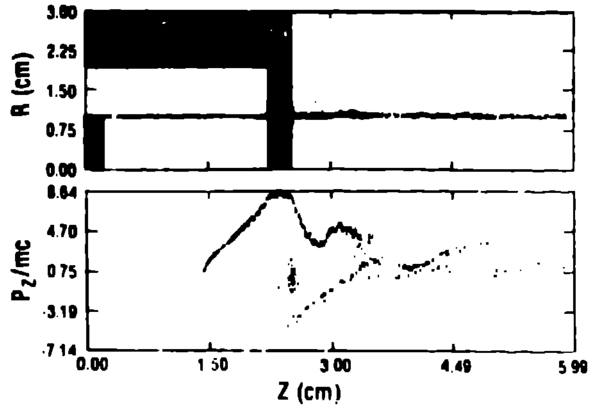

Fig. 3. Configuration and phase space diagrams of the electron beam showed the effect of the thick anode and strong modulation by the oscillating virtual cathode which was indicative of strong excitation of microwaves.

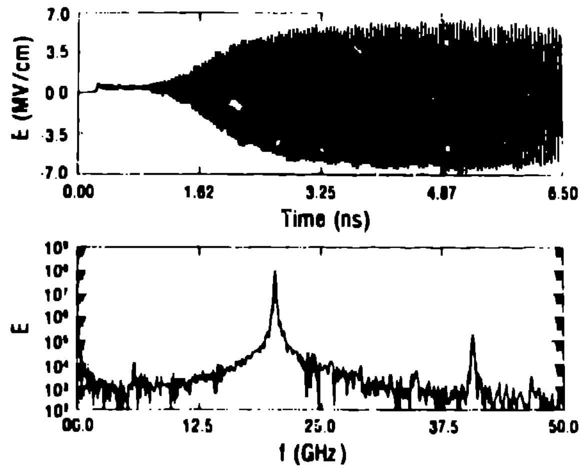

Fig. 4. Time history of the axial electric field and its Fourier transform showed the coherent generation of electromagnetic radiation.

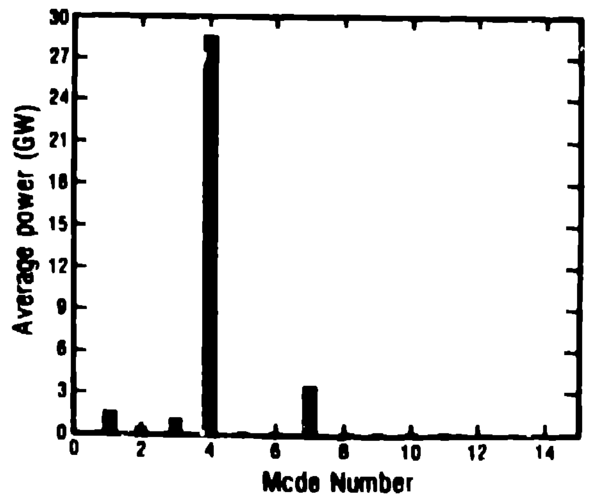

Fig. 5. Distribution of microwave power showed the virtual cathode design capable of generating high-power microwaves (TM modes) at a single mode.

time in Fig. 6. It rose during the rise-time of the electron beam and saturated at a level of about 12%. The rise-time of the electron beam was chosen to be artificially short for computational efficiency since it did not seem to have any effect in the process of microwave generation. The gap between the cathode and anode was found to be an important parameter in the efficiency of microwave generation. The dependence is shown in Fig. 7. The efficiency is at a maximum at a gap of about 0.7 cm for the configuration and parameters considered here. The reason for the functional dependence is that the current of the diode varies with the diode impedance which is determined by the gap spacing. Therefore, the resultant magnetic field (i.e., the sum of the self field of the beam and the axial magnetic field) varies with the gap spacing and, consequently, affects the effectiveness of the anode in the absorption of the reflected electrons.

CONCLUSIONS AND DISCUSSIONS

We 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 module 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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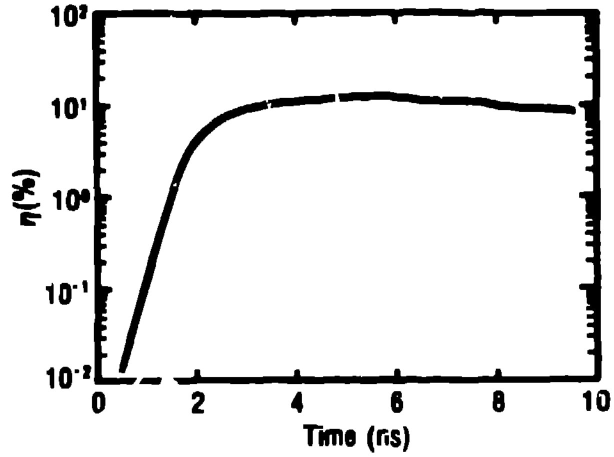

Fig. 6. Efficiency of generation of TM modes versus time showed the growth and saturation of microwave power.

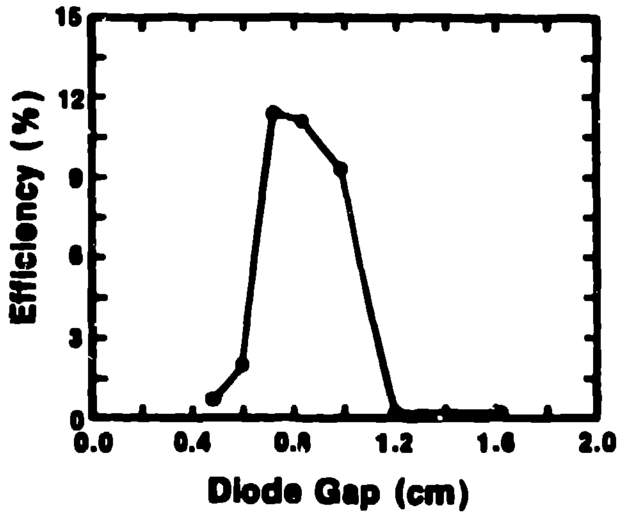

Fig. 7. Full particle-in-cell with Monte Carlo electron transport simulation showing the existence of optimal gap spacing for the efficiency of microwave production.

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