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HIGH POWER MICROWAVE GENERATION FROM A VIRTUAL CATHODE OSCILLATOR (VIRCATOR)

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Abstract

High power microwaves, up to Gigawatt levels in the centimeter regime, have been observed in reflex triode, foil and foilless diode systems. Generation efficiencies range from 1% to 12%. The source of the microwaves is an oscillating virtual cathode - the nonlinear state which develops when the electron beam injection current exceeds the space-charge limiting current defined by the beam energy and wave guide geometry. This stable oscillation results in severe longitudinal charge bunching giving rise to large time dependent current variations. The experimental frequency dependence and broadband characteristics are explained by the scaling of the oscillator frequency with $\sqrt{n_b/\gamma}$, where n_b is the beam density and γ its relativistic factor, in conjunction with the Child-Langmuir relation. The optimal design for a narrowband millimeter wave vircator is based on a foilless diode with a strong axial magnetic field. It will be tunable over an order of magnitude in frequency by varying the magnetic field strength.

Introduction

Of the several millimeter sources that are in various stages of development, the virtual cathode oscillator (Vircator) has a combination of characteristics which recommend it for high frequency use. First, the frequency of the vircator is tunable by changing the magnitude of an imposed axial magnetic field, eliminating any requirement to change the physical structure of the device. A single vircator will be tunable over an order of magnitude in frequency (e.g., 10 GHz - 100 GHz). Second, the bandwidth of the generator can be narrow or broad based on magnetic field shaping and the use of beam limiters described below. Third, because the vircator functions above the space-charge limiting current for the electron beam, given efficient operation, it should be capable of much higher power than other microwave sources. Finally, the lack of passive resonating structures to produce the transmitted wave reduces the problem of field emission. This also increases the maximum possible generator power.

Experimentally, the virtual cathode has already proven itself to be a copious microwave source.[1-7] Table 1 lists experiments which have been carried out to date. With the exception of the Didenko experiment at Tomsk,[4] the frequency spectra have all had a broad bandwidth and relatively low efficiency. Nevertheless, even at low efficiency the experiment at Harry Diamond Laboratories[5] using a foilless diode (1 MV, 30 kA) produced Gigawatts of power in the Ku band. It is one of the most powerful centimeter wavelength microwave sources available. It will be shown later that the foilless diode in a shaped axial magnetic field represents the best configuration for a high frequency device.

TABLE 1

HIGH POWER MICROWAVE GENERATION HAS BEEN WITNESSED IN VARIOUS ELECTRON BEAM CONFIGURATIONS WHEN VIRTUAL CATHODES ARE FORMED.

REFERENCE	SYSTEM	PEAK POWER	FREQUENCY	EFFICIENCY
1. MAHAFFEY, et al.	REFLEX TRIODE	100 MW	11 GHz (10.0 - 12.4 GHz)*	1.6%
2. BRANDT, et al.	REFLEX TRIODE	---	9.8 GHz (7.0 - 13.0 GHz)*	---
3. BUZZI, et al.	FOIL DIODE	1 GW	10 GHz (9.0 - 14.0 GHz)*	1.25%
4. DIDENKO, et al.	REFLEX TRIODE	1.4 GW	3.3 GHz (2.1 - 5.0 GHz)*	12%
5. BROMBORSKY, et al.	FOILLESS DIODE	3 GW	15 GHz (8.2 - 18.0 GHz)*	6%
6. CLARK, et al.	FOILLESS DIODE	---	WIDEBAND (1.7 - 40.0 GHz)*	---
7. EKDAHL, et al.	FOILLESS DIODE	>100 MW	>70 GHz	---

* DETECTOR BANDWIDTH IN PARANTHESES

Microwave Generation

Although only scaling relations are presently available, qualitative dependencies of virtual cathode parameters on beam kinetic energy and injected current are known.[8,9] First, potential amplitude, position, and oscillation frequency all have the same functional dependence on injected beam current. These parameters asymptotically approach a limiting value for current above the space-charge limit. Second, the fundamental oscillation frequency is approximately the relativistic beam plasma frequency given by

$$\omega_p^{rel} = \left(\frac{4\pi n_b^o e^2}{\gamma_o m} \right)^{1/2} , \tag{1}$$

where n_b^o is the electron beam number density at injection γ_o is the beam relativistic factor, e is the electron charge and m is its mass. In particular, the oscillation frequency from one-dimensional electrostatic and two-dimensional electromagnetic numerical simulations varies such that

$$\omega_p^{rel} \leq \omega_{osc} \leq \sqrt{2\pi}\, \omega_p^{rel} \tag{2}$$

The value of $\sqrt{2\pi}$ is an empirical result which has not yet been derived theoretically. The value of ω_{osc} increases with current monotonically. If the injection current exceeds the space-charge limiting current by a factor of three or greater, ω_{osc} is close to the maximum value. Equation 11 in conjunction with the Child-Langmuir law describing space-charge limited diode emission explains the experimental linear dependence of frequency on the square root of diode voltage in foil diodes and reflex triodes.

The virtual cathode oscillates stably at a set frequency in both time and space. This fluctuating potential barrier acts as a gate to reflect some electrons and transmit others. The motion of the gate bunches charge. In two dimensions the charge bunch and virtual cathode are separated spatially.

By analogy this configuration represents an LC oscillator. The virtual cathode acts as a capacitor to store the beam kinetic energy. During that portion of the limit cycle in which the potential is greater than the injected beam energy, charge is constrained to remain near the anode. This starves the virtual cathode so that its amplitude decreases below $(\gamma_o - 1)\, mc^2/e$. Once this occurs the charge bunch is transmitted. The electron motion represents a large time varying current through an inductor. The presence of charge away from the anode reestablishes the virtual cathode, and the cycle repeats. The effect on

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beam current can be examined using simulations. A net current diagnostic is given in Fig. 1 where the probe is positioned between the anode and virtual cathode. The injected current in units of mc^3/e, ν_0, is 3.4 times the limiting current, ν_ℓ, and γ_0 is 3.5. Note that the virtual cathode can actually reverse the direction of current. The average current value is ν_ℓ.

The oscillating current generates microwaves.[10,11] The wave frequency is the oscillation frequency of the virtual cathode. The wave propagates down the drift tube in a TM waveguide mode, which determines the wavelength and phase velocity of the wave in the guide. The field configuration is evident in simulations where there is no axial magnetic field. If a cold beam is injected and azimuthal symmetry is assumed by the code, the only nonzero fields are E_z, E_r, and B_θ in cylindrical geometry. These three fields define a TM wave traveling in the z direction.

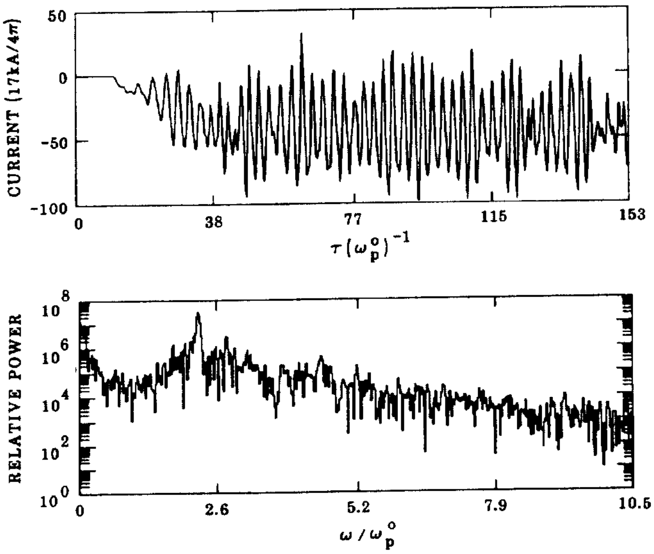

Figure 1. Net current amplitude and spectrum for a probe placed between the anode and virtual cathode. $\gamma_0=3.5$, $\nu_0=3.4\nu_\ell$.

The largest impediment to constructing an efficient vircator is the effect which heating has on the microwave generation efficiency. As noted earlier[12], beam temperature significantly damps out the amplitude of the potential oscillation. This can be understood in the following way. For a monoenergetic beam all of the charged particles bunch at the same location. Mathematically this represents a singularity where the charge density goes to infinity. In reality the charge bunch is not infinitely dense, but it does become several times greater than the initial beam injection density. The severity of the charge bunching leads to efficient microwave generation. If, on the other hand, the beam has a spread in axial momentum, the electrons will stop at different locations in the potential well. This tends to limit the charge bunching and the amplitude of the oscillating electric and magnetic fields. The effect of beam temperature in reducing the RF efficiency of the vircator has been witnessed in one-dimensional electromagnetic simulations.[13] A beam spread of less than 3% in energy reduces the microwave generation efficiency from 20% to approximately 2%. Under these conditions the vircator is nothing more than a Barkhausen oscillator.[14] Indeed, the low efficiency and broad bandwidth observed in most of the experiments to date can probably be attributed to the effects of electron reflexing in the diode region resulting in beam heating.

Vircator Design

Based on our current theoretical knowledge of the virtual cathode, numerical simulations, and experimental results, the following points must be considered in the design of a coherent, high frequency vircator. First, generation of high microwave frequencies requires large beam densities. Extremely high beam densities ($n_b^0 > 10^{14}$ cm^{-3}) have been obtained from a foilless diode. The beam plasma frequency scales linearly with the electron cyclotron frequency due to the magnetic field.[15] This is of significance, because it implies that a single vircator can be tuned over an order of magnitude in frequency (eg. 10-100 GHz) simply by changing the axial magnetic field strength without changing the physical structure of the device.

Second, both the oscillation frequency and net current asymptotically approach a value as injected current is increased above the space-charge limit. Thus, using a very large value of ν_0/ν_ℓ does not substantially increase frequency or RF efficiency where efficiency is given by

$$\eta \leq \frac{e\Delta\phi}{(\gamma_0-1)\, mc^2} \qquad (3)$$

A foilless diode in a strong axial magnetic field produces a very thin annular beam. Since ν_ℓ for an annular beam is larger than for a solid beam of the same area, the value of ν_0/ν_ℓ will be smaller for the same beam current.

In order to assure narrow bandwidth, high efficiency microwave generation at high or low frequency from the vircator, the following characteristics must be met. First, no reflexing of electrons in the region between the real and virtual cathodes must occur. Any axial magnetic field must be shaped to divert the electrons, or flux excluders must be employed to confine the magnetic field to the diode region. The latter arrangement will allow the radial space-charge electric field to perform the role of expelling electrons to the waveguide wall. In addition, if the beam is annular, a collimator may be used to help prevent reflexing of electrons back to the cathode. Second, the electron beam must be cold. Experimental[16] and theoretical[15] results indicate that foilless diodes create low emittance beams. Laminar flow, where the electron Larmor orbit is smaller than the beam thickness, is obtained when[16]

$$\omega_c > (\gamma_0 - 1)^{1/2} \frac{c}{\sqrt{a\delta/2}} \qquad (4)$$

where a is the orbit radius, δ is the radial spacing between the cathode and drift tube wall (which acts as the anode) and ω_c is the electron cyclotron frequency given by eB_z/mc. Low beam scatter is also assured, because of the lack of a foil. Finally, the diode voltage and injected current must be constant. More appropriately stated, the impedance must be constant. Flat-top voltage pulses can be attained in a variety of ways in several diode configurations. However, at high voltages the foilless diode operates as a purely resistive load, therefore $\omega_{osc} \propto \sqrt{I/V} = 1/\sqrt{Z}$ is constant. Also, absence of diode closure in some foilless diode experiments makes a long pulse device possible.

It is evident from this discussion that the foilless diode in a strong axial magnetic field represents the optimal configuration for a high frequency vircator. It optimizes microwave power and efficiency while generating high frequency, coherent radiation. For low frequency operation a foil diode or reflex triode utilizing a high transparency mesh for the anode can be used. No axial magnetic field should be employed in order to minimize electron reflexing.

A schematic of the configuration being used in the vircator experiment[17] at Mission Research Corporation is presented in Fig. 2. The pulse power parameters are 50 kV, 66 Ω matched impedance and a pulse length of 1 μsec. The magnetic field coil is capable of attaining 60 kG. We anticipate operating at frequencies as high as 100 GHz. Even with a low efficiency of 2.5% we will produce 1 MW of RF power. A multi-channel microwave grating spectrometer in the 30-110 GHz region developed by MRC will be the chief diagnostic on this experiment.[17]

In summary, the vircator has the potential for producing very high power microwave pulses in the centimeter and millimeter wavelength regimes. In a foilless diode configuration it is tunable by adjusting the imposed axial magnetic field. In a foil diode or reflex triode tuning is accomplished by changing the A-K gap spacing. The microwave generation will be coherent and efficient, if electron reflexing into the diode region is prevented.

For an injected current $\nu_o > 3\,\nu_\ell$, $f_{osc} \sim \omega_p^{rel}/\sqrt{2}\pi$. Because the oscillating beam is equivalent to a deformable dipole, the preferred waveguide mode for an axisymmetric beam in a straight-walled cylindrical guide is TM_{0n} where $n = D/\lambda_0$, D is the waveguide diameter and λ_0 is the free space wavelength. Thus, D/λ_0 should be chosen to be close to an integer value. Once n is known, the phase velocity, group velocity, wavelength and impedance of the wave in the guide are determined. Similar considerations hold for a rectangular waveguide. Note that both ν_ℓ and the cutoff wavelength, λ_c, depend on the guide dimensions and geometry. Both must be considered in choosing an experimental configuration.

BEAM TARGET ASSEMBLY

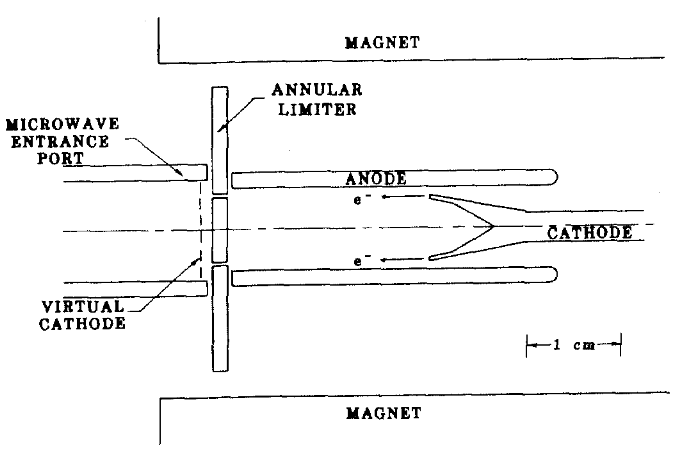

Figure 2. Schematic of the AFOSR/MRC Vircator.

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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. Bruns, and R. A. Kehs, in Proc. of the 2nd Intl. Top. Conf. on High Power Electron and Ion Beam Research and Technology, (Cornell University, Ithaca, New York, 1977), p. 649.

3. J. M. Buzzi, H. J. Doucet, B. Etlicher, P. Haldenwang, A. Huetz, H. Lamain, C. Rouille, J. Cable, J. Delvaux, J. C. Jouys and C. Peugnet, idem, p. 663.

4. A. N. Didenko, G. P. Fomenko, I. Z. Gleizer, Ya. E. Krasik, G. V. Melnikov, S. F. Perelygin, Yu. G. Shtein, A. S. Sulakshin, V. I. Tsvetkov, and A. G. Zerlitsin, in Proc. of the 3rd Intl. Top. Conf. on High Power Electron and Ion Beam Research and Technology, (Institute of Nuclear Physics, Novosibirsk, USSR, 1979), p. 683.

5. A. Bromborsky, H. Brandt, and R. A. Kehs, Bull. Am. Phys. Soc. 26, 165 (1981); and private communication.

6. M. C. Clark, private communication.

7. C. A. Ekdahl, private communication.

8. D. J. Sullivan and E. A. Coutsias in High Power Beams '81, Proceedings of the 4th Intl. Top. Conf. on High Power Electron and Ion Beam Research and Technology, edited by H. J. Doucet and J. M. Buzzi (Ecole Polytechnique, Palasieau, France, 1981), p. 371.

9. E. A. Coutsias and D. J. Sullivan, to be published in Phys. Rev. A., March, 1983.

10. D. J. Sullivan, Bull. Am. Phys. Soc. 25, 948 (1980).

11. D. J. Sullivan, in Proc. of the 3rd Intl. Top. Conf. on High Power Electron and Ion Beam Research and Technology, (Institute of Nuclear Physics, Novosibirsk, USSR, 1979), p. 769.

12. W. B. Bridges and C. K. Birdsall, J. Appl. Phys. 34, 2946 (1963).

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

14. H. Barkhausen and K. Kurz, Phys. Zeit. 21, 1 (1920).

15. M. E. Jones and L. E. Thode, J. Appl. Phys., 51, 5212 (1980).

16. R. B. Miller, K. R. Prestwich, J. W. Poukey, and S. L. Shope, J. Appl. Phys. 51, 3506 (1980).

17. D. J. Sullivan, D. E. Voss, W. M. Bollen, R. H. Jackson and E. A Coutsias, AMRC-R-451 (1983), unpublished.