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ANALYSIS OF OUTPUT POWER DELAY IN COAXIAL VIRCATOR

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Abstract—In this paper, a virtual cathode oscillator (VCO) is simulated based on FDTD algorithm. The geometrical structure is coaxial. Electromagnetic fields and current graphs are calculated. For the first time it has been shown that the delay between input pulse and output microwave signal originate from the waveguide transition delay time and the virtual cathode generation loop delay time.

1. INTRODUCTION

Virtual cathode oscillators are actually a class of sources that all depend on radiation generation by one or both of two phenomena that accompany the injection of an electron beam into a waveguide or cavity in which the beam current exceeds the local space-charge-limiting current: virtual cathode and electron reflex oscillations [1].

These sources are capable of gigawatt-level output in the 1 to 10-GHz frequency range, they are relatively simple to be built, since no magnetic field is required; and they generally operate at relatively low impedances, which makes them rather attractive from the standpoints of producing power at relatively low voltages and of coupling well to

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low-impedance power sources. They are also conspicuously tunable because their operation depends only on the charge density of the beam and not on any resonance condition. A single device can generate radiation over one or two octaves. The wide tunability of the vircator has made it a popular source in high power microwave (HPM) testing facilities [2], where the variation of effects with frequency can be surveyed conveniently [3].

Despite those advantages, these sources have historically suffered from relatively low efficiency, and they have been very sensitive to the problem of gap closure, which causes the diode current to be increased with time, so that the frequency chirps upward, upsetting the balance between resonances in a way that causes output to drop.

In this paper, we present coaxial vircator, originally proposed by Russian scientists [4]. Experimental results of a coaxial vircator, reported by Texas Tech University team [5]. Simulation of this structure with a FDTD particle in cell code is presented and compared with experimental results [5, 6]. As anticipated, simulation has good agreement with experimental results, we survey a new concept namely propagation delay.

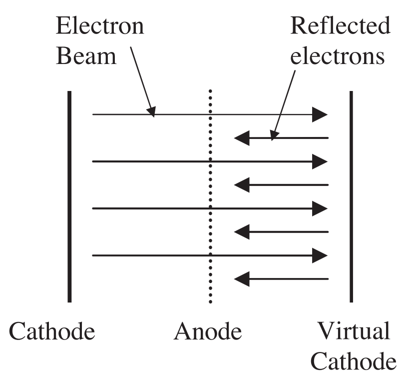


Figure 1. Virtual cathode oscillation concept.

2. MICROWAVE GENERATION

The principle of microwave generation by a vircator is illustrated in Fig. 1. An electron beam is accelerating in the diode gap where pulsed high voltage is applied between the anode and the cathode. The beam passes through the anode, and is injected into the area on the other side of the anode. When the beam current is higher than the space-chargelimited current of this area, a virtual cathode is formed at certain position that reflects a certain part of the electron beam [7].

The position of the virtual cathode and the ratio of beam reflection depend very much on the electron energy. Therefore, if the electron energy is modulated at a given frequency; both the virtual cathode position and reflected beam current will oscillate at the same frequency. The electron energy can be modulated by an electromagnetic field and the same field may interact with the modulated reflection current because they have the same frequency. In this interaction, if the phase relation is such that the electromagnetic field obtains energy from the modulated current, the result will be field amplification by the virtual cathode oscillation [8].

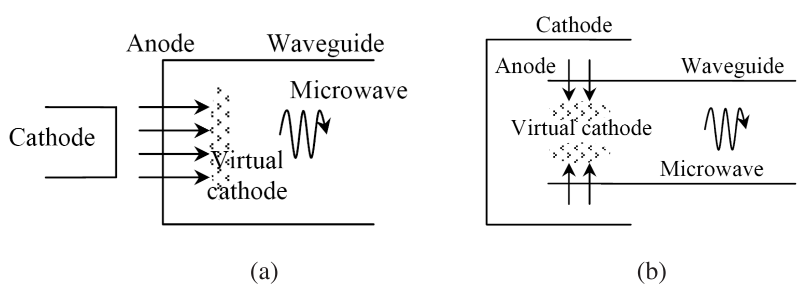


Figure 2. Configuration of (a) an axial vircator (b) a coaxial vircator.

Most vircators consist of an electron-beam diode and a waveguide with the configuration shown in Fig. 2(a) [9–13]. The electron beam is accelerated in the axial direction and is injected through the end wall of the waveguide. The interaction happens between the electron beam current and the axial electric field of the waveguide mode [14].

Another configuration is coaxial vircator illustrated in Fig. 2(b) (our interested case). It has a coaxial pair of cathode and anode that injects the electron beam radially into the circular waveguide [15]. There is an interaction between the electron beam current and the radial electric field of the waveguide mode [16].

3. SIMULATION GEOMETRY

In Fig. 3, the geometry of simulation is indicated. The 2-D steady-state analytical method for the inward-emitting coaxial vircator applied to define the dimensions [3]. Table 1 indicate the parameters used in our simulation.

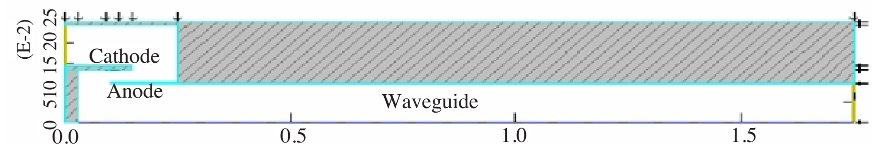


Figure 3. Geometry of simulation.

Table 1. Parameters used in simulation.

Cathode radius R_c	13.1 cm
Anode radius R_a	9.9 cm
Diode voltage V_d	500 Kv
Waveguide radius R_w	9.8 cm
Waveguide length	1.5 m
Cathode width	3 cm

4. VIRTUAL CATHODE POSITION

Since the virtual cathode potential is equal to the cathode potential, and anode is in ground potential, one dimensional steady-state analysis can be used [17], with potentials as boundary conditions, so radius of the virtual cathode is obtained as:

$$R_{vc} \approx 6.9\,\text{cm} \tag{1}$$

The radius of the virtual cathode obtained by analytical method, has good agreement with simulation.

5. OSCILLATION FREQUENCY

The time of flight of electron between the anode and the virtual cathode is obtained by

$$\tau = \int_{R_{vc}}^{R_a} \frac{dr}{v_e} \approx 0.19\,\text{ns} \tag{2}$$

The frequency of electron reflexing between the cathode and the virtual cathode is then obtained as [18]

$$f_{ref} = \frac{1}{4\tau} \approx 1.3\,\text{GHz} \tag{3}$$

And the oscillation frequency [8] is obtained by

$$f_{osc} = \frac{2}{3\tau} \approx 3.5\,\text{GHz} \tag{4}$$

Recently a new formulation for the frequency of the coaxial vircator has been derived, which is based on the relativistic-fluid-Maxwell equations as follow [19]:

$$f_{osc} \approx 9.44 \times 10^4 \cdot \frac{(R_a/R_c)^{1/4}}{(R_c - R_a)} V_d^{1/2} = 1.94\,\text{GHz} \tag{5}$$

It can be seen that the oscillation frequency differs using various methods, however it will be seen that the recent formulation agrees with the simulation and measurement.

6. COMPARISON OF SIMULATION AND MEASUREMENT

Figure 4 shows typical waveform of the diode voltage and the diode current obtained by simulation. The peak diode voltage and current are ∼500 Kv and ∼40 KA respectively; these values are same as measurement results.

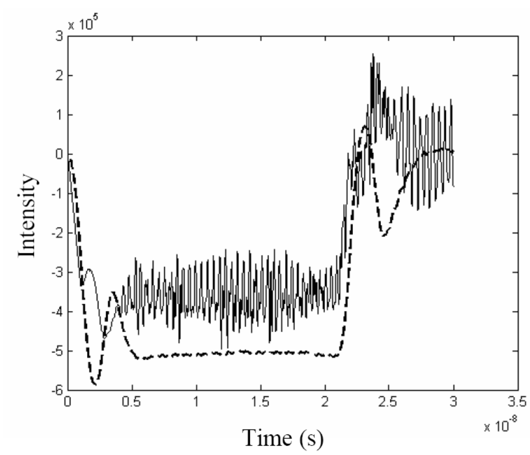


Figure 4. Waveform of the diode voltage (dashed line) and current (solid line) obtained by simulation.

It can be seen that the diode current oscillates after a specific time. We believe that this is the modulation of electron beam and its influence on the diode current. The result of fast Fourier transform (FFT) on diode current is shown in Fig. 5, from which we obtain the microwave frequency of ∼2.1 GHz. This frequency has good agreement with the measurement result [5] which is about 2 GHz.

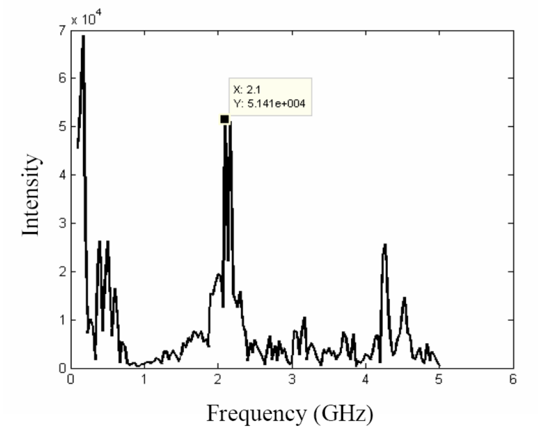


Figure 5. FFT of diode current.

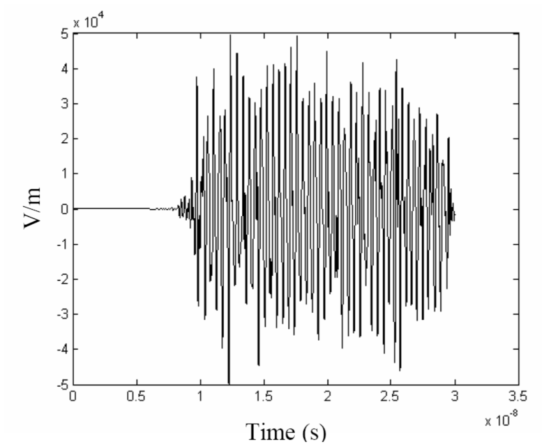


Figure 6. Waveform of the microwave oscillation obtained by simulation.

Figure 6 shows a typical waveform of microwave oscillation obtained by the simulation. The result of fast-Fourier transform on Fig. 6 is shown in Fig. 7. Analyzing this figure, we obtain the microwave frequency of ∼2.1 GHz. The frequency obtained from microwave oscillation confirms that the frequency of diode current is originated from the beam-wave interaction.

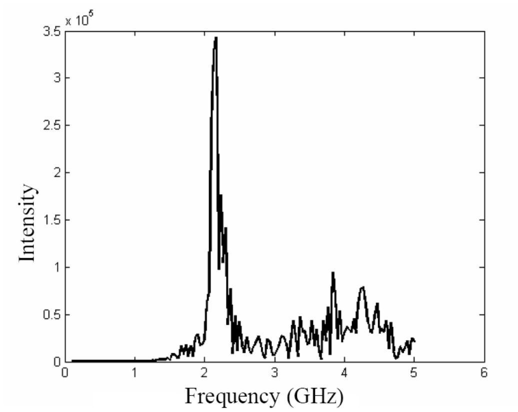


Figure 7. FFT of output microwave obtained by simulation.

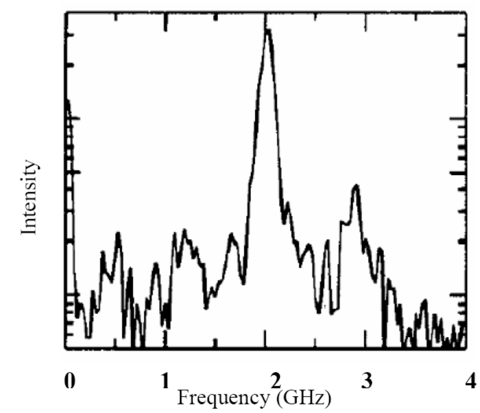


Figure 8. FFT of microwave oscillation obtained by measurement.

To compare the result of the simulation and the measurement, the FFT on the microwave oscillation obtained by experiment is shown in Fig. 8 [5].

The electron beam power calculated from Fig. 6 is shown in Fig. 9 together with microwave power obtained by simulation. The ratio of the peak beam and microwave powers results the efficiency about 2.2% that is match with experimental report (∼2%).

In Fig. 9, it can be seen that the microwave power occur at about 10 nanoseconds after the beam power. To the best of this search, this is a novel result and is not reported in any existing research papers. Here we will explain the question that "what is the matter of the delay between input power and output power?"

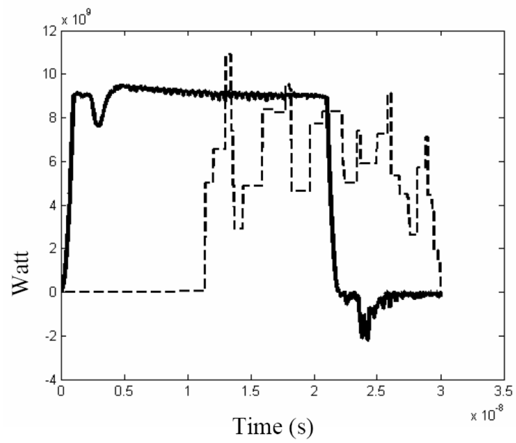


Figure 9. Electron beam power (solid line) and microwave power (dashed line).

7. RATIONALIZING OF THE DELAY

Electromagnetic wave propagation delay in waveguide is [20, 21]:

$$t = \frac{l}{c\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \tag{6}$$

where f, f_c, l, c are the operating frequency, cut-off frequency of the waveguide, the waveguide length and the speed of light, respectively.

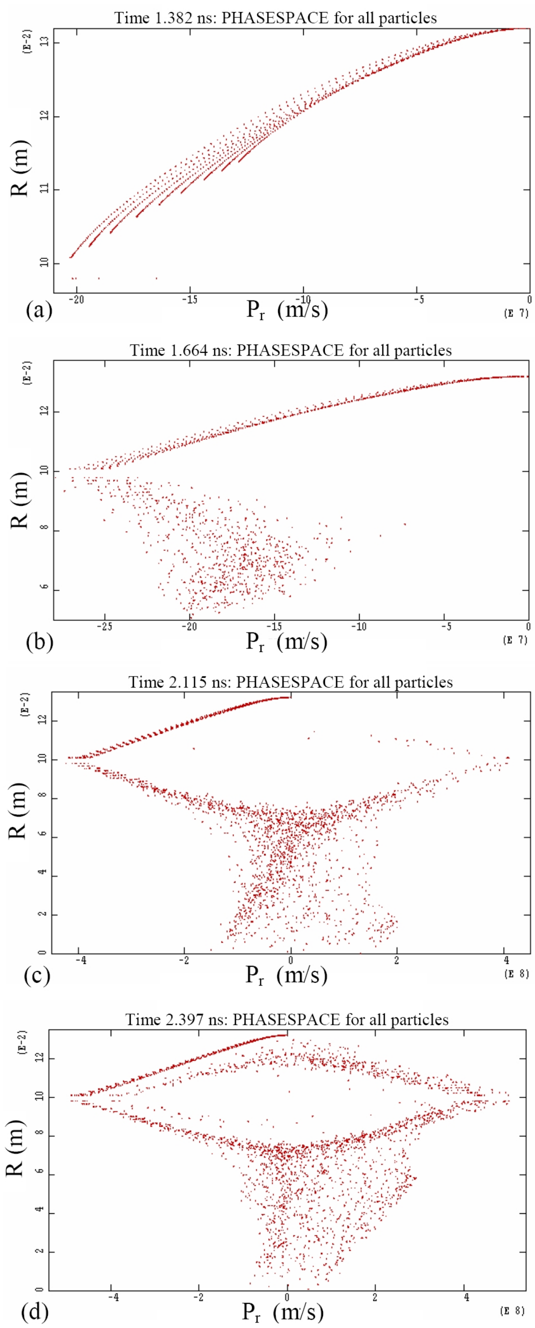
Typical TM_{01} cut-off frequency of a circular waveguide with radius 9.6 cm can be obtained as follows:

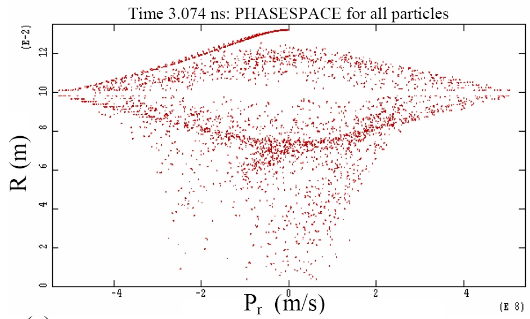
$$f_c = \frac{0.383 \times c}{R_w} = 1.17\,\text{GHz} \tag{7}$$

From (6) for a 2.1 GHz wave propagation, the delay time in a circular waveguide is about 6.2 ns. Simulation result of output microwave is indicated in Fig. 6. It can be seen that the first appearance of oscillation occur at time ∼6.5 ns.

Conclusion is which 10 nanoseconds delay is come from 6.5 nanoseconds delay of propagation in waveguide [22] and another reason that cause the microwave to generate 3.5 nanoseconds after beam entrance to the waveguide.

Figure 10 shows the electrons momentum versus their axial position just beginning the pulse. In Fig. 10(a) electrons leave the


Time 1.382 ns: PHASESPACE for all particles
R (m)
(a)
P_r (m/s)
Time 1.664 ns: PHASESPACE for all particles
R (m)
(b)
P_r (m/s)
Time 2.115 ns: PHASESPACE for all particles
R (m)
(c)
P_r (m/s)
Time 2.397 ns: PHASESPACE for all particles
R (m)
(d)
P_r (m/s)



(e)

Figure 10. Phase-space plot of electron beam forming a virtual cathode.

cathode with zero initial velocity and accelerate toward anode. In Fig. 10(b) the initial electrons reach the anode and pass through it. By passing electrons through anode, they enter to the waveguide region. Inside the waveguide, the potential of electrons (that is self-existing), barriers later electrons to move forward. So, electrons sense the virtual potential and move backward. Fig. 10(c) shows electrons that come back anode with inverse momentums. In Fig. 10(d) returned electrons pass again through anode and move toward cathode, but they have not sufficient energy to reach the cathode. Returned electrons that are now next to cathode, sense the cathode potential and come back to the anode together with electrons that for the first time leave the cathode (Fig. 10(d)). Those electrons which comeback to cathode play an important role in generating microwave this is a feedback role; the electrons feedback the field present in waveguide to the cathode current. Moreover, in the second order they enter waveguide region, fundamental component of microwave will produce (Fig. 10(e)).

As we can see in Fig. 10(e) the desired time to electrons for the second order inter the waveguide is 3.5 nanoseconds.

8. CONCLUSION

A virtual cathode oscillator (VCO) was simulated based on the FDTD algorithm. it has been shown that the delay between input pulse and output microwave comes from the waveguide transition delay time and the virtual cathode generation loop delay time. The delay is depend on the waveguide length, waveguide cut-off frequency, output frequency, anode-cathode distance and applied voltage. For the future work, we are going to develop a formulation for the propagation delay time in vircators.

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