

MICROWAVE EMISSION VIRTUAL CATHODE DRIVEN BY MAGNETIZED RELATIVISTIC ELECTRON BEAM

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ABSTRACT:

The recent development of high-voltage pulse technology has resulted in possibility for production of charge particle beams with currents in excess of 10 kA at accelerating voltages of several hundred kV and more. When such an intense electron beam propagates inside an evacuated conducting drift tube under certain conditions the non-neutralized beam space-charge leads to the formation of virtual cathode. The virtual cathode phenomenon can be used for ion acceleration or high-power microwave generation. The process of virtual cathode formation and the emission of microwave radiation at gigahertz frequencies by virtual cathode have been investigated using computer simulation.

1. INTRODUCTION

The investigation of space-charge effect commenced in the beginning of the century with classic works of Child and Langmuir, where a stationary solution for 1-D electron flux in a planar diode was obtained with self-consistent account for space charge. These works in particular concluded that under certain condition a so called virtual cathode would be formed. The term virtual cathode refers to the potential minimum created by the beam space-charge when it is high enough to reflect some electrons back to the emitter region.

Recent advance of pulse power technology led to production of charge particle beams with currents in excess of 10 kA at voltages of 1 MV and more. When such an intense beam of charge particles propagates into a grounded drift tube the non-neutralized beam self-charge reduces the kinetic energy of the particles. If the beam current is above a specified current (called space-charge limited current or also vacuum limited current) the potential minimum created by the beam self-charge exceeds the initial kinetic energy of the particles. In this case the electrons are reflected back by the potential barrier and the virtual cathode is formed.

The space-charge limited current is a very important parameter for vacuum electronics. All vacuum microwave tubes (with only one exception of the so called virtual cathode oscillator) as gyrotrons, free electron lasers, magnetrons, klystrons, traveling wave tube, backward wave oscillators and so on are limited in their operation below this critical vacuum current. In case of monoenergetic, homogeneous in cross-

section high-current relativistic electron beam with radius r_b which is driven by infinite external magnetic field in a long grounded cylindrical vacuum drift tube with radius R the value of the space charge limited current is given by the well-known formula of Bogdankevich and Rukhadze [1]:

$$I_{scf}(kA) = 17.07 \frac{(\gamma^{2/3} - 1)^{3/2}}{1 + 2 \ln \left(\frac{R}{r_b} \right)} \quad (1)$$

where γ is the beam relativistic factor.

The space charge limited current is the maximal beam current which can be transported at conditions of steady state flow in a given drift tube. If the beam current is above the critical current, the virtual cathode is formed. The virtual cathode phenomenon has been subject to numerous studies but many of its features are still unclear because the virtual cathode has an unstable oscillating behavior [2]. It oscillates in space and time reflecting some of the incoming electrons back to the emitter region and transmitting others. The average value of beam current passed downstream the virtual cathode is approximately equal to the space-charge limited current.

The phenomenon of virtual cathode formation in case of intense relativistic electron beam propagation in vacuum drift tube is used for high power microwave generation. The microwave devices whose operation is based on virtual cathode are named Virtual Cathode Oscillators (VCOs) or simply Vircators. The vircator has the attribute of conceptual simplicity, high-output power capability, and wide tuning ability [3]. Also, virtual cathode oscillators operate above the space charge limited current so they can be a source of extraordinary high power [4].

Two processes lead to microwave emission in vircators. In the first the temporal and spatial oscillations of the unstable virtual cathode emit microwave radiation while in the second the oscillations of the reflected by virtual cathode electrons between the real and the virtual cathode give rise to the radiation [3]. In general both processes co-exist but one may dominate over the other. The presence of two sources for microwave emission in Vircators is disadvantageous since they interfere destructively leading to an inefficient, broadband microwave output [4]. Typical vircators have efficiencies in the range of 1 to 3% with bandwidth in the order of 10% and more.

Both above mentioned radiation mechanisms emit microwaves at different frequencies. The microwave frequency emitted by virtual cathode itself scales with the beam plasma frequency [5,7]:

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$$\omega \approx \sqrt{2\pi\omega_p}$$

$$\omega_p = \left(\frac{4\pi e^2 n}{m\gamma} \right)^{1/2} \quad (2)$$

where n is the electron number density, γ is beam relativistic factor, e and m are the electron charge and mass respectively. Here the coefficient $\sqrt{2\pi}$ was found empirically.

In the second case the reflected electrons oscillating inside the potential well between the real and the virtual cathode emit microwave radiation at frequency equal to the electron bounce frequency inside the potential well [6,7]:

$$f = \frac{1}{2} \frac{\beta c}{2d} \quad (3)$$

where d is the anode-cathode gap, $\beta = v/c$, c is speed of the light and v is the electron velocity.

Because of the complex nonlinear behavior of the virtual cathode and the presence of two microwave emission processes, the theory of vircator operation is far from complete. For this reason, computer simulations are widely used for studying the virtual cathode phenomenon.

This paper deals with computer simulations that demonstrate the formation of virtual cathode in magnetized vircator and possibility for high-power microwave generation by the virtual cathode as well. The results of computer simulation are compared with results of laboratory experiments.

2. COMPUTER SIMULATIONS.

The simulations were carried out using a 2.5 dimensional (two spatial coordinates and three velocity components) particle-in-cell computer code KARAT, which is fully relativistic and electromagnetic [8]. It self-consistently solves Maxwell's equation together with relativistic equation of motion including complicated boundary conditions. For the present numerical simulation more than ten thousands of particles have been used. A cylindrical geometry with azimuthal symmetry is considered. Fig. 1 shows a schematic layout of the simulation geometry.

High voltage with negative polarity is applied to the cathode while the drift tube and the anode are grounded. The anode is a thin metal foil positioned 5 mm away from the cathode. The foil is transparent for electrons but is opaque for the electromagnetic waves. The right-side of the simulation region is left open so that generated electromagnetic waves can be emitted through it. The cathode voltage is 300 kV and it reaches its maximal value for 1.0 ns. The current in the simulation increases from zero to 5 kA for about 1.5 ns. The electron beam is guided by an external magnetic field of 1 T. All parameters in the simulations were chosen as close as possible to the experimental ones [10].

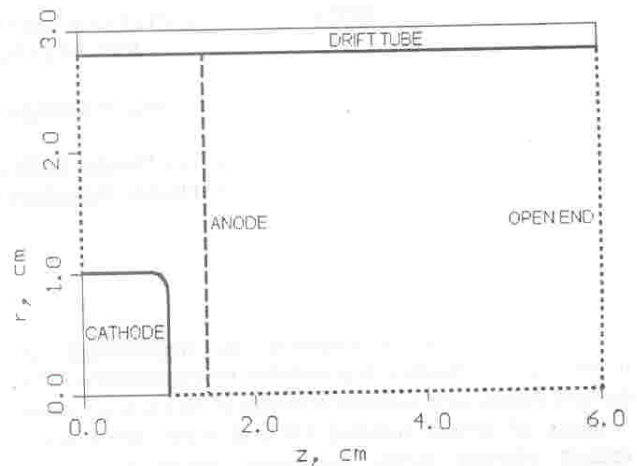


Fig. 1. Schematic layout of the simulation geometry

The space-charge limited current for the geometry shown in Fig. 1 is about 2 kA and the virtual cathode is formed when the beam current exceeds this value. In Fig. 2 one can see three sets of snapshots taken at times of 0.3 ns, 0.5 ns, 0.9 ns, 1.0 ns, 1.1 ns and 1.2 ns. Fig. 2a and Fig. 2b show axial distributions of the potential and the charge density at subsequent times, while Fig. 2c shows the corresponding evolution in phase space of the electron beam. The process of virtual cathode formation can be well seen from these sets of time snapshots. When the beam current is below the space charge limited current of the drift tube (pictures at time $t < 1$ ns) the virtual cathode does not exist. The potential minimum created by the beam self-charge (Fig. 2a) is smaller than the accelerating voltage and there is no space charge accumulation inside the drift tube as well (Fig. 2b). The peak of charge density distribution at $z=1$ cm is caused by intense electron emission from the cathode surface. Deceleration of the electrons in the drift tube due to charge-effects can be seen in Fig. 2c. Still the velocity reduction due to the space charge is not significant and the electrons can reach the end of the simulation region. However at $t=1$ ns when the beam current is about the space charge limited current the potential barrier created by the space-charge is approximately equal to the accelerating voltage (Fig. 2a) and the velocity of some electrons is reduced nearly to zero by the virtual cathode (see Fig. 2c). At subsequent times ($t=1.1$ ns and $t=1.2$ ns) one can see that the virtual cathode has already been formed. It reflects back to the diode some of the incoming electrons and transmits others (Fig. 2c). The location of the virtual cathode and its movement in space can be clearly observed in Fig. 2a at $t=1.1$ and 1.2 ns. A second peak associated with electrons gathering into the virtual cathode appears in the charge density distribution as well (Fig. 2b). The electrons reflected back by the virtual cathode pass through the anode, decelerate by the real cathode (see Fig. 2c) until they are stopped and reflected forward. After that, the electrons are accelerated towards the anode, pass through it and start decelerating again by the space charge.

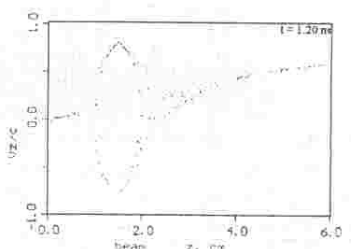
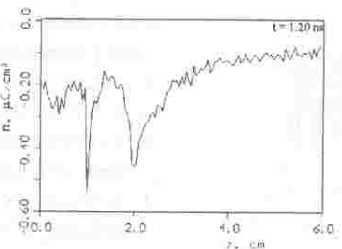
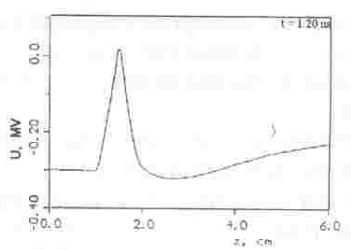
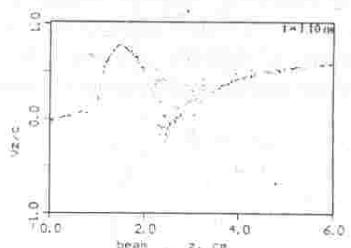
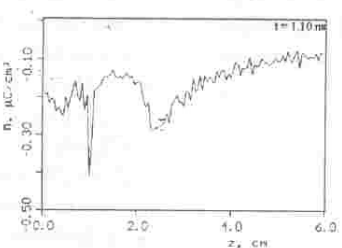
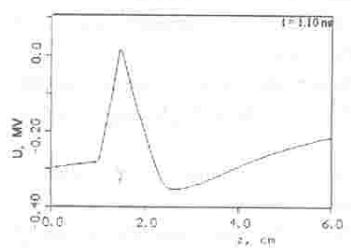
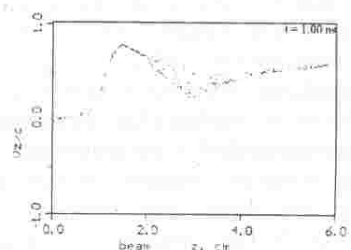
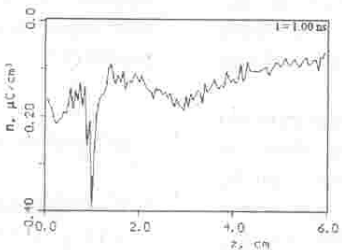
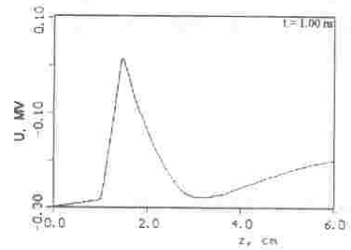
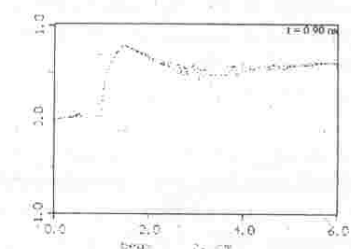
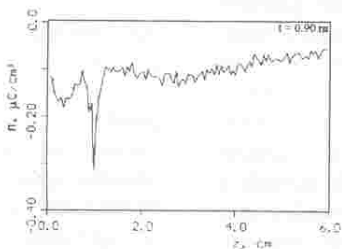
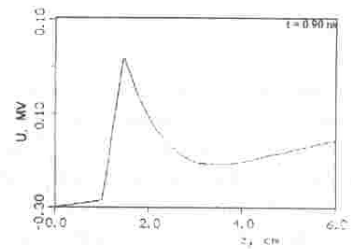
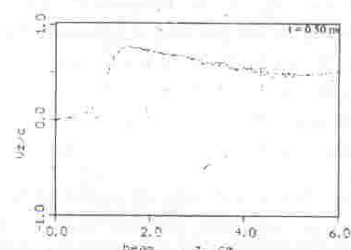
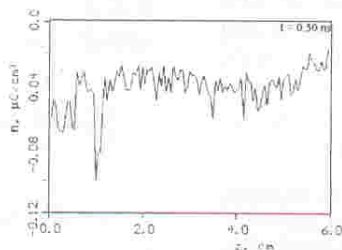
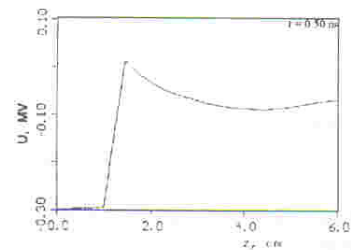
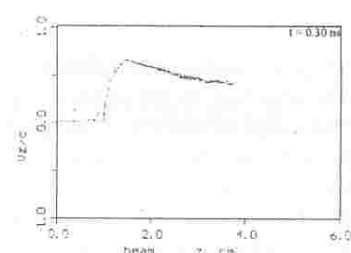
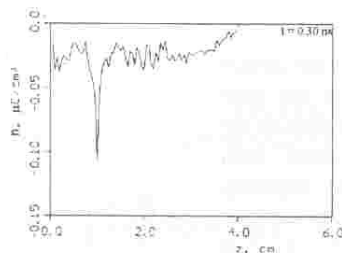
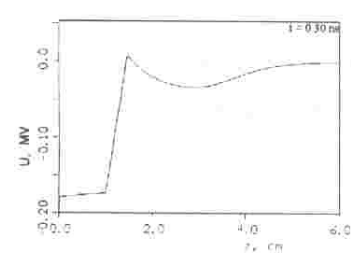


Fig. 2a. Evolution of the axial potential distribution.

Fig. 2b. Evolution of the axial charge distribution.

Fig. 2c. Evolution of the electron beam in phase space.

High power microwave radiation emitted by the virtual cathode was observed in simulation. Fig. 3 shows the time history of the radial component of the electric field near to the open right side of the simulation region at point with coordinates $r=2.7$ cm and $z=5.9$ cm. Strong high frequency oscillations of the electric field appear after virtual cathode formation. A Fourier transform of the signal of Fig. 3 is presented in Fig. 4. A frequency peak at about 14 GHz corresponding to the emitted microwave frequency can be well seen. The DC-component in the Fourier transform accounts for the static electric field of the electron beam.

Knowing the beam parameters from the simulation we can calculate the beam density by following formula:

$$n_b = \frac{NQ}{eV} \quad (4)$$

where N is the number of the particles used in the simulation, Q is the charge of an individual particle, e is the electron charge and V is the volume occupied with the electron beam. In our case $N=9775$, $Q=1.44 \times 10^{-10}$ C and $V=1.57 \times 10^{-5}$ m³ so that using formula (4) we obtain for the beam density $n_b=5.6 \times 10^{17}$ m⁻³. Substituting this value and the beam relativistic factor from the simulation ($\gamma=1.59$) in the formula (2) for the radiation frequency emitted by the virtual cathode a microwave frequency of 13.4 GHz is calculated, which is in a good agreement with the numerical results. So we can conclude that the source of microwave radiation in our simulation is the virtual cathode itself. No microwave emission from the electrons oscillating between the real and virtual cathode was observed in the simulation.

The mode structure of the electromagnetic waves could not be clearly identified in the simulations. As it was shown in [9] several transverse magnetic modes (up to five) can be excited in the same time. However at the microwave frequency of 14 GHz observed in the simulation only the lowest two transverse magnetic modes TM_{01} ($f_c=4.09$ GHz) and TM_{02} ($f_c=9.42$ GHz) can be excited. The total microwave power emitted through the open right side of the system was 29 MW which corresponds to about 2% efficiency.

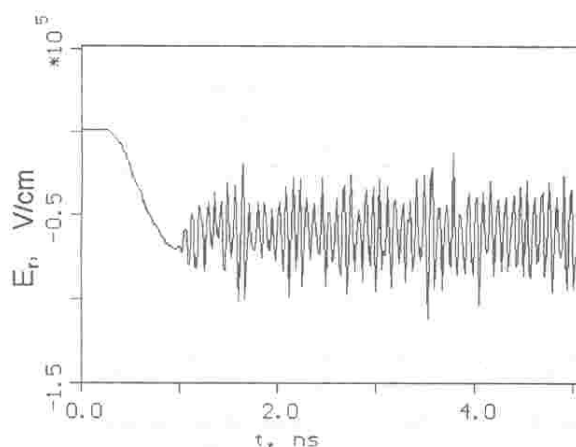


Fig. 3. Time history of the electric field.

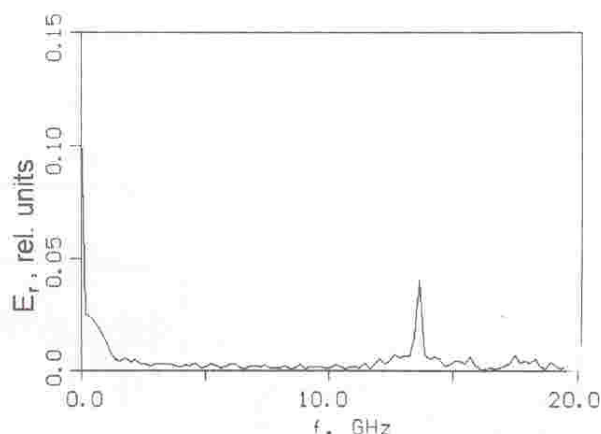


Fig. 4. Fourier spectrum of the electric field.

3. CONCLUSIONS

The presented computer simulations demonstrate a possibility for high power microwave generation by virtual cathode oscillator with an external guide magnetic field. The vircator operates in a range of intermediate voltages (several hundred kV) and relatively low current (below 10 kA) which is not well explored. The emitted microwave radiation frequency and power in the simulations are in good agreement with experimental results [10] obtained in similar vircator geometry.

4. REFERENCES

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