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Influence of the Cathode Rim Size on the Emitting Current in Virtual Cathode Oscillator

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Abstract

This paper investigates the effects on the current amplitude and the homogeneity of current density, when a rim is added to the cathode of a vacuum diode. Results were obtained by particle-in-cell simulations. The results indicate that rims size can affect both current amplitude and angular divergence.

1. Introduction

The virtual cathode oscillator (Vircator) is a High-Power Microwave (HPM) device that can deliver peak powers up to gigawatt levels. This HPM source is characterized by its simple mechanical construction since it does not require a magnetic field guide [1]. The electron beam is emitted and injected into the diode from the cathode, therefore cathodes plays a crucial role in the performance of the source [2].

The initial step for understanding the basic functioning of a diode and, consequently, the Vircator itself is by reviewing the work of Childs and Langmuir [3], [4]. The study involved calculating the electron emission when a static potential is applied to an infinite parallel plate in vacuum. Their findings indicated that the flow of current density (J_{1DCL}) between the electrodes is the following:

$$J_{1DCL} = \frac{4}{9}\varepsilon_0 \sqrt{\frac{2e}{m}} \frac{{V_0}^{3/2}}{d^2}, \qquad (1)$$

where ε_0 is the permittivity of free-space, m is the rest mass of electron, e is the electron charge, V_0 is the gap voltage, and d is the gap separation.

Equation (1) is known as the Child-Langmuir Law (C-L) and determines the Space Charge Limit (SCL) current. C-L provides the maximum steady-state current density in a 1D vacuum gap.

C-L is derived based on assumptions that prevent its direct application in other situations or geometries. E.g., the Child-Langmuir Law deals with the assumption that the electric field is zero at the cathode's surface. However, for practical emitters, particularly on field emission, large electrical field at the cathode surface are necessary to obtain electron emission [5].

Various papers [6]–[8] expanded the C-L to two dimensions. Most papers considered a geometry with infinite electrodes and finite emission area. Practical diodes used in Vircators have cylindrical symmetry with outer drift tube, i.e. all electrodes have finite dimensions.

Benjamin Ragan-Kelley [9] examined the SCL in such 2D case. The geometry considered is a planar diode with axial emission from a cathode of radius r, outer drift tube radius $R>r$, and gap length L. The geometry of the axisymmetric diode is shown in Fig. 1.

The derived expression for the 2D current density (J_{2DCL}), predicted in [9] is the following:

$$\frac{J_{2DCL}}{J_{1DCL}} = 1 + \frac{0.419}{r/L} + \frac{0.036}{(r/L^2)} \qquad (2)$$

where r is the cathode radius and L is the gap separation length (see Fig. 1).

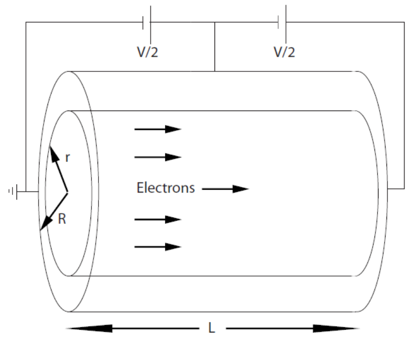

Figure 1. Axisymmetric diode [9]

In this paper, the influence of adding a rim to the cathode is studied (see Fig. 2). This parameter, which to the authors' best knowledge has been neglected in previous studies, could improve the emission process. The result will be compared with Eq. (2).

The paper is organized as follows: Section 2 describes the simulation geometry and domain. In Section 3, simulation results are provided. These consist mainly of the current amplitude and the angular divergence of the electron beam, calculated for cathodes with different rim sizes. Finally, Section 4, conclusions are drawn.

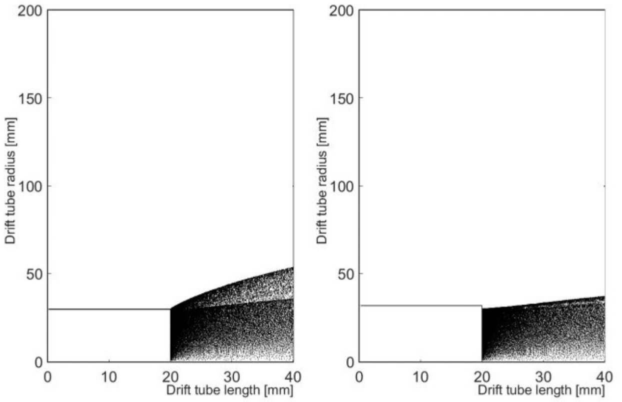

Figure 2. Figure shows the beam general characteristic of cathode without rim (left) and cathode with rim (right).

2. Simulation of cathodes with rims

This section is divided in two parts. In the first one, the simulation setup is verified by comparison with the J_{2DCL} current predicted by the Eq. (2) for diodes without rims. In the second part, the simulation geometry and domain are presented. All the simulations were carried using XOOPIC [10] with axisymmetric geometry.

2.1 Simulation benchmark

As a first step and in order to verify the simulation setup in XOOPIC, a simple parametric variation of r_c/l (without rim) was done. Results are presented in Fig. 3 together with the theoretical results anticipated by Eq. (2).

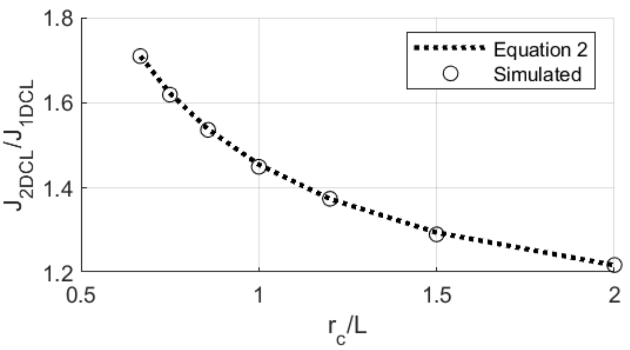

Figure 3. The scaling law for the ratio of 2D axisymmetric SCL current to 1D.

As it can be seen, both results are in good agreement. Notice that the ratio of the J_{2DCL} to the theoretical 1D value J_{1DCL} is always decreasing function of the ratio between emission radius and the gap separation [9].

2.2 Simulation geometry and domain

The geometry of the simulation domain, including the cathode with rim and anode (diode region of axial vircator) is shown in Fig. 4 and Table 1, respectively. Table 1 summarizes the simulation parameters for a cathode with emitting radius of 30 mm (typical for axial vircator).

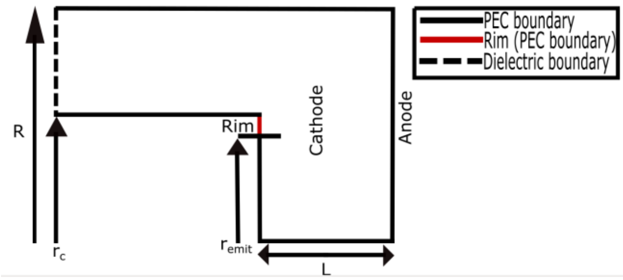

Figure 4. Figure represents the geometry of the cathode and calculation domain for XOOPIC. Here r_c is the cathode radius, r_{emit} is the radius of emitting surface on the cathode (r_c - r_{emit} is the radial size of the rim) and R is the radius of the calculation domain (drift tube radius). The red line denotes the rim.

Table 1. Simulation parameters for a cathode with emitting radius of 30 mm.

Simulation parameters	Value
Voltage	350 kV
Cathode radius	Varied depending on rim size (32 – 44 mm)
Emitting radius	30 mm
Gap separation length (**L**)	20 mm
Drift tube radius	200 mm

3. Results

Equation (2) provides the ideal current without the influence of the cathode rim. The cathode edge exhibits field enhancement, resulting in significantly different emission characteristics than the one-dimensional case.

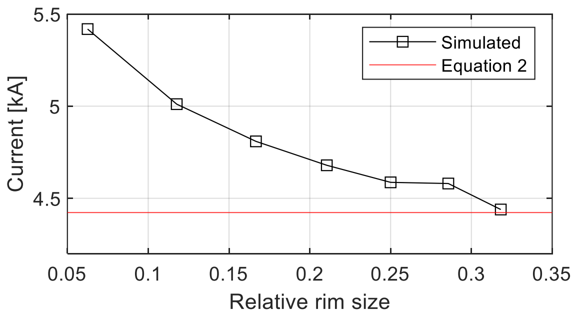

Figure 5. Current dependency on relative rim size of cathode with 30 mm emitting radius (relative rim size= rim size / total radius), gap separation length of 20 mm, and voltage of 350 kV.

Figure 5 presents the effect of increasing the rim size on the generated current for an emitting radius of 30 mm. As it can be interpreted from the figure, increasing the rim size decreases the current. This happens because the edge effect is reduced. The ideal current (red solid line) denotes the current without the influence of the rim.

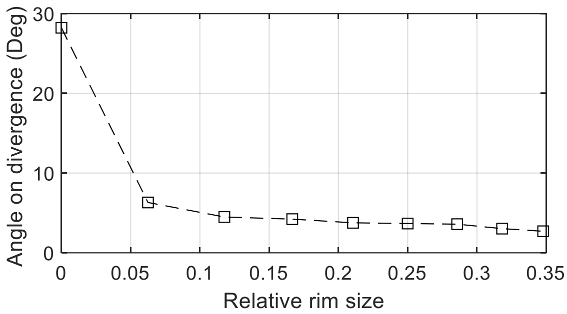

Figure 6. Angular divergence dependency on relative rim size of cathode with 30 mm emitting radius (relativize rim size= rim size / total radius), gap separation length of 20 mm, and voltage of 350 kV.

The dependence of the angular divergence on the relative rim size was obtained and is presented in Figure 6. High dispersion of electron beam causes energy loss, which reduces the Vircator efficiency [11], [12]. As it can be seen, there is a decrease in divergence as the rim size increases. This effect stalls when the relative rim size to electrode radius surpasses the 6%.

4. Conclusion

We have demonstrated that adding a rim to the cathode permits to control two parameters of the cathode emission. According to the results presented, an increasing relative rim size reduces the current amplitude. On the other hand, the same parameter homogenizes the emitted current, reducing the divergence angle. Both parameters impact the total efficiency of the source. Higher current means that more charge will be available to form the virtual cathode, however high divergence means that part of that charge might disperse and not join the virtual cathode. These dependencies might be utilized to select an optimal rim size. Future work will focus on additional PIC simulations including the drift tube, in order to understand the impact of the relative rim size in the final performance of the Vircator.

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