Efficiency Enhancement for an S-band Axial Vircator using 5-stage Two-step Tapered Radiators

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Abstract: *An S-band multistage axial virtual cathode oscillator with efficiency enhancement for high pulsed power electromagnetic applications is presented. The Particle-in-Cell (PIC) results of the designed 5-stage Vircator, with two-step negative tapering in the reflectors, carried out by CST Studio suite 2021 simulation code show a peak power value of 5.54 GW and an efficiency value of 13.65% at 2.45 GHz, under a beam voltage and current equal to 520 kV and 20 kA, respectively.*

Keywords: HPM; Vircator; multistage; reflectors; high-efficiency; plasma frequency; high-efficiency.

Introduction

The virtual cathode oscillator is largely used as a HPM source for its high output power, simplicity of design, and realization as it can operates without external magnetic field. However, the main disadvantage is its low efficiency, especially for the axial configuration [1]. In literature, several geometric schemes have been proposed to increase the energy conversion efficiency. The multistage architecture proposed in [2] is based on the formation of multi-virtual cathodes created by introducing thin anodic foils with the same radius. In this paper, the PIC simulation results of a high-efficient S-band axial Vircator with 5-stage two-step tapered reflectors are reported.

Axial Multistage Vircator Design

In Fig. 1, the schematic block diagram of an axial Vircator comprising a cathode, an anode mesh, and a chamber is shown.

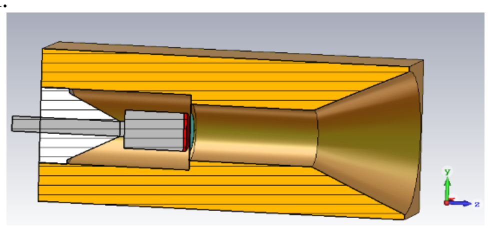

Figure 1. Schematic model of the axial vircator.

The virtual cathode oscillations takes place when the beam current exceeds space-charge limited current given by the Child-Langmuir Law. The oscillation frequency of the virtual cathode f_{OSC} is related to the frequency of the beam plasma f_p and given by the frequency range $f_P \leq f_{OSC} \leq (2\pi)^{1/2} f_P$ [3, 4]. For an axial Vircator, according to [5], the virtual cathode oscillation frequency is given by:

$$f_{OSC} = \frac{4.77}{d_{AK}} \ln\left(\gamma + \sqrt{\gamma^2 - 1}\right) \qquad (1)$$

where d_{AK} is the anode to cathode distance.

The reflected electrons of the virtual cathode oscillate at a frequency f_{reflex} given by:

$$f_{reflex} = \frac{1}{4\tau_{AK}} \qquad (2)$$

where τ_{AK} is the transit time from the cathode to the anode.

As the efficiency of the axial configuration is lower than 5%, the geometry of the axial vircator is modified by introducing 5 thin conducting foils into the cylindrical waveguide to the aim of obtaining a high-efficiency Vircator [5]. The CST schematic model of the 5-stage axial Vircator is shown in Fig. 2. The reflectors are centered in the cross section of the waveguide, partially closing it, leaving an annular aperture between the periphery of the reflector and the wall of the tube. The reflectors have been designed with a two-step reduction in the radius.

At first, the values of the reflectors radii were set equal and with a value equal to 0.75*RG to overlap the maximum value of transverse components of pseudo-cavity modes and ensure amplification of the microwave fields at the targeted frequency. For an emission frequency equal to 2.45 GHz, the anode-to-reflector distance d_{AR} is set equal to 7.6 cm [2].

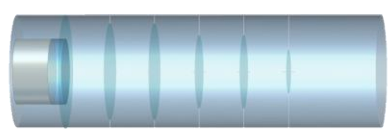

Figure 2. CST schematic model of the 5-stage vircator.

However, the power conversion efficiency in TM_{01} mode increases with the number of reflectors for devices including up to three reflectors. The introduction of more than three reflectors in the drift region triggers through the pseudo cavity the generation of microwaves that propagate as the fundamental mode TE_{11} of the cylindrical waveguide. The resulting mode competition occurring between TE_{11} and TM_{01} propagation modes leads to a decrease in the TM_{01} conversion efficiency as the number of reflectors increases. For this reason, for the first time, a structure with 5 reflectors with decreasing radius is adopted. For the radii a two-step decreasing profile was adopted. Other profile can be

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considered as the linear one. The two-step profile is the simplest one. The simulation parameters of the 5-stage axial vircator are reported in Table I.

Table 1. Simulation Parameters

Beam Voltage (KV)	520
Beam Current (KA)	20
Cathode anode gap (mm)	2,3
Axial and radial grid width (mm)	4,5
Radius of the guide (cm)	8
1^{st} and 2^{nd} stage radius (cm)	6
3^{rd} and 4^{th} stage radius (cm)	5
5^{th} stage radius (cm)	4
Distance between stages (cm)	7.5
Length of the cathode (cm)	6

Particle-in- Cell Simulations

The electron energy distribution with five virtual cathodes, in addition to that formed with the anode, is shown in Fig. 3.

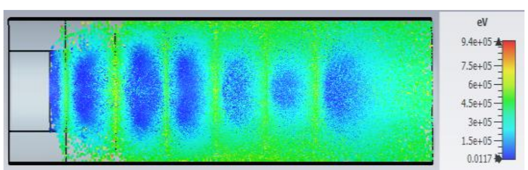

Figure 3. Electron charge distribution.

The spectrum of the Fourier transform for the TM_{01} fundamental mode, plotted in Fig. 4, shows that the total output power is entirely supported by the TM_{01} mode at a frequency equal to 2.45 GHz. The instantaneous output power is plotted in Fig. 5. A peak power of 5.54 GW, an average power of 1.42 GW, and an efficiency of 13.65% are achieved, with an input power of approximately 10 GW.

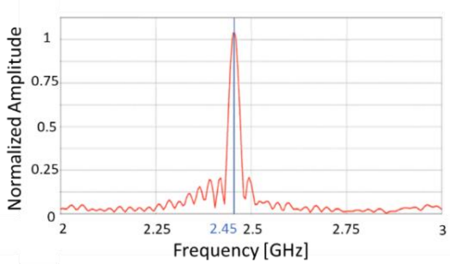

Figure 4. Fourier transform for the TM01 mode.

Cathode Materials

At first, polymeric velvet, graphite, and steel were considered. Higher HPM power was achieved with the polymer velvet cathode. This is due to the shorter ignition time and better beam uniformity. Experimental results indicate that this type of material is superior to graphite in terms of peak power and pulse width [6]. Despite this, plasma is the biggest drawback of this material. The formation of plasma constitutes a large source of neutral

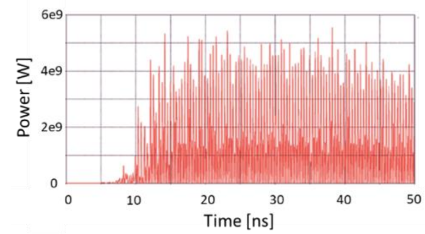

Figure 5. Instantaneous output power.

atoms acting as a conductive surface that closes the anode-cathode gap. It also has a very short life that reaches about 1000 pulses. In order to eliminate these problems, carbon fiber cathodes, with and without CsI coating, have been taken into considerations. A comparison between carbon fiber cathode and steel cathode shown that under the same experimental conditions the conversion efficiency increased from 2- 3% to 8-10%. In terms of pulse width, the carbon fiber cathode shows an increase of about 200 ns [7].

Anode Materials

Molybdenum wires were analyzed as they produce the least amount of gas per shot. The analysis in [8] was adopted.

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