PIC Simulation of HPM Generation in an Axial Vircator

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Abstract—This paper discusses the Particle-In-Cell (PIC) simulation of the high power microwave (HPM) generation from the axial vircator using the Magic code considering the electron beam parameters to be 200kV, 100ns. Magic is a three dimensional electromagnetic specific simulation code which is based on PIC method and Finite Difference Time Domain (FDTD) techniques. The simulation studies have been carried for an intense relativistic electron beam (IREB) generated from a high pulsed power system KALI-1000. The vircator characteristics has been studied for different radii of the vircator chamber for a specified anode-cathode gap (AK) gap. The results so obtained on doubling the chamber radius indicated significant changes in the output power and frequencies of the HPM produced, especially output power showed a tenfold increase as compared to those obtained for the original radius.

Keywords—Axial vircator, FDTD, HPM, IREB, PIC.

I. INTRODUCTION

High power microwave (HPM) sources generate single shot and repetitive nanoseconds duration pulses for various applications like plasma heating, particle acceleration, high power radar, industries and military applications. One such HPM device is the virtual cathode oscillator (vircator). This device is a source of intense microwave radiation with a high output power and possesses easy tuning of frequency and mode of oscillation. A typical axial vircator usually consists of a high power diode and a drift tube [1][2]. The virtual cathode is formed in the drift tube where the cathode surface emits electrons which are accelerated towards an anode. The cathode is an electron emitting material usually graphite and the anode is a semitransparent foil made of metal meshes or wires. The electrons on emission from the cathode penetrate through the anode mesh to form an electron cloud called the virtual cathode, as the current exceeds the space charge limit [1][2][3]. The high power microwave radiation is produced in two possible ways:

(i) when the virtual cathode oscillates

(ii) when the electron beam gets reflected between real and virtual cathode.

The schematics of an axial vircator with HPM generation and position of the virtual cathode is as shown in Fig (1) [4].

Fig. 1 Axial vircator schematics

In either cases, the radiation frequencies can be different. From the virtual cathode, electrons are reflected and they re-enter the diode region and oscillate between real and virtual cathodes [2][3]. The PIC simulation of an axial vircator in Magic has been reported previously in literature for different pulsed power systems limiting the discussion to vircator characteristics. This paper discusses the simulation of such HPM generation in an axial vircator designed for a different high pulsed power system (KALI-1000) using Magic three dimensional code to investigate the effect of increasing vircator chamber radius on HPM output power and frequency and Child-Langmuir current.

II. PIC SIMULATION CODE

The PIC simulation code is three dimensional Magic code which depends on Finite Difference Time Domain (FDTD) and Particle-In-Cell (PIC) techniques. It is used to simulate plasma physics processes that involve interactions between space charge and electromagnetic fields. In its basic framework, a selection of coordinate systems, grids (these specify the structure of the geometries), spatial objects, outer boundaries, material properties, emission processes, numerical algorithms, output, etc. is provided in order to [5]:

• cover broad classes of physical phenomena, and
• provide higher simulation fidelity, where cost limitations arising are also resolved by the cost algorithm.
Given the particle position and velocity, current and charge densities can be computed which are further solved to give the electric and magnetic field components that are used to compute the Lorentz force. This is further used to solve for particle future position and velocity, and the cycle continues. This computational cycle as shown in Fig (2) forms the basis of this PIC technique.

![Fig. 2 The computational cycle](image)

### III. AXIAL VIRCATOR

The KiloAmpere Linear Injector or KALI-1000 is the pulsed power system developed at Accelerators and Pulse Power Division (APPD), Bhabha Atomic Research Center (BARC) to produce high pulsed power intense relativistic electron beams of approximately 300kV with a pulse duration of 100 nanoseconds fullwidth at half maximum (FWHM) [1].

When a high voltage pulse generated from KALI-1000 was applied to the cathode, IREBs were generated in the vacuum explosive diode. The basic parts of the diode are:
* A graphite cathode
* A copper anode mesh

The electron beam parameters are 200kV, 100 nanoseconds. The IREB is emitted from the cathode and these accelerated electrons travel through the drift tube with this high energy and strike the anode mesh. In the drift tube, if the electron current exceeds the space charge limited value, the electrons mutually repel to form the virtual cathode. These reflected electrons re-enter the diode region where they are opposed by an applied field [11][12]. Thus, the electrons keep oscillating between the real and the virtual cathodes. This virtual cathode is formed at a distance approximately equal to AK gap. Also, the electrons forming the virtual cathode oscillate. In either type of oscillations, the microwave frequencies generate HPM [1][13].

The space charge limited current through the diode can be obtained from the Child-Langmuir law [1][2] is given by (1):

$$J_{\text{SCL}} = \frac{4}{9} \varepsilon_0 \frac{2e}{m_0} \left| \frac{V}{D^2} \right|^3$$  \hspace{1cm} (1)

where,
- $J_{\text{SCL}}$ is the space charge limited current density
- $e$ is the charge on the electron
- $m_0$ is the initial mass of the particle
- $V$ is the beam voltage
- $D$ is the AK gap

Now, the Child-Langmuir current, $I_{\text{SCL}}$ is calculated by the following equation.

$$I_{\text{SCL}} = J_{\text{SCL}} \cdot \pi R_k^2$$  \hspace{1cm} (2)

where $R_k$ is the radius of the cathode.

As the vircator is formed, the virtual cathode reflects a portion of the electron beam which oscillates between the real and virtual cathodes causing the generation of HPMs. The reflection frequency is given by (3) [1].

$$f_v \approx \frac{V}{4d}$$  \hspace{1cm} (3)

where, $v$ is the velocity of electrons, $d$ is the AK gap, and $d/v$ is the time taken by the electrons to travel between anode and cathode. The oscillation frequency of the virtual cathode is given by (4) [1].

$$f_{vc} = 10.0 \left( \frac{J}{\beta \gamma} \right)^{\frac{1}{2}} \text{GHz}$$  \hspace{1cm} (4)

where, $J$ is the current density in kiloamperes per square centimeter and $\beta = v/c$ where $c$ is the velocity of light. Due to cathode plasma expansion, AK gap closes resulting in decreasing impedance, increasing current and thus, increasing electron beam plasma frequency. The HPM frequency at which maximum power is emitted is between $f_v$ and $f_{vc}$.

The energy efficiency of the vircator has been defined as the ratio of the HPM energy to the IREB energy which turns out to be few percent. This can be increased by making the cathode coaxial giving rise to coaxial viractor which results in higher HPM output power and frequency as discussed in [2], where the cathode has been connected to a drum and made coaxial. This gives a larger cross-sectional area of the diode gap resulting in decrease in current density and thus, reducing a decrease of damage on both cathode and anode leading to a longer life enabling better repetitive performance, because the anode mesh vaporises if the pulse duration is nearly $1\mu$s.

### IV. PIC SIMULATION RESULTS WITH MAGIC

#### A. Geometry of Axial Vircator

The axial vircator has been characterized for different diode radii. The dimensions of the planar diode geometry of the apparatus in APPD, BARC are as follows:

1. Cathode Radius = 3.5 cm
2. Cathode is made of graphite
3. Vircator Chamber inner radius = 12.5 cm
4. Vircator Chamber is made of any conducting material - Stainless Steel in this case
5. Diode Chamber length = 27cm
6. Axial vircator Chamber length = 27cm
7. AK gap = 7.5mm
8. Anode is a foil with thickness = 2 mm with mesh size 0.5mm × 2mm
9. Perspex window is made of plexiglass and also, the end cap is made of the same.
10. The IREB parameters are as mentioned before as 200kV, 100ns.

The planar diode geometry with graphite cathode, copper anode mesh, stainless steel chamber and a plexiglass perspex window is generated with the above dimensions in Magic using the polar coordinate system which is as shown in Fig 3.

![Fig. 3 Axial vircator geometry](image)

**B. Formation of the Vircator**

The vircator which is formed beyond the anode mesh after emission from the cathode at a distance nearly equivalent to the AK gap, is as shown in Fig 4.

![Fig. 4 Vircator formation](image)

**C. Voltage, Child-Langmuir Current and Ratio Waveforms**

The voltage along the axis and the current obtained by Child-langmuir law have been plotted as shown in the following graphs in Fig (4) and Fig (5) with time on the x-axis and the parameter on the y-axis. Fig (6) indicates the Child-Langmuir ratio to be 1.15 approximately. The voltage plot below in Fig (5) indicates that for a rise time of 25ns the voltage at the cathode is 200 kV.

![Fig. 5 The port voltage](image)

The Child-Langmuir or the space charge limited current beyond which the vircator formation takes place as shown in Fig (5), indicates a current of approximately 12.5 kA which is nearly the same as obtained by the formula as stated in (1).

![Fig. 6 Child-Langmuir current](image)

The Child-Langmuir ratio is the ratio of Child-Langmuir current to the total current which is ideally 1.0, and here by simulation we have verified to be approximately 1.15.

![Fig. 7 Child-Langmuir ratio](image)
The Power Waveform

The power of the vircator is calculated by subtracting the incident power in Fig (8) from $I_{SCL}$ times Voltage (12.5kA times 200kV). This is obtained to be approximately 20MW.

![Fig. 8 Incident Power](image)

The HPM output power and frequency for the above diode geometry are approximately 20MW and 5.5GHz respectively. The vircator characteristics obtained in the PIC simulation of the apparatus given dimensions have been compared by taking greater dimensions of the vircator chamber inner and outer radii which results in greater chamber cross-sectional area.

V. COMPARISON WITH TWO DIFFERENT RADII OF DIODE CHAMBER

Using the Magic simulation code the desired results of HPM output power and frequency are obtained as shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter (Unit)</th>
<th>For Diode radius 12.5cm</th>
<th>For Diode radius 25cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>20</td>
<td>215</td>
</tr>
<tr>
<td>Frequency (GHz)</td>
<td>5.5</td>
<td>3.78</td>
</tr>
</tbody>
</table>

A. Comparison of the Voltage, Child-Langmuir Current and Ratio and the Power plots with a bigger diode radius

When the radius of the vircator chamber is nearly doubled, the respective plots hence obtained are as shown below in Fig (9), Fig (10) and Fig (11). From Fig (9), it is seen that after doubling the vircator chamber inner radius there is no effect on the port voltage as IREB parameters remain the same.

![Fig. 9 The voltage plot with diode radius doubled](image)

As seen from (6) and Fig (10) the Child-Langmuir current is independent of the change of the vircator chamber radius and does not change with the change in chamber radius.

![Fig. 10 Child-Langmuir current with diode radius doubled](image)

The plot in Fig (10) shows that according to the Child-Langmuir law, the Child-Langmuir ratio is found to be nearly 1.15 in this case also, thus showing no change in the space charge limited current with change in vircator chamber radius.

![Fig. 11 Child-Langmuir ratio with diode radius doubled](image)
As shown in Fig (12), same way calculating the power gives the HPM output power to be 215 MW, nearly a tenfold increase. Thus, from the comparison of the two results of simulation, it is observed that with doubling of the diode radius the power increases nearly ten times while the frequency reduces by nearly some GHz.

VI. CONCLUSION

The simulation of axial vircator designed for the KALI-1000 pulsed power system has been carried out in the three dimensional Magic, PIC simulation code. The electron beam typically used was of 200kV, 100nanoseconds FWHM. On simulation, it was found that increase in the diode radii causes a drastic increase in the output power and a decrease in the HPM frequency. By comparing two different radii of the vircator chamber, it was observed that the HPM output power nearly increased by ten times while there was a drop of around 1.72GHz in the HPM output frequency. It can also be concluded that the Child-Langmuir current is independent of any changes with vircator chamber radius.

ACKNOWLEDGMENT

The authors take this opportunity to express gratitude and sincere thanks to Accelerators and Pulse Power Division (APPD), Bhabha Atomic Research Center (BARC), for sponsoring this project and providing the necessary research facilities. The first two authors also express their sincere thanks to Sushma Waghi, colleagues and other faculty members of the Control Systems Research Group, VJTI for extending their cooperation and support for conducting this research.

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