CHAPTER 6

HIGH POWER MICROWAVE GENERATION FROM VIRTUAL CATHODE OSCILLATOR (VIRCATOR)

6.1 HPM GENERATION FROM AXIAL VIRCATOR

KALI 1000 pulse power system has been used to generate HPM from axial vircator using the planar diode described in the previous section. A vacuum explosive Emission Diode was used to generate Intense Relativistic Electron Beam (IREB). The high voltage pulse

![Diode voltage and current waveform for 6 mm AK gap 70 mm diameter graphite cathode.](image)

FIG. 6.1 Diode voltage and current waveform for 6 mm AK gap 70 mm diameter graphite cathode.
generated from the pulse power system is applied to the field emission diode. The diode consists of a planar graphite cathode (70 mm diameter) and copper anode mesh (240 mm diameter) at various AK gaps and various voltage levels. A resistive CuSO₄ Voltage Divider and a self integrating Rogowski Coil were used to measure the diode voltage and current pulses respectively. After the copper mesh anode flange, there is a axial virtual cathode oscillator (vircator) chamber (length 25 cm, diameter 25 cm) for microwave generation. The IREB is injected to the vircator chamber for HPM generation. In the VIRCATOR chamber, the beam front forms a virtual cathode at a distance equal to the AK gap if the injected current is greater than the space charge limiting current by four times. It is given by [6]

\[ I_i = \frac{4\pi e^2 m_e c^3 (\gamma^{2/3} - 1)^{3/2}}{e [1 + 2 \ln(R/r_b)]} , \]  

(6.1)

where \( r_b \) is the beam radius, \( R \) is the drift column radius, \( \gamma \) is the relativistic factor and \( e \) and \( m_0 \) are the electron charge and rest mass respectively.

The virtual cathode reflects the electrons that follow the beam front. The electrons thus oscillate between the cathode and virtual cathode which causes microwave emission. The reflection frequency is given by

\[ f_r = \frac{v}{4d} , \]  

(6.2)

where \( v \) is the velocity of electrons and \( d \) the AK gap.

The virtual cathode oscillation frequency in GHz is given by

\[ f_{vc} = 10(J/\beta \gamma)^{1/2} , \]  

(6.3)

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where $J$ is the current density in kA/cm$^2$.

Scaling law derived from the two dimensional oscillation of the virtual cathode and can also be derived from a harmonic one dimensional oscillator model of reflexing electrons.

$$f_s = \frac{4.77}{d} \ln[\gamma + (\gamma - 1)^{1/2}]$$  \hspace{1cm} (6.4)

The frequency at which maximum power is emitted will be in between $f_r$ and $f_{vc}$ and the emission is broadband.

FIG. 6.2 The temporal behavior of the diode perveance and impedance for 6 mm AK gap.
A vacuum level of the order of $< 5 \times 10^{-5}$ mbar was maintained in the diode chamber as well as the vircator chamber. High power microwave has been detected by neon lamp discharge by HPM illumination when placed a few meter distances from the vircator window. Microwave power has been optimized by changing the anode-cathode gap. It was found that the peak power occur around 6 mm AK gap.

The diode voltage and current waveforms for 6 mm AK gap is shown in Fig. 6.1 As can be seen from the Fig. 6.1 that the voltage rises to a peak ~ 325 kV and then suddenly decreased to ~150 kV. This voltage peak is due to the fact that the explosive emission cathode plasma formation takes few ns time, during that time diode voltage rises to a peak as the pulse forming line see an open circuit load. Electron beam diode time varying impedance and perveance values were calculated using the voltage and current waveforms. The starting point or the zero time for perveance calculations was taken when the voltage pulse started rising. The experimental impedance and perveance derived from the diode voltage and current is shown in Fig. 6.2. There is an initial plateau region in time where the perveance is almost constant. At this time the diode perveance is $< P_{CL}$ indicating that the emission occurs over a fraction of the cathode area only. The cathode plasma expands both radialy and axially, increasing the diode perveance. The diode perveance increases rapidly after ~ 120 ns showing gap closure.

Various components used in the diagnostics were calibrated using standard modulated RF source. For each shot, the beam parameters were recorded using Lecroy model WS 454 (500MHz, 2GS/s) scope. Microwave detector output was recorded using Tektronics make oscilloscope TDS 520D (500MHz, 1GS/s). The microwave signal after detection was carried to the scope by a BNC cable which was kept inside a metal conduit. Initially, the detector output could not be recorded due to the high noise level persisting in the ambiance. To reduce the
noise level, different techniques were tried such as grounding the conduit to the signal cable ground, to the inner wall of the shield room etc. Isolating the scope supply from the AC mains was also tried during the recording, but in vain. It was observed that ~ 300mV noise persisted throughout. To override the noise signal and to improve the microwave signal amplitude from the diode detector, a pre amplifier (BMC 1595) was used at the output of the microwave detector. This could not also help in detecting the microwave signal as the noise level too got amplified.

It was observed that noise was picked up by the BNC cable when the BNC cable along with the conduit was kept inside the shield chamber, though the amplitude was low. So the use of BNC cable was avoided hence forward. Microwave signal was recorded successfully when RF

FIG. 6.3 HPM signal recorded from axial vircator.
cable was used to carry the signal from the receiving antenna and the diode detector was at the scope end.

Finally HPM pulse has been successfully detected using wide band antenna RF cable and diode detector setup. Estimated microwave peak power ~ 59.8 dBm (~1 kW) at (within the effective aperture area of the receiving antenna) 7 m distance from the vircator window. Fig. 6.3 displays a typical HPM signal recorded by the diode detector. The corresponding beam peak voltage and current was 256 kV and 9 kA. It was observed that there was a shot to shot variation in the microwave peak power. For different shots microwave peak power at 7 m distance varied to the maximum of ~ 1 kW. Few attempts were also made to measure frequency of the radiation using YIG base tunable band pass filter. As the pass band of the filter is only ~ 100 MHz we are unable to detect any signal using the filter.

6.2 HPM GENERATION FROM COAXIAL VIRCATOR

A coaxial virtual cathode oscillator (vircator) has been designed to generate High Power Microwaves. Coaxial virtual cathode oscillators are known for better efficiency compared to the axial virtual cathode oscillators. This Coaxial vircator has been designed for the KALI-5000 pulse power system. Provision for a large anode-cathode gap has been kept to avoid the prepulse effect during the electron beam generation from the KALI-5000 system. Experimental studies are carried out to generate and characterize High Power Microwaves in the presence of significant prepulse voltages. Relativistic Electron Beams are generated by the Coaxial Explosively emitted graphite cathodes as described in the previous section. Electron beam voltage has been measured by a copper sulphate voltage divider and beam current by a B-dot probe. High Power Microwaves are detected by the glow of neon lamps placed closed to the output window.

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The coaxial vircator consist of an cylindrical electron beam diode and a waveguide. The electron beam is accelerated in the coaxial direction and is injected into the waveguide. Electron beam is accelerated in the diode gap where pulsed high voltage is applied between the anode and the cathode. The beam passes through the copper mesh anode, and is injected into the area on the other side of the anode. Coaxial diode impedance calculated from the Langmuir-Blodgett law for various anode cathode radiiuses is given in the Table I.

TABLE I. Coaxial diode impedance for various anode cathode radiiuses.

<table>
<thead>
<tr>
<th>Diode Voltage (kV)</th>
<th>Cathode Radius (cm)</th>
<th>Anode Radius (cm)</th>
<th>AK Gap (cm)</th>
<th>Cathode Width (cm)</th>
<th>Diode Impedance (ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>5.5</td>
<td>4.5</td>
<td>1.0</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>4.5</td>
<td>1.4</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>4.5</td>
<td>1.8</td>
<td>2</td>
<td>41</td>
</tr>
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<td></td>
<td>6.9</td>
<td>4.5</td>
<td>2.4</td>
<td>2</td>
<td>71</td>
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<tr>
<td>400</td>
<td>5.5</td>
<td>4.5</td>
<td>1.0</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>4.5</td>
<td>1.4</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>4.5</td>
<td>1.8</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>6.9</td>
<td>4.5</td>
<td>2.4</td>
<td>2</td>
<td>61</td>
</tr>
</tbody>
</table>

TABLE II. The calculated coaxial vircator frequency for various anode cathode radiiuses and diode voltages.

<table>
<thead>
<tr>
<th>Diode Voltage (kV)</th>
<th>Cathode Radius (cm)</th>
<th>Anode Radius (cm)</th>
<th>AK Gap (cm)</th>
<th>(f_r) (GHz)</th>
<th>(f_c) (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>5.5</td>
<td>4.5</td>
<td>1.0</td>
<td>5.8</td>
<td>4.8</td>
</tr>
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<td>4.0</td>
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<td>1.8</td>
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<td>4.5</td>
</tr>
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<td></td>
<td>6.9</td>
<td>4.5</td>
<td>2.4</td>
<td>2.4</td>
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<tr>
<td>400</td>
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<td>4.5</td>
<td>1.0</td>
<td>6.2</td>
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<tr>
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<td>1.4</td>
<td>4.4</td>
<td>4.3</td>
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<tr>
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<td>4.5</td>
<td>2.4</td>
<td>2.6</td>
<td>3.9</td>
</tr>
</tbody>
</table>
The vircator microwave reflex and virtual cathode oscillation frequency are calculated from Equations (6.2) and (6.3) respectively and listed in the Table II. The Coaxial Vircator emits the maximum microwave power when the reflex and virtual cathode oscillation frequency are same. For 400 kV diode voltage both the frequency are same for 1.4 cm diode gap and the calculated frequency is around 4.4 GHz.

FIG. 6.4 Coaxial vircator diode voltage (Top 100 kV/Div) and diode current (Bottom 10kA/Div) (Time 200 ns/Div).

Since Blumlein impedance is 18 ohm, the diode impedance matches at 1.4 cm AK gap for 400 kV diode voltage. But the Prepulse voltage as shown in Fig. 6.4 reduces the diode impedance significantly and perfect matching occurs at 1.8 cm diode gap. In this gap no reversal in the Marx generator output (Fig. 6.5) voltage confirms the impedance matching.
HPM generation studies were carried out in the Coaxial Vircator for 1.8 cm and 1.2 cm AK gap. For 1.8 cm AK gap the peak diode voltage obtained was 350 kV and the peak current was 25 kA. For 1.2 cm AK gap the peak diode voltage was 200 kV and the peak diode current was 40 kA.

![Figure 6.5 Marx output voltage (Bottom 80 kV/Div) and diode current (Top 10 kA/Div) (Time 200 ns/Div)](image)

The microwave pulse was measured by using the set up shown in Section 3.6. The HPM radiation was received by a double-ridge horn antenna located a distance 4 meter away from the output window and after suitable attenuation given to a diode detector. The diode detector output is shown in the Fig. 6.6. Also HPM discharge observed on Tube light and Neon Lamp placed a distance away from the output window.
For both the cases HPM generation was observed and microwave pulse recorded by the diode detector (Fig. 6.6.). For 1.2 cm diode gap HPM has got more peak power as the diode detector was getting saturated even when the antenna has been placed at around 4.5 meter distance from the vircator output window. At this place the measured HPM peak power was more than 20 dBm (within the effective aperture area of the receiving antenna). Also Neon Lamp Glow was observed at a distance of 10 cm from the output window and the power density required for HPM discharge is more than 1 kW/ cm$^2$. So the estimated peak power of the Coaxial Vircator was more than 1 MW. Further experiments are required to measure the HPM power more accurately.
6.3 CONCLUSIONS

HPM generation studies have been carried out using the pulsed power generator KALI 1000. The typical electron beam parameter was 200 kV, 14 kA, 100 ns. High power microwave has been detected by neon lamp discharge by HPM illumination when placed a few meter distances from the vircator window. A graphite explosive emission cathode has been used to generate intense electron beams. Microwave power has been optimized by changing the AK gap. It was found that the peak power occur around 6 mm anode cathode gap. HPM measurements were done using zero bias schottky diode detectors along with a horn antenna and sufficient attenuation so as to reduce the power level below the power rating of the diode detector. Various components used in the diagnostics were calibrated using standard modulated RF source. The estimated microwave peak power ~1 kW at 7 m distance from the vircator window (within the effective aperture area of the receiving antenna). The corresponding peak power at the vircator window was 196 MW. It was observed that there was a shot to shot variation in the microwave peak power.

HPM generation studies were carried out with a coaxial vircator using cylindrical electron beam diode in the presence of significant prepulse voltages. For 1.2 cm diode gap HPM has got more peak power as the diode detector was getting saturated even when the antenna has been placed at around 4.5 meter distance from the vircator output window. At this place the measured HPM peak power was more than 20 dBm (within the effective aperture area of the receiving antenna). The estimated peak power of the Coaxial Vircator was more than 1 MW. Further experiments are required to measure the HPM power more accurately.