Stage II of Metamaterial Based Backward Wave Oscillator Experiment at MIT

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09/02/2016
Outline

• Review of Stage I experiment
  – Jason Hummelt thesis research

• Design of Stage II structure
  – Current research

• Stage II first experimental results (preliminary)

• Conclusions
Test facilities at MIT

- Design and test of an S-band backward wave oscillator (BWO)

<table>
<thead>
<tr>
<th>Design $P_{\text{out}}$</th>
<th>5 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Current</td>
<td>80 A</td>
</tr>
<tr>
<td>Voltage</td>
<td>500 kV</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>1 μs</td>
</tr>
</tbody>
</table>

Experiment before installation on gun
Stage I MTM structure design

- Complementary split ring resonators
- Beam travels between two identical MTM plates in a waveguide

<table>
<thead>
<tr>
<th>$f_0$</th>
<th>2.40 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period ‘p’</td>
<td>10 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>3.125 mm</td>
</tr>
<tr>
<td>Waveguide Dimensions</td>
<td>63 x 43 mm</td>
</tr>
</tbody>
</table>
• Two types of interaction
  – Cherenkov interaction: $\omega = k_z v_z$
  – Cherenkov-cyclotron (Anomalous Doppler): $\omega = k_z v_z - \Omega_c / \gamma$
High power measurement

- Low magnetic field (< 450 G), antisymmetric mode, Cherenkov-cyclotron interaction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{out}$</td>
<td>2.3 MW</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.39 GHz</td>
</tr>
<tr>
<td>Current</td>
<td>60 A</td>
</tr>
<tr>
<td>Voltage</td>
<td>400 kV</td>
</tr>
<tr>
<td>RF Pulse Length</td>
<td>300 ns</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>375 G</td>
</tr>
</tbody>
</table>
Stage I accomplishments

• Designed, built and successfully tested the first high power microwave source using a MTM structure

• Two competing spatial modes: symmetric / antisymmetric symmetry in the MTM structure

• Measured megawatt level power in the antisymmetric mode in a Cherenkov-cyclotron interaction

• Cherenkov modes observed at very low power levels (~100 W)

• Thesis research of Jason Hummelt
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Stage II MTM Structure

- Design goal: generate high power in the antisymmetric mode
- Asymmetry introduced by reversing one of the MTM plates
- Built a complete new structure

<table>
<thead>
<tr>
<th>Antisymmetric Cherenkov</th>
<th>Antisymmetric Cherenkov-cyclotron with 400 Gauss</th>
<th>Symmetric Cherenkov</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45 GHz</td>
<td>2.39 GHz</td>
<td>2.52 GHz</td>
</tr>
</tbody>
</table>
• Uneven power in two arms, high power in antisymmetric mode
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Sample pulse 1 - wide microwave pulse

- Lens $B_z = 725$ G, solenoid $B_z = 349$ G

- Megawatt output pulse, one microsecond long

- Electron beam interception, indicative of the deflecting antisymmetric mode
Sample pulse 2- high peak power

- Lens $B_z = 794$ G, solenoid $B_z = 437$ G
- Peak power of 3.5 MW
- Pulse width $\sim 200$ ns
Different operating conditions have different interaction types

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Symmetric Cherenkov-cyclotron with 400 Gauss</th>
<th>Symmetric Cherenkov</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45 GHz</td>
<td>2.39 GHz</td>
<td>2.52 GHz</td>
</tr>
</tbody>
</table>
Conclusions

• In Stage I experiment, high power is generated in the antisymmetric mode.

• Stage II experiment is designed to work with the antisymmetric mode.

• CST PIC simulation shows cyclotron type interaction even with high Bz field.

• New results in Stage II (preliminary)
  – First observation of full 1 μs pulses in MTM experiment at megawatt level
  – Highly unequal power levels in two arms
Future work

• Unexplored parameter space
  – Beam energy
  – Tapered solenoid field shape
  – Lens axial position

• Unsolved problems
  – Why is there no MW level power above 500 Gauss?
  – What is the condition for the Cherenkov type interaction to transform into the anomalous Doppler type?
  – …
Acknowledgement

- **Faculty and staff**
  - William Guss
  - Sudheer Jawla
  - Ivan Mastovsky
  - Guy Rosenzweig
  - Michael Shapiro
  - Jacob Stephens
  - Richard Temkin
  - Paul Woskov

- **Graduate students**
  - Hannah Hoffmann
  - Julian Picard
  - Samuel Schaub
  - Alexander Soane
  - Haoran Xu