Hot Test Experiment Design Considerations for a Backward Wave Oscillator based on a Novel Slow Wave Structure

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3. Preparation for hot test experiment at M.I.T. P.S.F.C.
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Applying Slow Wave Concepts to HPM sources

Dispersion Engineering
- Corrugated waveguides can be viewed as smooth guides periodically loaded with cavities that are coupled by electromagnetic modes.
- Careful design of the loading cavities can be exploited to engineer desired dispersion properties of the SWS.

$$\beta = \beta_0 + \frac{2\pi n}{P},$$

$$v_{\text{phase}} = \frac{\omega}{\beta} < c,$$

Corrugated Waveguide: A Capacitively coupled LC loaded transmission line
Conventional Slow Wave Structures for BWOs have Poor Mode Purity and Interaction Impedance

**Conventional SWS Issues**
- Low interaction impedance.
- Poor mode purity.
- Poor mode control capabilities.
- Hybrid mode excitation at SWS discontinuities due to mode overlap.

**Dispersion Diagram for Conventional SWS**

![Dispersion Diagram](image)

**Interaction Impedance** $K_{co}$ of a Slow Wave Structure

$$K_{co} = \frac{|E_{zm}|^2}{2\beta_{zm}^2 P} \quad |E_{zm}| = \frac{1}{P} \left| \int_0^p (E_{zr}(z) + jE_{zi}(z)) e^{-j\beta_{zm}z} \right|$$

$$E_z = \sum_{m=-\infty}^{m=\infty} E_{zm}(x, y) e^{-j\beta_{zm}z}$$
New S.W.S For High Power BWO’s with Mode Control

**Mode Control**
- Cavity increments and deeper corrugations reduce TM$_{01}$ mode group velocity.
- Metallic ring inclusions control SWS modes.
- **Clear Stopbands now exist** between modes.
- **Mode dominance reversal**, TM$_{01}$ is now dominant mode.

**Interaction Impedance**
- Interaction impedance improvement (over 100% improvement)

**New SWS improves efficiency by 40% (3 section SWS vs Homogeneous SWS)**

**Dispersion Diagram for Proposed SWS**

![Dispersion Diagram](image1)

**Interaction Impedance Comparison**

![Interaction Impedance Comparison](image2)

Fig. 1 Dispersion properties of proposed SWS.

Fig. 3 Interaction impedance for conventional vs proposed SWS.
Novel SWS Design leads to Excellent Mode Purity

**Mode Purity**

- Strong $E_z$ fields increase interaction impedance which improves BWO efficiency.
- Hybrid $TE_{11}$-$TM_{01}$ modes have weak $E_z$ fields (see fig. below).
- Hybrid modes can exist in a SWS if it is excited at a frequency in the overlapping passband region (a).
- Excellent mode purity is achieved through passband overlap elimination and mode dominance reversal (b).
Slow Wave Structure Fabrication

Fabricated Components

1) Smooth waveguide section and 6 SWS unit cells
2) Metallic ring inclusions and enlarged cavity recessions
3) End caps on both ends of the waveguide create resonant cavity
4) SWS unit cell to be placed inside smooth waveguide section

Novel SWS Design

1) Entire SWS components include: end caps, waveguide section and unit cells.
2) Metallic ring insertion and cavity recessions realization is achieved in fabricated SWS unit cell.
3) End caps on both ends of the waveguide create resonant cavity.
4) SWS unit cell is to be loaded into smooth waveguide section
S\textsubscript{11} Response of TM\textsubscript{01} Mode

- 7 resonances corresponding to TM\textsubscript{01} mode were observed and their locations agree with simulated results.
- Resonances can be used to derive the dispersion curve of the TM\textsubscript{01} mode in SWS.
Resonant Frequencies Location

• Results from measured resonances show excellent agreement with commercial software packages CST and HFSS.

Dispersion Curve

• Derived dispersion curve is in excellent agreement with CST and HFSS simulation results.

<table>
<thead>
<tr>
<th>GHz</th>
<th>Measured</th>
<th>CST</th>
<th>HFSS</th>
</tr>
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<tbody>
<tr>
<td>( f_0 )</td>
<td>2.551</td>
<td>2.552</td>
<td>2.567</td>
</tr>
<tr>
<td>( f_{\pi/6} )</td>
<td>2.566</td>
<td>2.561</td>
<td>2.574</td>
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<tr>
<td>( f_{2\pi/6} )</td>
<td>2.588</td>
<td>2.583</td>
<td>2.594</td>
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<tr>
<td>( f_{3\pi/6} )</td>
<td>2.618</td>
<td>2.614</td>
<td>2.622</td>
</tr>
<tr>
<td>( f_{4\pi/6} )</td>
<td>2.651</td>
<td>2.644</td>
<td>2.649</td>
</tr>
<tr>
<td>( f_{5\pi/6} )</td>
<td>2.674</td>
<td>2.666</td>
<td>2.668</td>
</tr>
<tr>
<td>( f_\pi )</td>
<td>2.684</td>
<td>2.674</td>
<td>2.675</td>
</tr>
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</table>

\[ f = \sum_{m=0}^{\infty} a_m \cos(m\beta L) \]
Validation Process

- $S_{11}$ data confirm $TM_{01}$ mode dominance reversal.
- $TM_{01}$ mode is the first mode to be excited followed by a weaker $TE_{11}$ mode.
- Bandgap between modes is also observed clearly as expected.
- Excellent agreement between $S_{11}$ data and simulated dispersion curves is observed.

Dispersion Curve of First 2 modes in SWS

![Dispersion Curve Image]
Objective:
Experimentally validate the SWS design properties and generate high power microwaves at 30-40% efficiency.

Design Challenge:
Adopt OSU’s novel SWS design to MIT’s existing hot test infrastructure and test bed. Specifically:
• Couple SWS mode to 490 kV, 84 A beam guided by 0.15 T. (SWS was designed for 341 kV, 50 A & 1T).
• Adopt original endfire output power system to the MIT dual rectangular waveguide system.
• Design mode converter for coupling generated power to measurement waveguides.
• Fit the whole design in a 14 inch by 6 inch vacuum space.
• Measured output power in TE$_{01}$ mode using a TE$_{10}$ mode measurement system.

Fig. 1: Proposed experimental setup. OSU’s components will replace the Metamaterial SWS used by MIT in previous experiments (CAD drawing courtesy of Jason Hummelt (MIT))
Preparations For Hot Test Experiment at M.I.T. PSFC: Interaction Concept

Challenges

- Intense bunching permits transverse electron trajectories that are permitted by available magnetic field (0.18T).
- Electron beam starts to diverge due to intense bunching.
- Transverse electron beam trajectories reduce efficiency of energy exchange with $TM_{01}$ mode (symmetric mode).

**Proposed Interaction Concept**

- Interaction is Cerenkov type interaction with backward waves of $TM_{01}$ and hybrid $TE_{11}$ modes.
- Hybrid $TE_{11}$ mode has strong $E_z$ fields near the corrugations allowing interaction with electron beam once it diverges.
- Initial beam velocity modulation is done by $TM_{01}$ mode. Final interaction is with hybrid $TE_{11}$ mode.

Fig. 1: Dispersion curves for $TM_{01}$ and hybrid $TE_{11}$ modes within the novel SWS. Dispersion line of 490 kV electron beam intersects with the backward waves of both modes $p=36\text{mm}$, $r_{th}=i\text{c}$, $R_{int}=20\text{mm}$, $R_{cav}=24\text{mm}$, $R_{ext}=30\text{mm}$.

Fig. 2: $E_z$ fields for $TM_{01}$ and hybrid $TE_{11}$ modes across the diameter of SWS. Fields go to zero on actual SWS surface.
Preparations For Hot Test Experiment at M.I.T. PSFC: Interaction Concept

Stage 1: Premodulation with $TM_{01}$ Mode

Stage 2: Final Interaction with Hybrid $TE_{11}$ Mode

Fig. 1: Two-stage beam-mode interaction. a) Electron beam first interacts with the axially symmetric $TM_{01}$ mode to establish significant bunches at the center. b) Final beam–mode interaction occurs with hybrid $TE_{11}$ mode near corrugations.

Higher efficiency is obtained with hybrid $TE_{11}$ mode (non-symmetric) than with $TM_{01}$ mode (symmetric).
Preparations For Hot Test Experiment at M.I.T. PSFC: 

Design

OSU original design for endfire output system.

- Fig. 1: Original SWS design
  a) Section view of original full SWS with output horn port
  b) 3-D view of full SWS and output horn
  c) PIC simulation demonstration of symmetric beam coupling and velocity modulation under strong magnetic field.

MIT specific design for rectangular waveguide output system.

- Fig. 2: MIT specific SWS design
  a) Section view of full SWS with output coupler and mode converter,
  b) 3-D view of full SWS, output coupler and mode converter,
  c) PIC simulation demonstration of asymmetric beam coupling and velocity modulation.

Main interaction is with TM$_{01}$ mode, NO transverse electron beam trajectories permitted

Main interaction is with hybrid TE$_{11}$ mode, transverse electron beam trajectories permitted
Preparations For Hot Test Experiment at M.I.T. P.S.F.C.:  

**Design features:**

- 6 SWS cells as main interaction region.
- Mode converter.
- Beam exit hole.
- Dual WR284 waveguides for coupling output power.
Preparations For Hot Test Experiment at M.I.T. PSFC: Mode Converter

- Conversion from endfire to dual rectangular waveguide output system requires a mode converter.
- Current BWO design operates in hybrid $TE_{11}$ mode.
- Mode converter design is restricted by strict space constraints to allow SWS to fit in provided vacuum space.
- Design converts hybrid $TE_{11}$ mode to $TE_{10}$ and $TE_{01}$ modes.

Fig. 1: SWS design showing the mode converter design for converting hybrid $TE_{11}$ mode to $TE_{10}$ and $TE_{01}$ modes.

Fig. 2: HFSS simulation setup and S21 [dB] at 5 GHz. Mode at port 1 is the $TE_{11}$ mode which propagates SWS as a hybrid $TE_{11}$ mode.

**ElectroScience Laboratory**
1. **Excitation**
490 kV (0.86c), 84 A DC electron beam. 2mm radius

2. **Beam Transport**
Electron beam is guided by a uniform 0.15 T magnetic field

3. **Output Power Ports**
- Output power is measured at two ports with WR284 waveguide dimensions.
- Ports are symmetric and therefore predicted to give the same output power.
- Power is measured before the 90° waveguide bends.

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Fig. 1: CST modelling of the electron beam excitation. a) Cylinder geometry b) Discretization of the electron beam c) Electron beam parameters

Fig. 2: Magnetic field profile used in CST simulation.

Fig. 3: Output ports for CST PIC simulation setup.
Preparations For Hot Test Experiment at M.I.T. P.S.F.C.: PIC Simulation Results

- PIC simulations conducted with CST show output power of over 16 MW at 5 GHz. Predicted efficiency is 40%.
- Output mode is TE_{01} in WR284 Waveguide

**Fig. 1**: Normalized transverse momentum of the electron particles

**Fig. 2**: Output signals of the TE_{10} and TE_{01} modes at rectangular port of the SWS

**Fig. 3**: Output power signal from SWS ports

**Fig. 4**: Spectrum of output signal (TE_{01} mode)
Preparations For Hot Test Experiment at M.I.T.
P.S.F.C.:
Side Coupling and Propagation of $\text{TE}_{01}$ mode

Fig. 1: Propagation of $\text{TE}_{01}$ mode along 2 waveguide bends in a WR284 waveguide.

Fig. 2: $S_{21}$ [dB] of $\text{TE}_{01}$ mode propagating in WR284 waveguide with two 90 degree bends at 5GHz.

Fig. 3: Proposed narrow wall hole coupling in WR284 waveguide technique used to measure the output power from a TE$_{01}$ mode at 5GHz.

Fig. 4: Coupling of $\text{TE}_{10}$, $\text{TE}_{20}$ and $\text{TE}_{01}$ modes to the measurement waveguide when the starting mode at the input port is TE$_{01}$.
Preparations For Hot Test Experiment at M.I.T. 
P.S.F.C.: 
Modal Power Content Analysis with CST

Table 1: Output power carried by first 5 modes and corresponding coupling factors at 5GHz

<table>
<thead>
<tr>
<th>Mode</th>
<th>Output power carried by mode [MW]</th>
<th>Coupling factor at 5 GHz [dB] (calculated by MIT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE_{10}</td>
<td>2</td>
<td>-180</td>
</tr>
<tr>
<td>TE_{20}</td>
<td>0.49</td>
<td>-180</td>
</tr>
<tr>
<td>TE_{01}</td>
<td>8</td>
<td>-51</td>
</tr>
<tr>
<td>TE_{11}</td>
<td>0.016</td>
<td>-52</td>
</tr>
<tr>
<td>TM_{11}</td>
<td>0.25</td>
<td>-45</td>
</tr>
</tbody>
</table>

Fig. 1: Simulated geometry of SWS with output waveguides and the electric field intensity.
## Preparations For Hot Test Experiment at M.I.T. P.S.F.C.:

### Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MIT / Available</th>
<th>OSU / Achieved</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Beam voltage [kV]</td>
<td>490 kV</td>
<td>490 kV</td>
<td>Matched</td>
</tr>
<tr>
<td>Beam Current [A]</td>
<td>84 A</td>
<td>84 A</td>
<td>Matched</td>
</tr>
<tr>
<td>Beam Type</td>
<td>Solid</td>
<td>Solid</td>
<td>Matched</td>
</tr>
<tr>
<td>Beam Radius</td>
<td>2mm radius at 0.15 inside SWS</td>
<td>2mm cathode radius at emission point</td>
<td>If radius is larger, analysis will be adjusted. Only slight change in output power is expected.</td>
</tr>
<tr>
<td>Magnetic field [T]</td>
<td>Peak field of 0.18T</td>
<td>0.15 T</td>
<td>0.15 T is the optimum operating field</td>
</tr>
<tr>
<td>Pulse length [s]</td>
<td>1 μs</td>
<td>700 ns</td>
<td>Peak power achieved is at 500 ns</td>
</tr>
<tr>
<td>Overall SWS Length</td>
<td>14.081 Inches</td>
<td>12.52 Inches</td>
<td>Design length meets constraint</td>
</tr>
<tr>
<td>Overall Transverse</td>
<td>5.84 Inches diameter</td>
<td>4.48 Inches</td>
<td>Design length meets constraint</td>
</tr>
<tr>
<td>Output ports</td>
<td>1.34 Inches by 2.840 Inches</td>
<td>1.34 Inches by 2.840 Inches</td>
<td>Matched (Dimensions are for WR284 waveguide)</td>
</tr>
</tbody>
</table>
Preparations For Hot Test Experiment at M.I.T. P.S.F.C.:

Future Work

Hot Test Experiment

• Resolve output power differences between full SWS with output and SWS without output waveguides
• Develop CAD drawings for proposed SWS design.
• Fabrication of full SWS, mode converter and output coupler.
• Cold testing of SWS and output coupling system.
• Fabrication and cold testing of a TE$_{01}$-mode based measurement system.
• SWS excitation and power measurements.

Novel Concepts for BWO SWSs

• Multi-section, inhomogeneous SWS study.
• Fabrication and cold testing of inhomogeneous SWSs.
• Exploitation of higher order dispersion for efficiency enhancement in BWOs.
• High frequency (W band SWS) design.
• Efficiency enhancements for W band BWOs.
• SWS fabrication and cold testing.