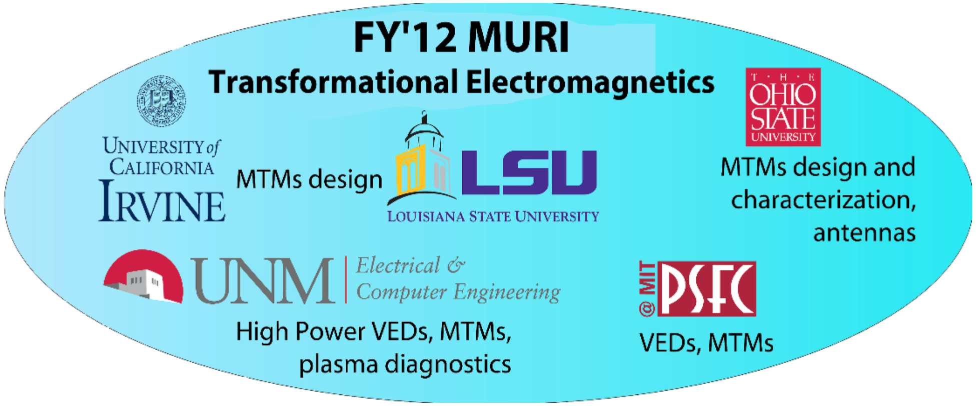
Novel Slow Wave Structure for High Power BWOs with Mode Control

MURI Teleconference
January 9th 2015

Ushe Chipengo



Outline

- **Introduction**
- **Design of BWO slow wave structure with mode control**
- **Efficiency enhancement in BWO's.**
- **Inhomogeneous SWSs and X Band BWO.**
- **Design Considerations for Proposed S-Band MIT hot test.**
- **Proposed fabrication technique for SWS structures**
- **Summary & Conclusion**

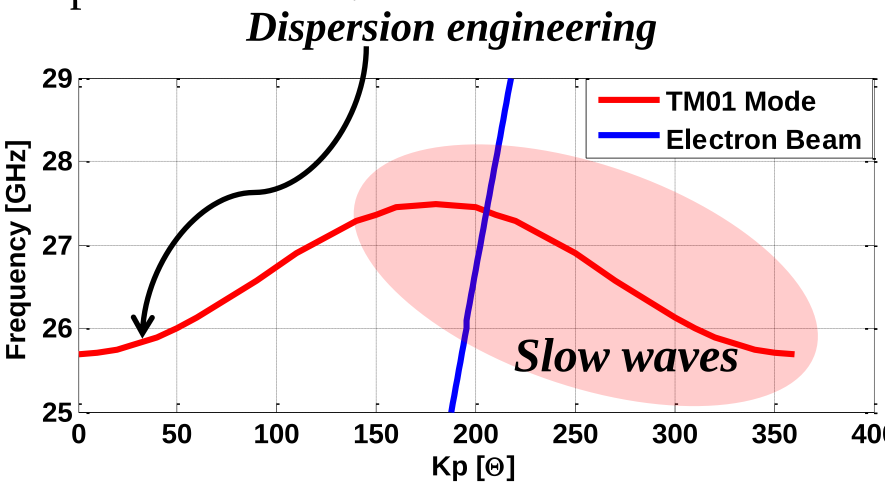
Slow Waves and Dispersion Engineering

Slow Waves on Transmission Lines

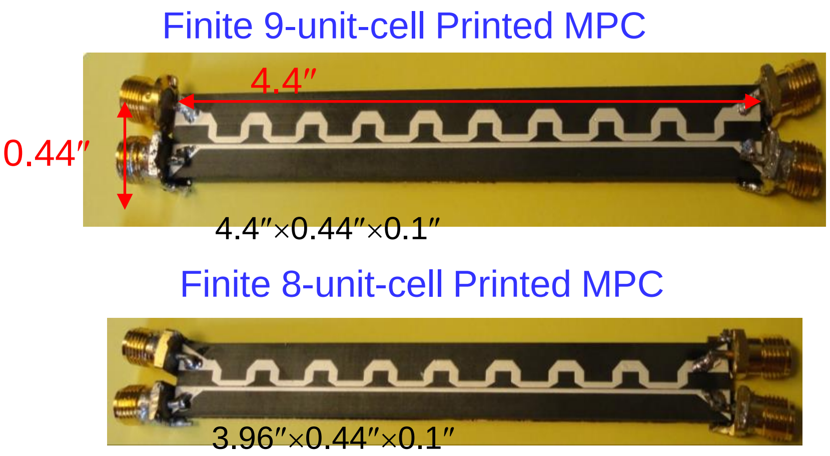
- Coupled transmission lines slow down group and phase velocity of waves.
- Coupling induces capacitive effects that control wave slow down.

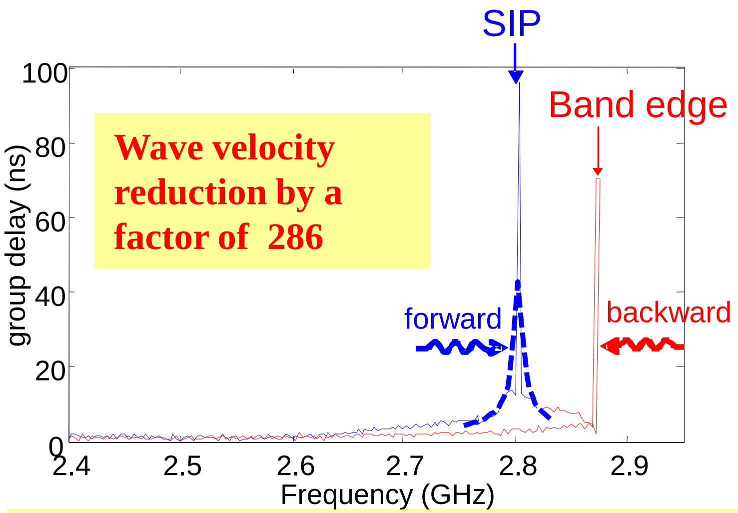
Dispersion Engineering

- Coupled TL concepts and periodicity can be exploited to engineer desired dispersion curves.



$$\beta_z = \omega\sqrt{\mu_0 \varepsilon_{eff}} = \omega\sqrt{LC}$$

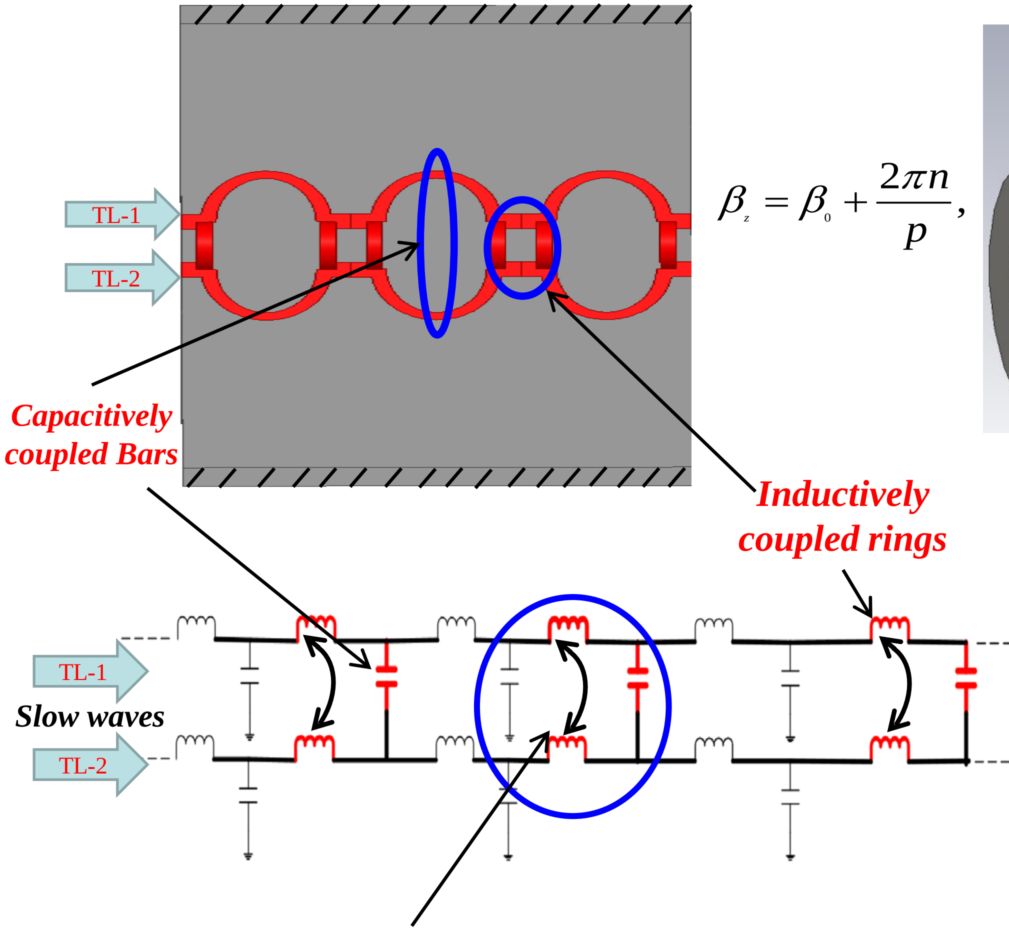




Periodically Coupled TL slows down wave!!!

Implementation of Coupled Transmission Lines in Wave Slow Down

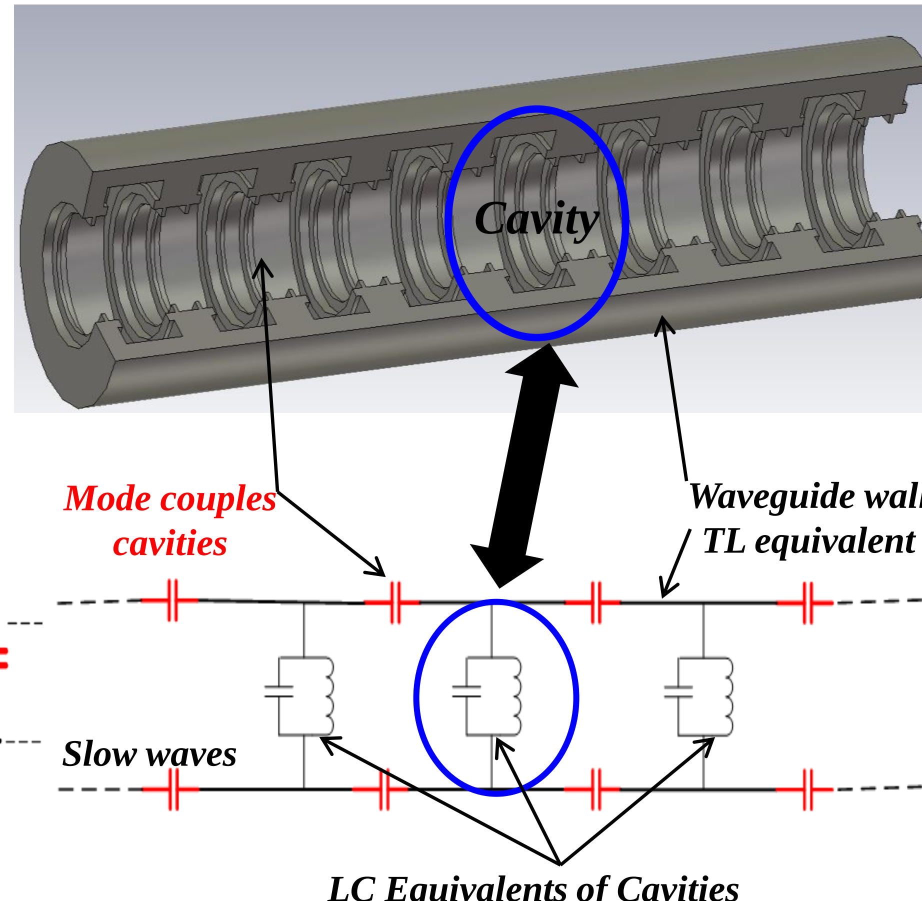
Curved-Ring-Bar: Coupled Transmission Lines



$$\beta_z = \beta_0 + \frac{2\pi n}{p},$$

LC Equivalents of Coupled Transmission Lines

Corrugated Waveguide- A Capacitively coupled LC loaded transmission line



$$\beta_z = \omega\sqrt{\mu_0 \varepsilon_{eff}} = \omega\sqrt{LC}$$

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

Slowdown!

Conventional SWS for BWO's: 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.

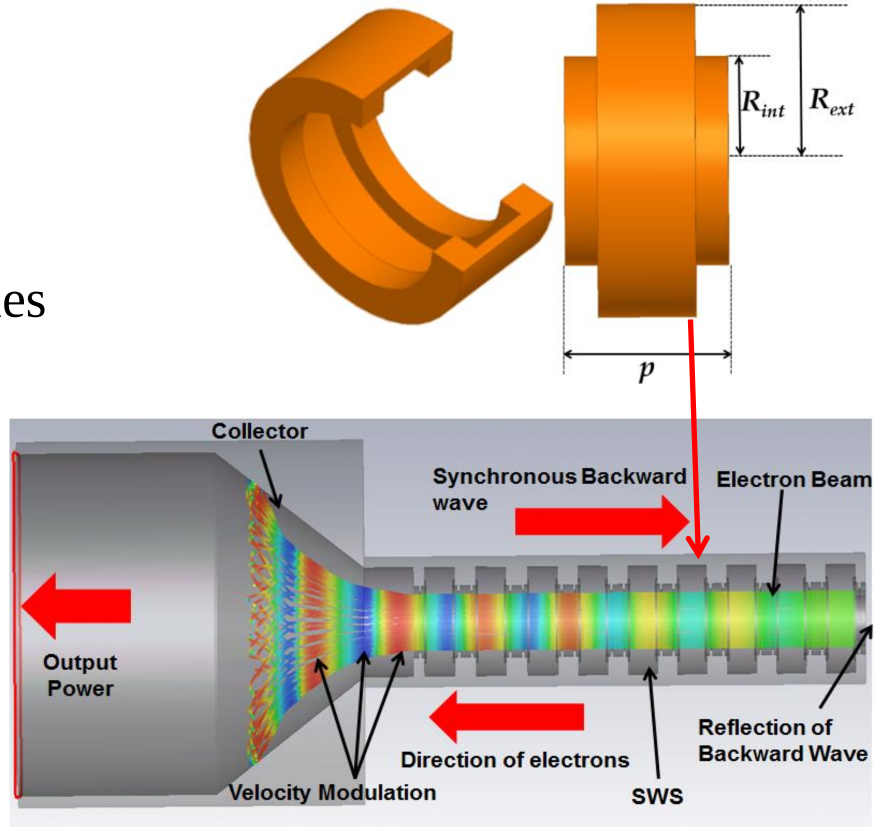


Fig. 1: Conventional SWS and BWO setup.

Dispersion Diagram for Conventional SWS

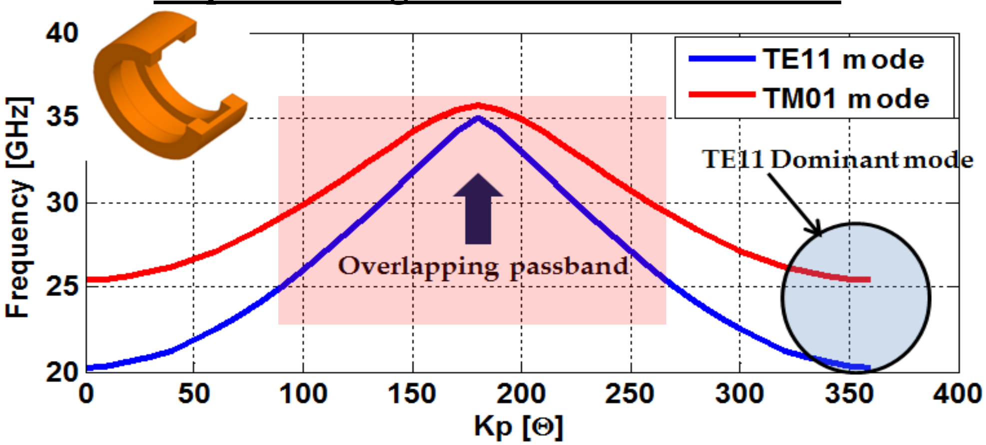
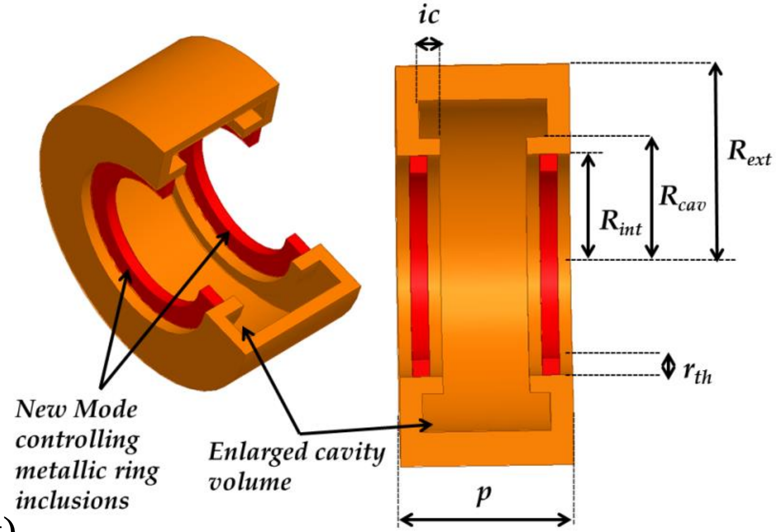


Fig. 2: Dispersion Diagram for conventional SWS's

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.
- Non overlapping passbands between modes.
- Mode dominance reversal, TM_{01} is now dominant mode.



Interaction Impedance

- Interaction impedance improvement (over 100% improvement)

Fig. 1: Proposed design of SWS for high power BWO

Dispersion Diagram for Proposed SWS

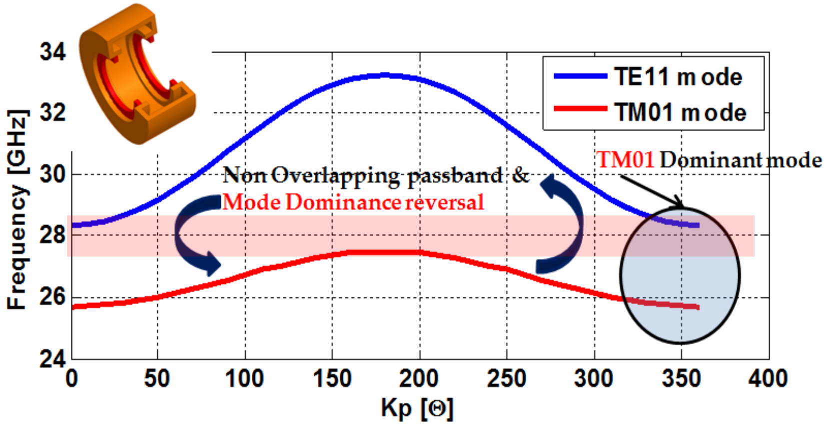


Fig. 2 Dispersion properties of proposed SWS.

Interaction Impedance Comparison

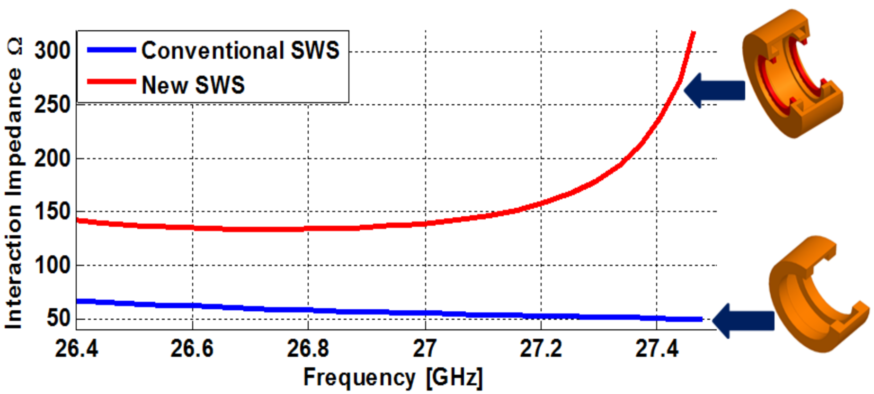


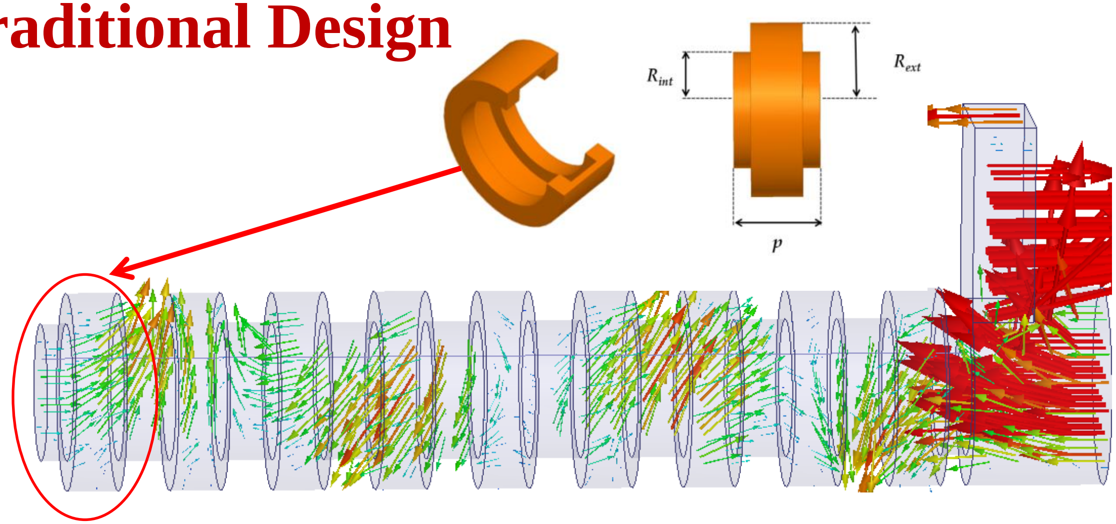
Fig. 3 Interaction impedance for conventional vs proposed SWS.

TM_{01} Mode Purity in BWO SWS

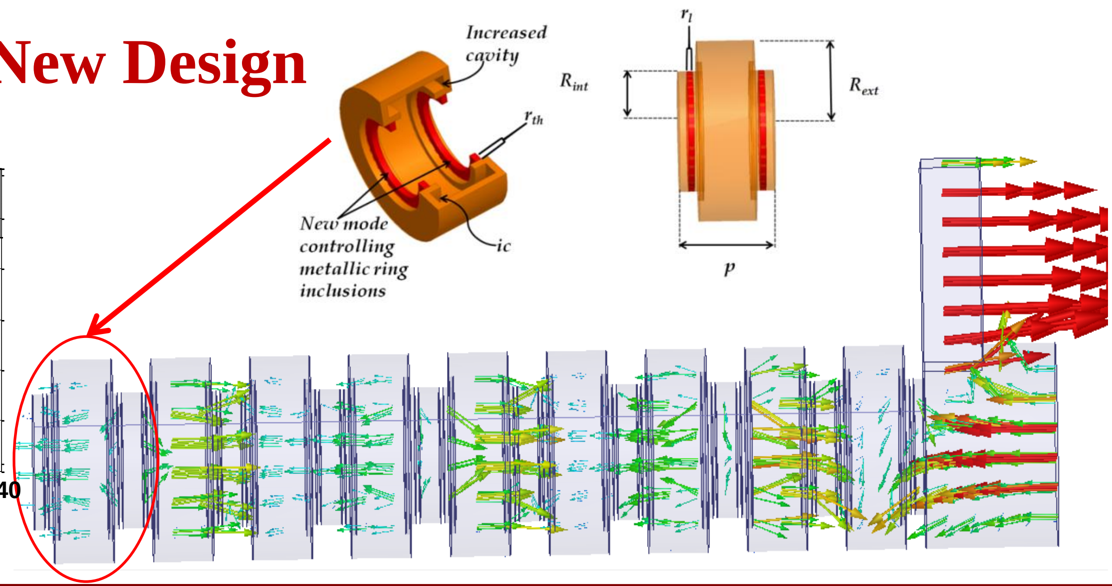
Mode Purity

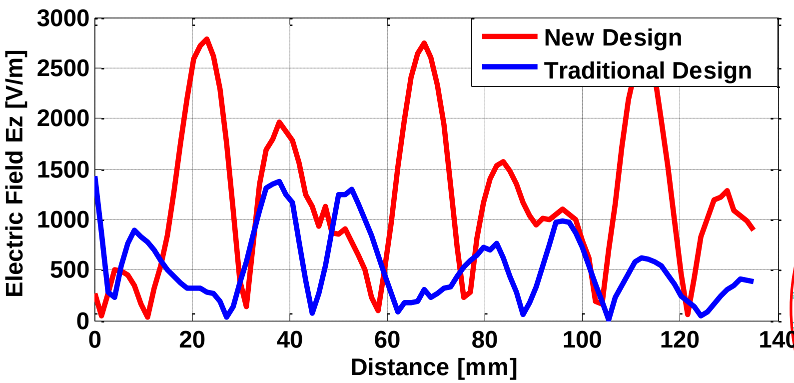
- TM_{01} mode of SWS interacts with electron beam.
- Traditional SWS supports hybrid TM_{01} mode with weak Ez fields due to end reflections and passband overlap between TE_{11} and TM_{01} mode .
- New SWS supports pure TM_{01} mode as dominant mode.
- A pure TM_{01} mode leads to increased interaction impedance due to stronger Ez electric field .

Traditional Design



New Design

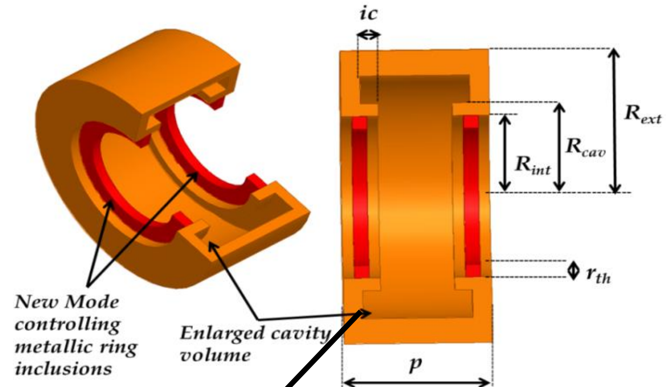




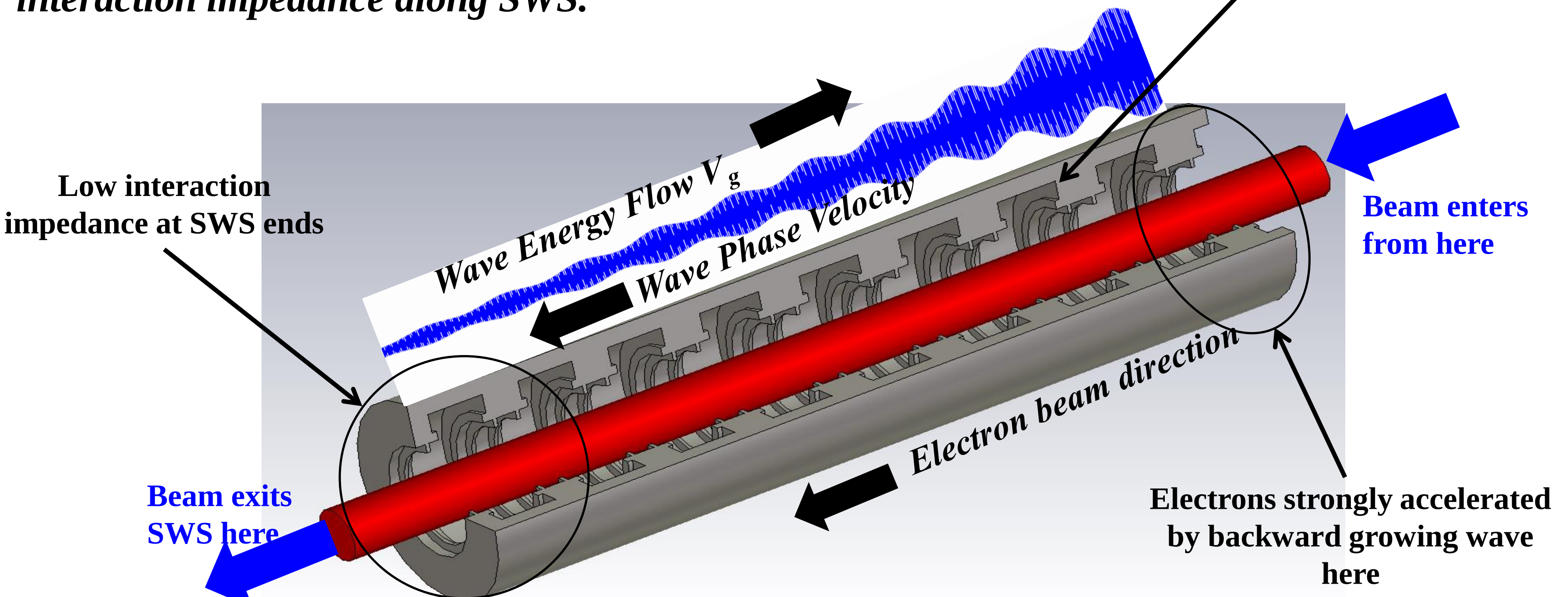
Efficiency Limitations of BWO's

BWO efficiency using homogeneous SWS limited by:

1. Heavily accelerated electrons retaining wave energy.
2. Low interaction impedance at collector end of SWS.



Efficiency of homogeneous SWS's can be improved by non-uniform distribution of phase velocity and interaction impedance along SWS.



Inhomogeneous SWS Design Approach

To achieve high efficiency :

- **Strong fields at the collector end of the SWS are required to extract energy from highly accelerated electrons.**
- **A higher mode phase velocity is required to re trap accelerated electrons in a retarding phase for optimum energy extraction.**

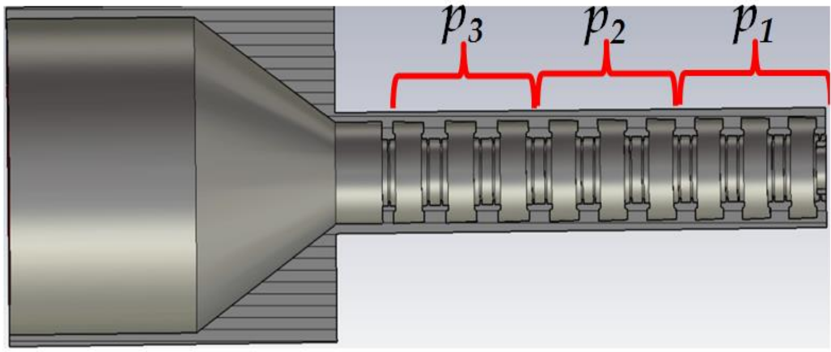


Fig. 1. 3 Section SWS for BWO

Our Design achieves this by :

1. **Gradually speeding up the phase velocity V_{phase} of the TM_{01} mode as it progresses.**

2. **Gradually increasing the interaction impedance K_o of the TM_{01} mode as it progresses in the SWS.**

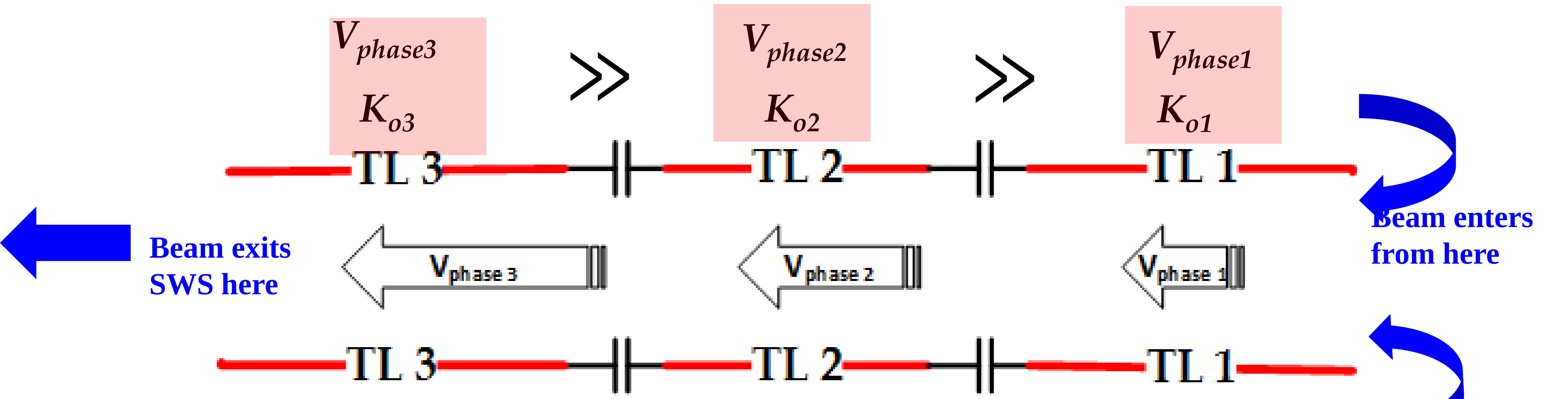


Fig. 2 Capacitively coupled Transmission line model of 3 Section SWS

Optimum BWO Operating Region for 3 Section Inhomogeneous SWS

BWO Operating Regions

1: Homogenous SWS Region –Low Efficiency

2: Optimum Operating Region – High Efficiency

3: Isolated SWS Region- Low Efficiency

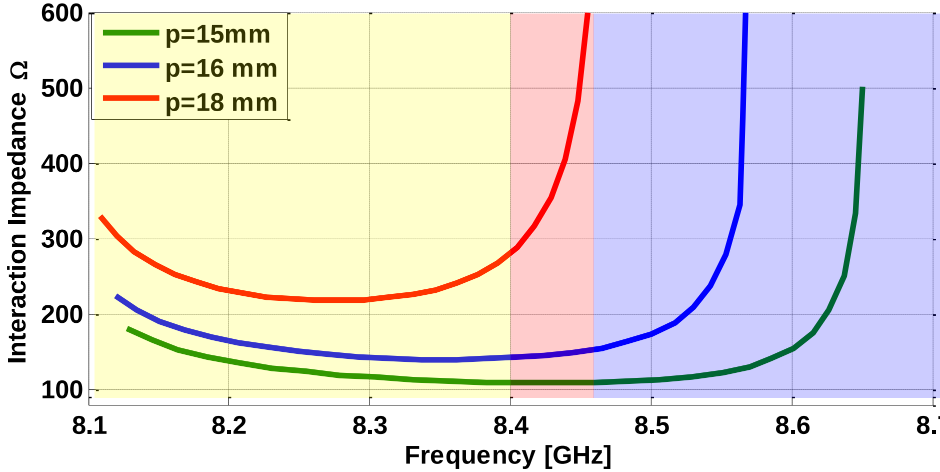


Fig. 2 Interaction Impedance for Various Periods

Optimum frequency range is 8.4 GHz to 8.48GHz

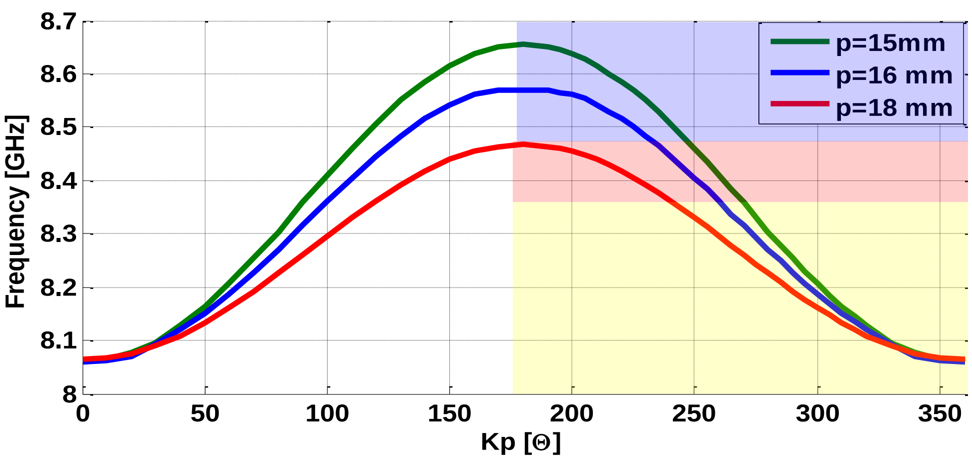


Fig. 1 Dispersion Curve for Various Periods

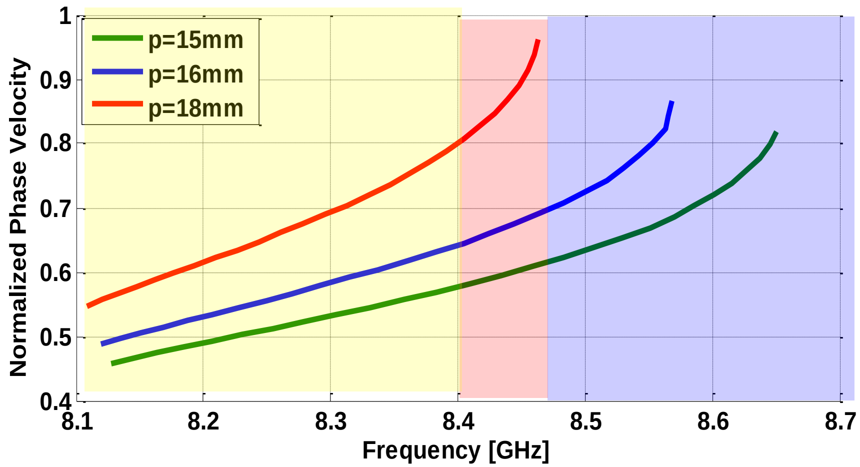


Fig. 3 Phase Velocity Curve for Various Periods

X Band BWO SWS Final Design

Simulation Parameters:

Beam type : annular

Beam Voltage : 249kV-431 kV

Beam Current : 30 A

Electron Velocity : 0.74c – 0.84c

Beam Power : 7.47 MW - 12.93 MW

Magnetic Field : 2 Tesla

p_1 = 15 mm

p_2 = 16 mm (6.67% increase from p_1)

p_3 = 18 mm (20% increase from p_1)

- Design dimensions have been modified for easier fabrication.

Normalized Beam Phase Velocity

$$\beta_b = \frac{v_b}{c} = \sqrt{1 - \frac{1}{\left(1 + \frac{eV_b}{mc^2}\right)^2}}$$

Oscillation Frequency

$$\omega_o \approx k_z \beta_b c$$

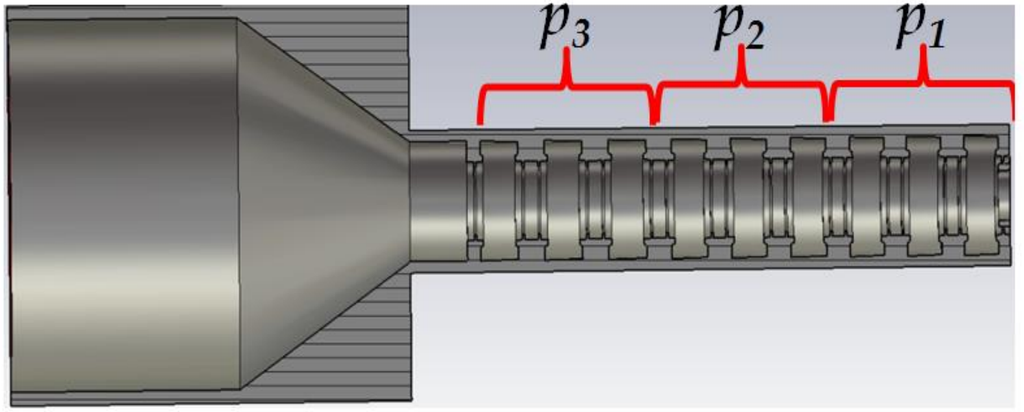


Fig . 1 : 9 Period, 3-section SWS

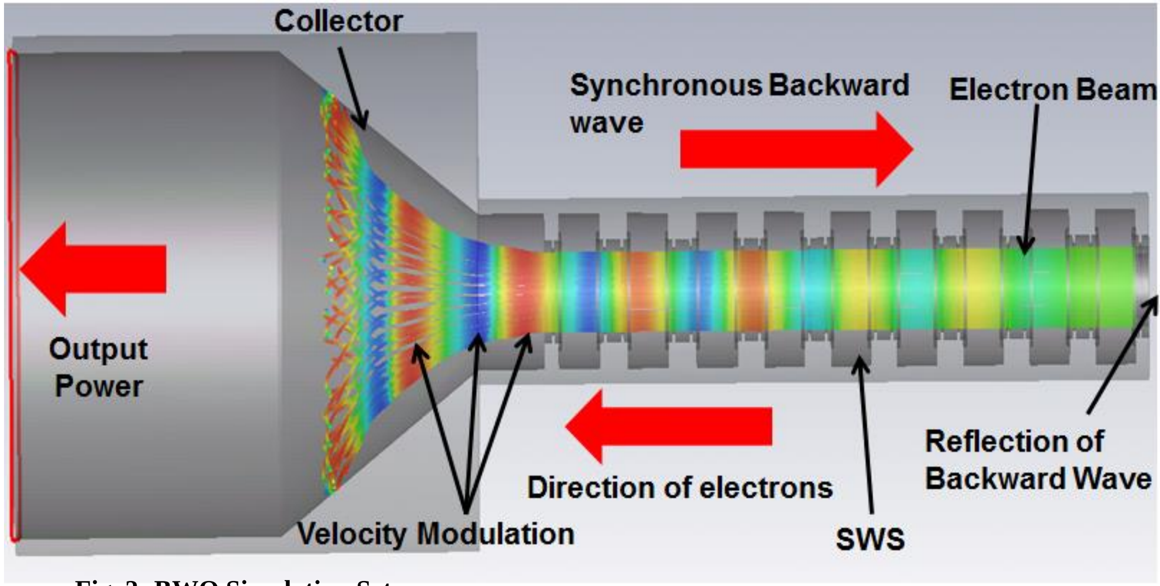
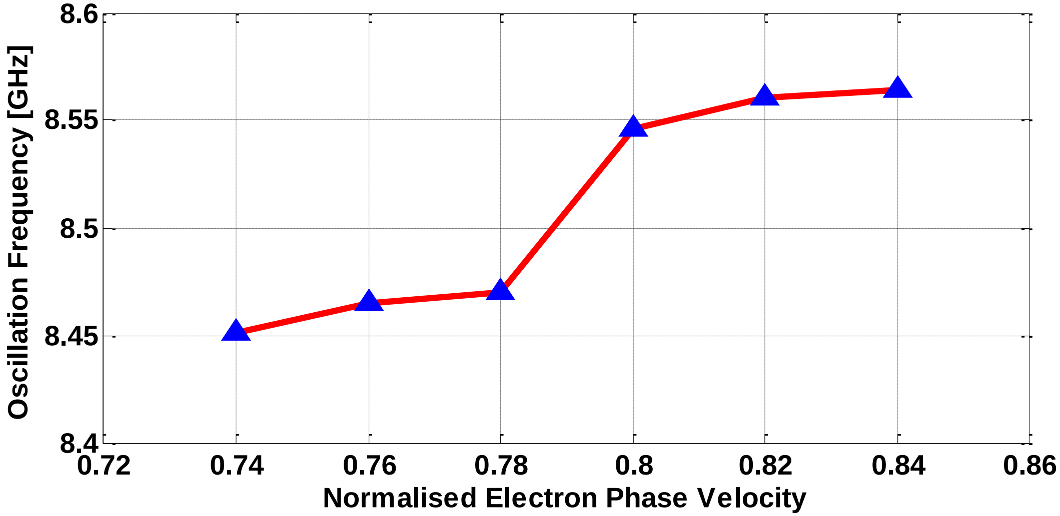


Fig. 2 :BWO Simulation Setup

X Band BWO PIC Simulations

Beam Velocity vs Frequency

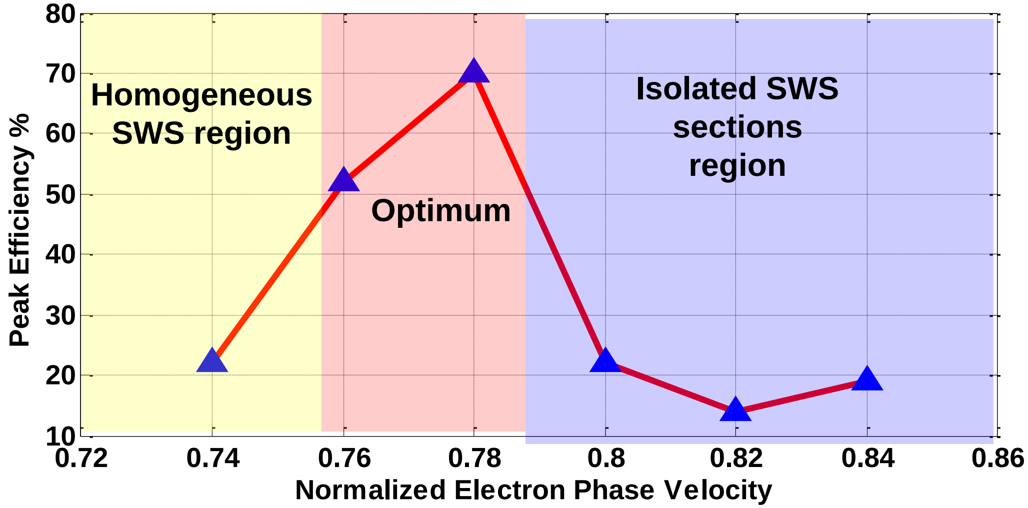
- Beam velocity used to control oscillation/operation frequency
- Frequency increases as beam velocity increases - Consistent with BWO theory



Beam Velocity vs Peak Efficiency

- Peak efficiency rises and drops as frequency increases
- Peak efficiency at 8.47 GHz .

Peak Efficiency in PIC simulation is in agreement with Eigenmode analysis !



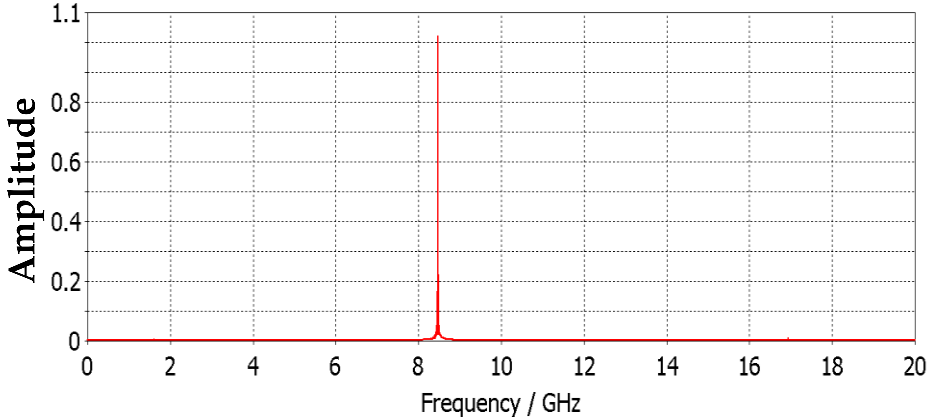
Optimized 3 Section SWS for X Band BWO

Highest efficiency is obtained when BWO is operated in optimum frequency range as predicted by eigenmode analysis.

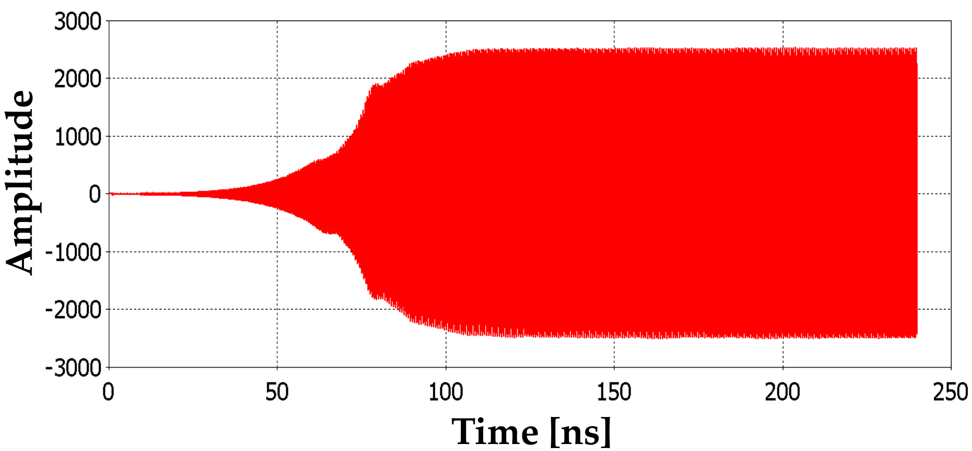
Beam current = 30 A
Beam voltage = 306 kV
Electron velocity = 0.78c
Input power = 9.18 MW
Peak Output Power =6.44 MW
Frequency = 8.47 GHz

Efficiency = 70 %

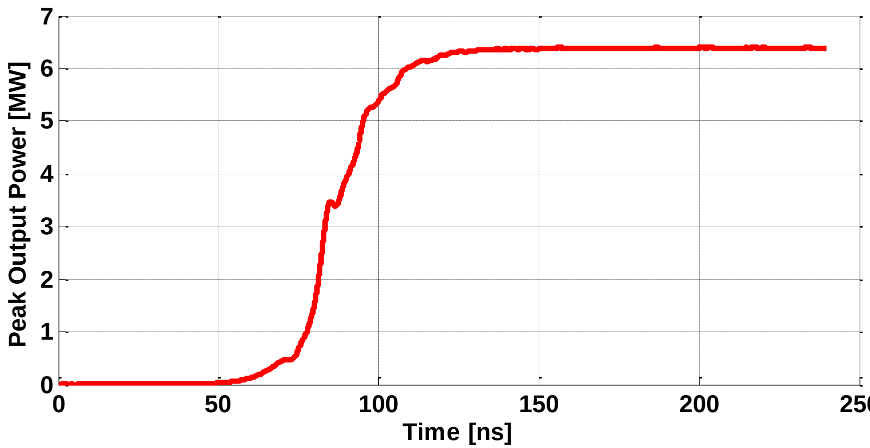
DFT of output Signal



Output Signal



Output Power



High Efficiency BWO: Comments

70 % Efficiency Feasibility

- Results are in close agreement with theoretical predictions (see Figures to right)
- Our 10 % higher efficiency is likely due to :
  1. The new SWS and higher interaction impedance with superior mode purity.
  2. Used 3 section SWS with impedance taper.
  3. Beam current is low (30 A), reducting detrimental space charge effects.

Theoretical Prediction of Efficiency [1]

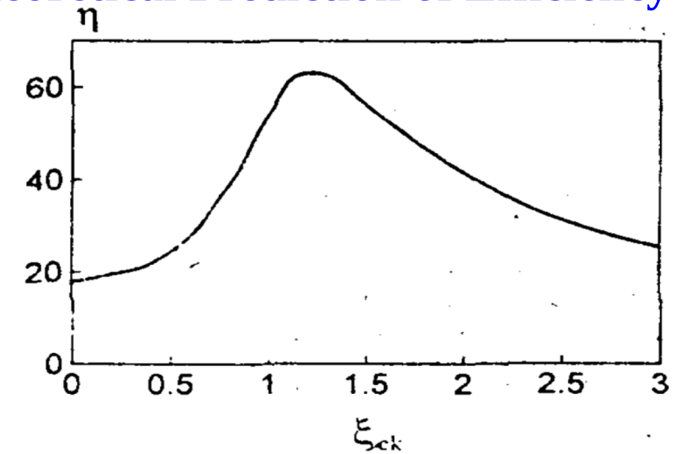


Fig. 1 Efficiency of BWO vs the phase velocity change parameter

O.S.U Simulated results

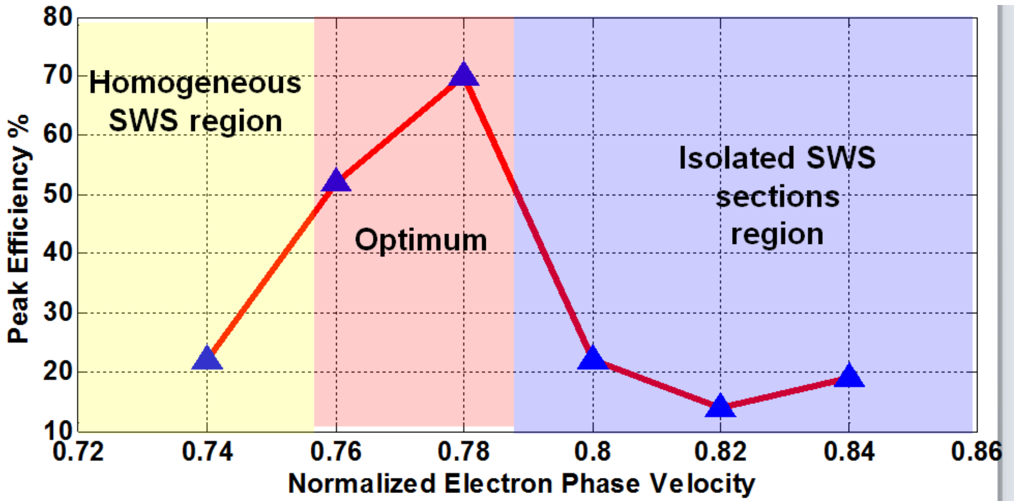


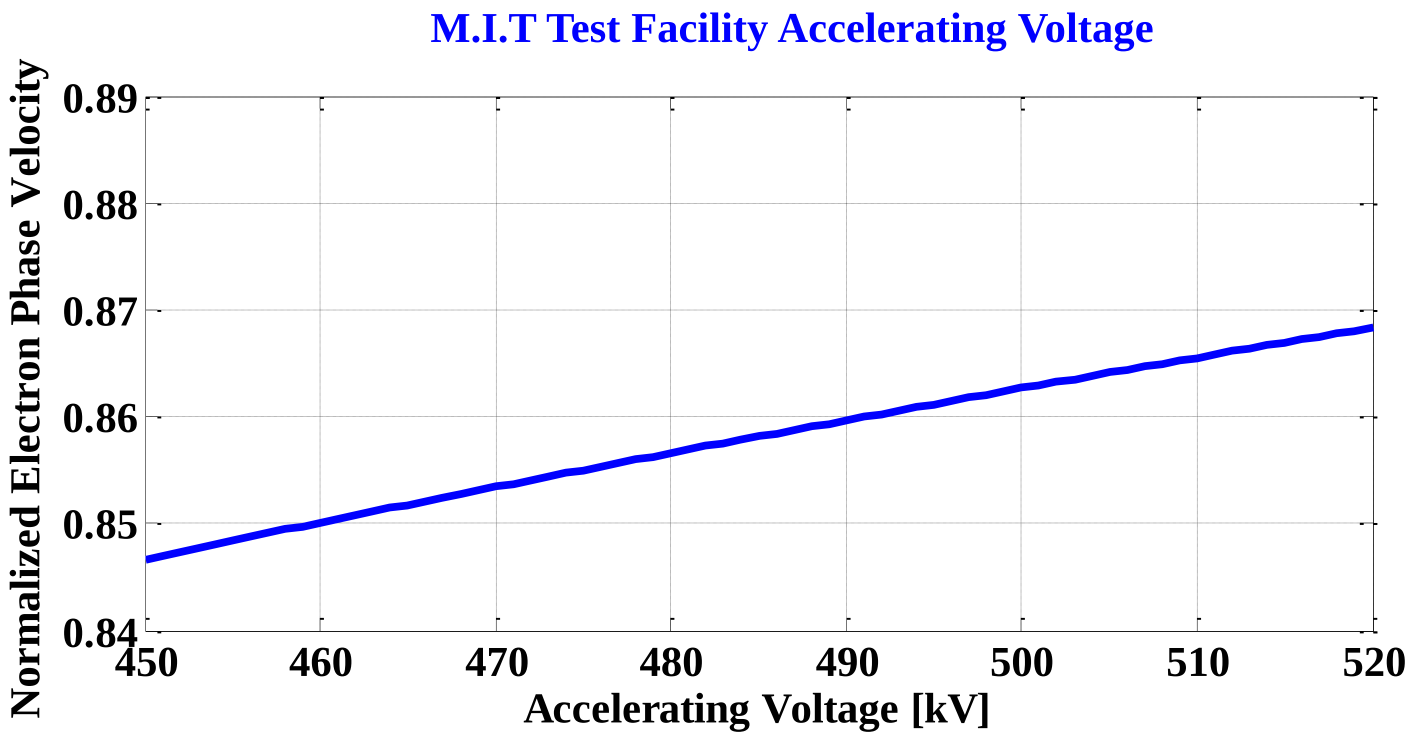
Fig. 2 Efficiency of BWO vs the initial phase velocity of beam.

Comments

- Reviewed Papers provide strong evidence that high efficiencies in inhomogeneous BWOs are attainable.
- High efficiency operation is very sensitive to beam parameters.
- High efficiency operation requires high interaction impedance and low operating currents.

[1] *S.D. Korovin, S.D. Polevin, A. M. Roitman , and V.V Rostov, "Relativistic Backward Wave with Non Uniform Phase Velocity of the Synchronous Harmonic" Russian Physics Journal Vol. 39 , No. 12 1996 .*

Electron Beam ***Voltage*** *Constraints*



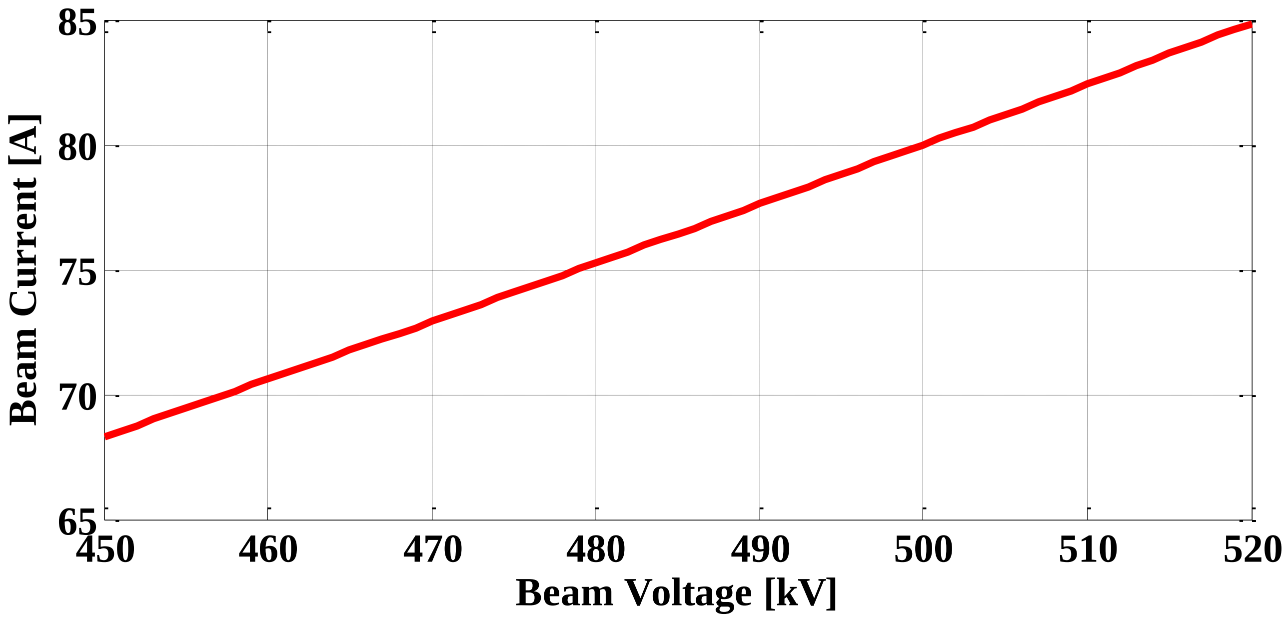
- MIT test facility uses 450-515 kV beams.
- Voltage corresponds to phase velocities of ***0.8467c-0.8683c***
- Current SWS operates between ***0.7c-0.8c***
- Current design phase velocity is too low for MIT test facility.
- SWS must be redesigned to support faster waves.

Normalized Phase Velocity $\boldsymbol{\beta}$

$$\beta = \sqrt{1 - \frac{1}{\left[\frac{eV_b}{mc^2} + 1\right]^2}}$$

*Electron Beam **Current** Constraints*

M.I.T Test Facility Beam Current



For MIT Beam :

$$\left(V_{beam}^{\frac{3}{2}}\right)/I_{beam} = Constant$$

- MIT test facility uses 450-515 kV beam.
- Voltage corresponds to beam currents of 68A-83A
- Current SWS operates at 30 A
- BWO operating current needs to be increased to $\approx 80\ A$ for MIT test facility.
- SWS design must be adjusted have higher starting current (to avoid over bunching at 80 A)

MIT Testing Facility Constraints

Other MIT testing facility requirements are:

Parameter	Value
Beam Radius	Varies with focusing magnetic field (3 mm at 0.15 T)
Beam Type	Solid
Pulse Length	1μs
Magnetic Field	0-0.18 T
Maximum SWS Radius	74 mm
Maximum SWS Length	450 mm

Design Challenges

- Small beam radius may reduce power and efficiency since beam is no longer close to walls
- Beam control issues arise in simulations due to low magnetic fields (previously 1 T was used)
- Small magnetic field depletes beam quality, possibly reducing energy exchange process.
- SWS length and radius constraints may affect realization of reversed mode dominance.

Proposed S Band BWO Design for MIT Hot Test

Design Goal

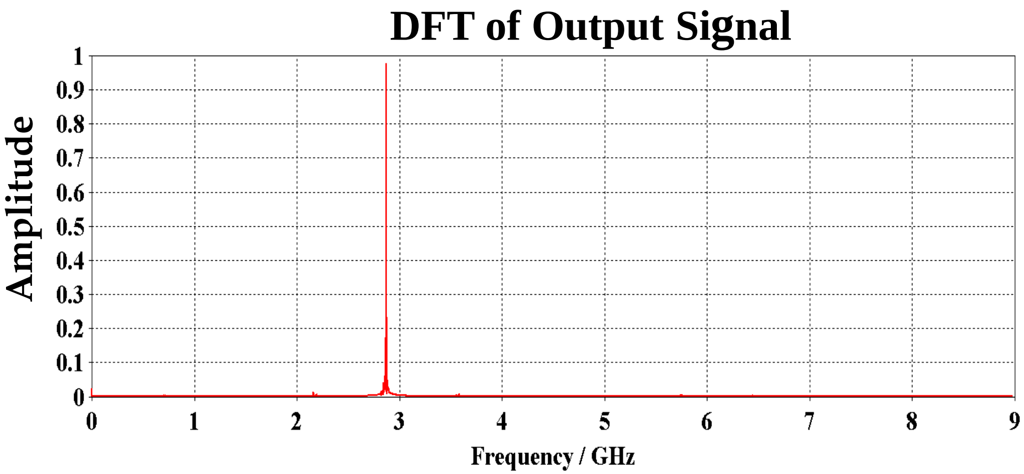
- Inhomogeneous, 3 section SWS for an S-Band BWO operating at 500 kV and 80 A

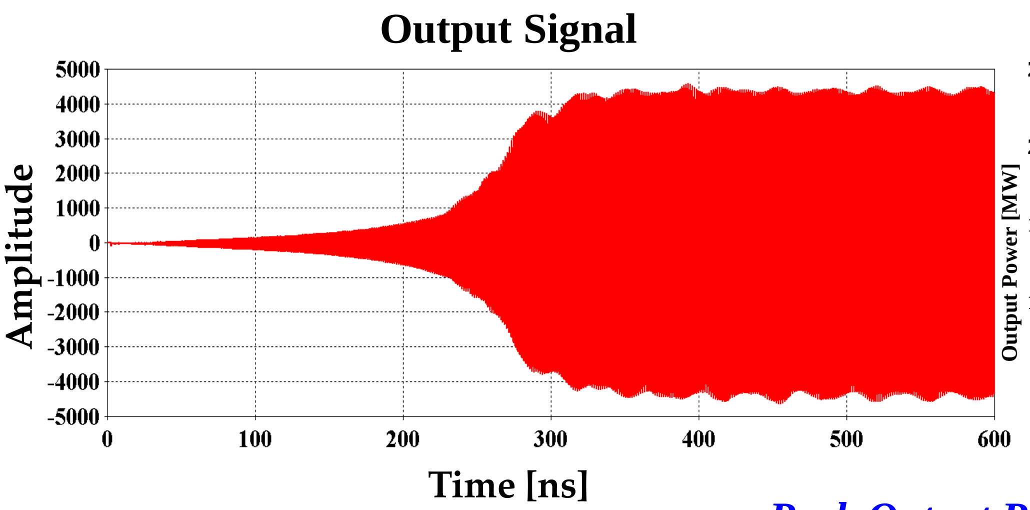
SWS Properties

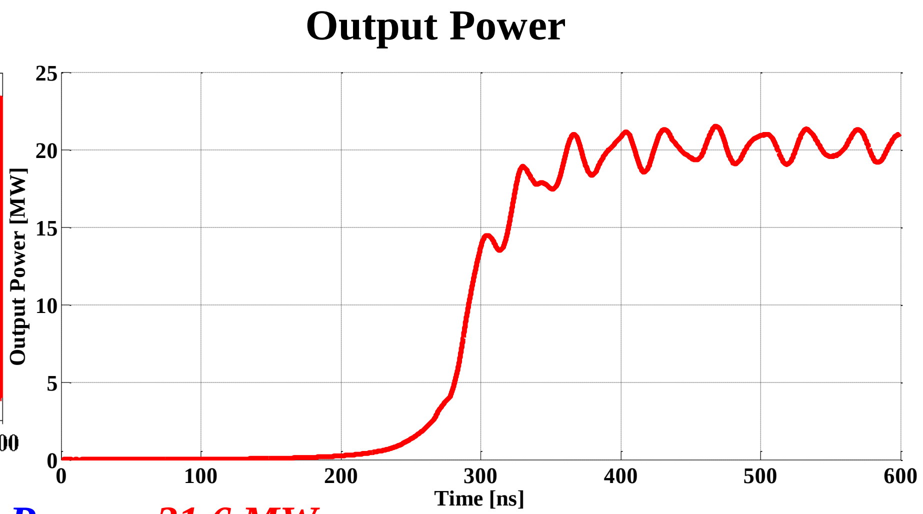
- 3 Section, 6 period SWS ($\boldsymbol{p}$=50mm,$\boldsymbol{p_1}$=54mm and $\boldsymbol{p_2}$=60mm)
- ***SWS Radius*** : 42mm, ***SWS Length*** : 370mm

Beam Parameters

- 500 kV , 80 A , ***Input Power***: 40 MW







Peak Output Power* : *21.6 MW
Frequency*: *2.83 GHz
Peak Power Efficiency*: *54%

Fabrication Challenges in Realizing New SWS Design

Objective

Fabricate a SWS consisting of multiple periods for the new design.

Challenges

- Cavity increments and metallic ring inclusions make axial profile complex and challenging to fabricate.
- EM process can be used but is expensive.
- Alternative fabrication techniques may need be considered

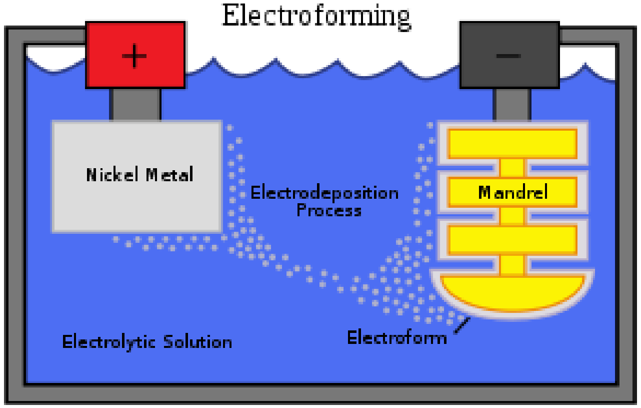


Fig. 1 Electroforming process

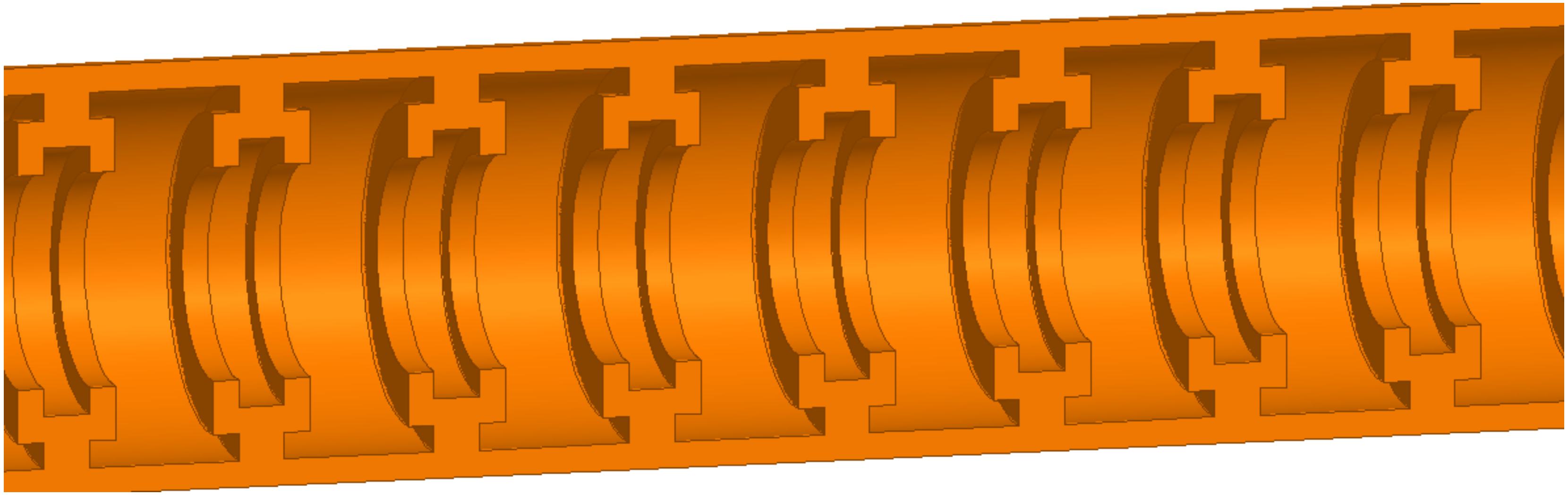
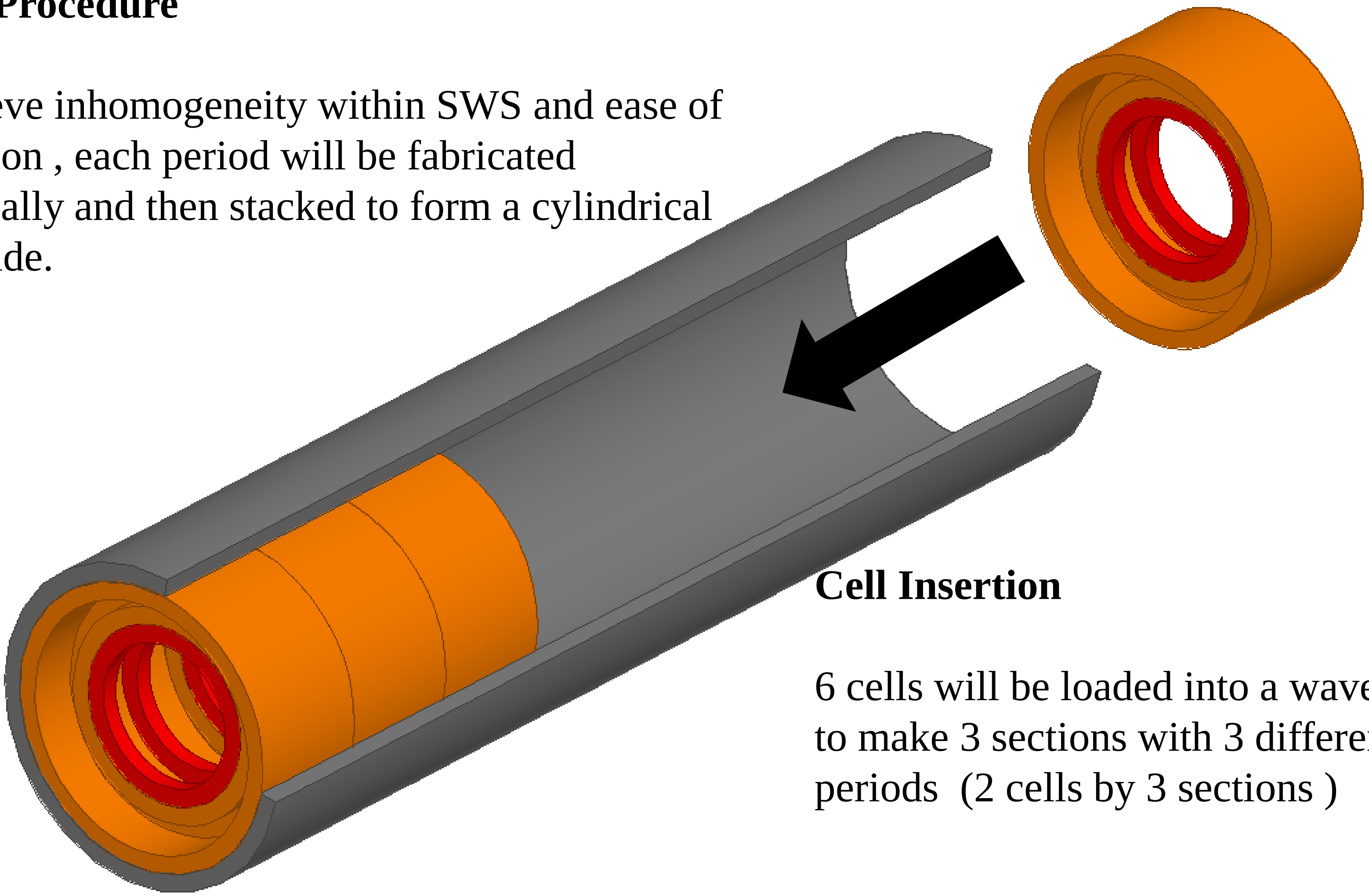


Fig. 2 Cutaway of new SWS Design.

Proposed Fabrication Technique

Design Procedure

To achieve inhomogeneity within SWS and ease of fabrication , each period will be fabricated individually and then stacked to form a cylindrical waveguide.



Cell Insertion

6 cells will be loaded into a waveguide to make 3 sections with 3 different periods (2 cells by 3 sections)

Summary

Summary of Efforts

- Presented Novel SWS for high power BWO and demonstrated mode control capabilities.
- Efficiency enhancement techniques using 3 section SWSs were presented.
- Cold test eigen mode analysis for inhomogeneous SWSs ware presented.
- Hot test simulation results for X Band BWO using inhomogeneous SWSs were presented (6.44 MW at 8.47 GHz).
- S Band SWS design (for fabrication and testing at MIT) was presented. (21.6 MW at 2.83 GHz)

Current Work

- Finalizing BWO SWS design
- Fabricate proposed BWO SWS

Thank You