2D Periodic Surface Lattice Backward Wave Oscillator Experiment

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ABP

Atoms, Beams & Plasmas

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Introduction

- Aim of project: to find a route to higher power millimetre waves that can scale to THz frequencies.

- One of the strategies we are using is to increase the transverse dimensions of the interaction region so that the diameter to wavelength ratio is large while avoiding multi-mode operation.

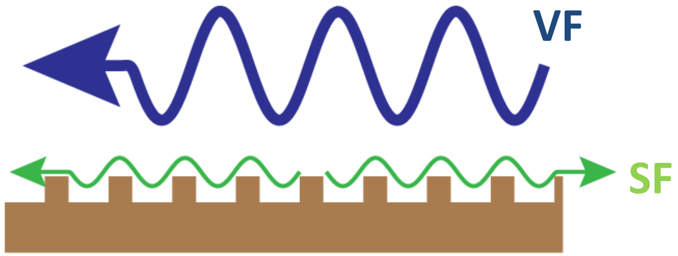
- This approach is particularly attractive for the shorter wavelengths in the mm-wave and THz ranges.

- To avoid multi-mode operation we are using a two dimensional periodic surface lattice (PSL) that sustains a surface mode which couples to a volume mode resulting in eigenmode formation that can be efficiently driven by an electron beam.

Theory

The Two-Dimensional Periodic Surface Lattice (2D PSL) provides a mechanism for inducing coupling of an incident near cut-off ($TM_{0,n}$) Volume Field (VF) and the $HE_{m,1}$ Surface Field (SF) that is formed around the perturbations when the Bragg conditions are satisfied.

$$\bar{k}_{\pm} = \bar{k}_i - \bar{k}_s \qquad \bar{m} = \pm(m_1 - m_2)$$



The perturbations are defined analytically as:

$$\mathrm{r} = \mathrm{r}_0 + \Delta \mathrm{r} \cos\left(\bar{\mathrm{k}}_z \mathrm{z}\right) \cos(m_{azi}\bar{\phi})$$

Where r_0 is the unperturbed waveguide radius, Δr is the perturbation amplitude and $\bar{k}_z$ and m_{azi} are the longitudinal wavevector and the azimuthal variation respectively.

Coupled mode theory describes the VF/SF interaction:

$$\frac{dA_V}{dz} + i\kappa A_S = 0 \qquad \frac{dA_S}{dz} - i\kappa A_V = 0$$

A_V , A_S = Amplitudes of the volume and scattered waves. The amplitude of the incident volume wave is dependent on the amplitude of the scattered wave through a coupling coefficient κ.

I. V. Konoplev, A. R. Phipps, et al, Appl. Phys. Lett. 102, 141106 (2013)

Dispersion of Coupled Fields Inside Cylindrical Periodic Surface Lattice

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$$\left(\omega_e^2-\Lambda^2\right)\left[\Lambda^4-2\Lambda^2\left(2+\Gamma^2+\omega_e^2\right)+\left(2-\Gamma^2+\omega_e^2\right)^2\right]=2\alpha^4\left(2-\Gamma^2+\omega_e^2-\Lambda^2\right)$$

- α is the normalised coupling coefficient
- Λ is the normalised wave vector
- ω_e is a variable angular frequency
- The detuning parameter Γ is a function of the geometry of the structure

.

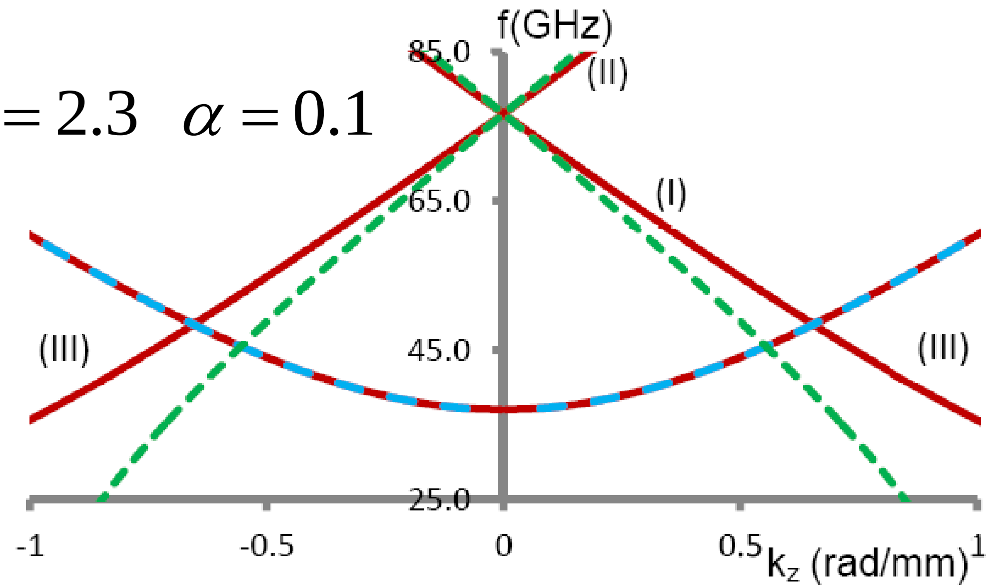
$$\Gamma = \frac{\lambda_c}{d_z}$$

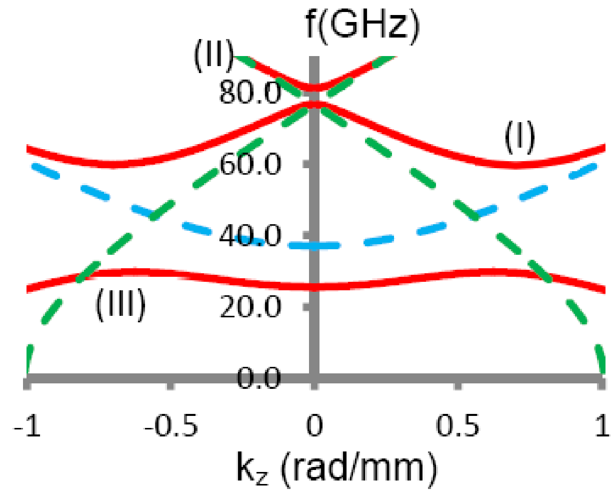
where λ_c is the cut-off wavelength of the volume field inside the cylindrical waveguide and d_z is the longitudinal lattice period.

I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, et al., "Cylindrical, periodic surface lattice - Theory, dispersion analysis, and experiment", *Appl. Phys. Lett.*, **101**, 121111, 2012.

Dispersion Analysis of Cylindrical Periodic Surface Lattice: Γ=2.3

$\Gamma = 2.3 \quad \alpha = 0.1$





$\Gamma = 2.3 \quad \alpha = 1$

Uncoupled surface field =
Uncoupled volume field =
Coupled dispersion =

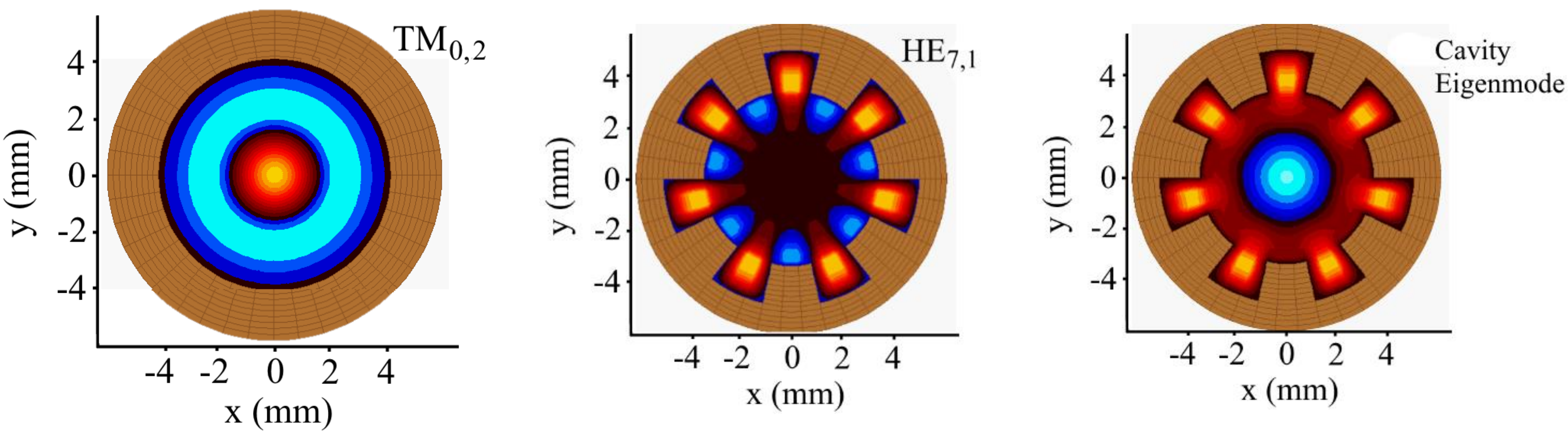
- The position of maxima and minima points $\partial f / \partial k_z = 0$ of the dispersion indicate the positions of the cavity eigenmodes.
- The $\partial f / \partial k_z$ sign variation illustrates that slow forward or backward waves may be observed.

I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, et al., "Cylindrical, periodic surface lattice as a metadielectric: Concept of a surface-field Cherenkov source of coherent radiation", *Phys. Rev. A.*, **84**, 013826, 2011.

CST Microwave Studio Simulations

PSL Parameters (BWO structure):

- Frequency = ~83GHz:
- Azimuthal variations = 7
- Inner radius = 4 mm
- Perturbation amplitude dr = 0.8 mm
- Prominent modes = $TM_{0,1}$, $TM_{0,2}$ and $TM_{0,3}$



Construction of W-band 2D PSL

2D PSL

- 3D printed wax former (high resolution)
- Molten silver (92.5%) – chromium (7.5%) alloy deposited into mold
- +/- 125 micron resolution

Parameters	
Unperturbed Radius	4 mm
Azimuthal Variations	7
Azimuthal Period	~ 3.6 mm
Longitudinal Period	1.6 mm
Number of Periods	16
Perturbation Amplitude	0.8 mm

Vector Network Analyser Measurements of High Frequency 2D PSL

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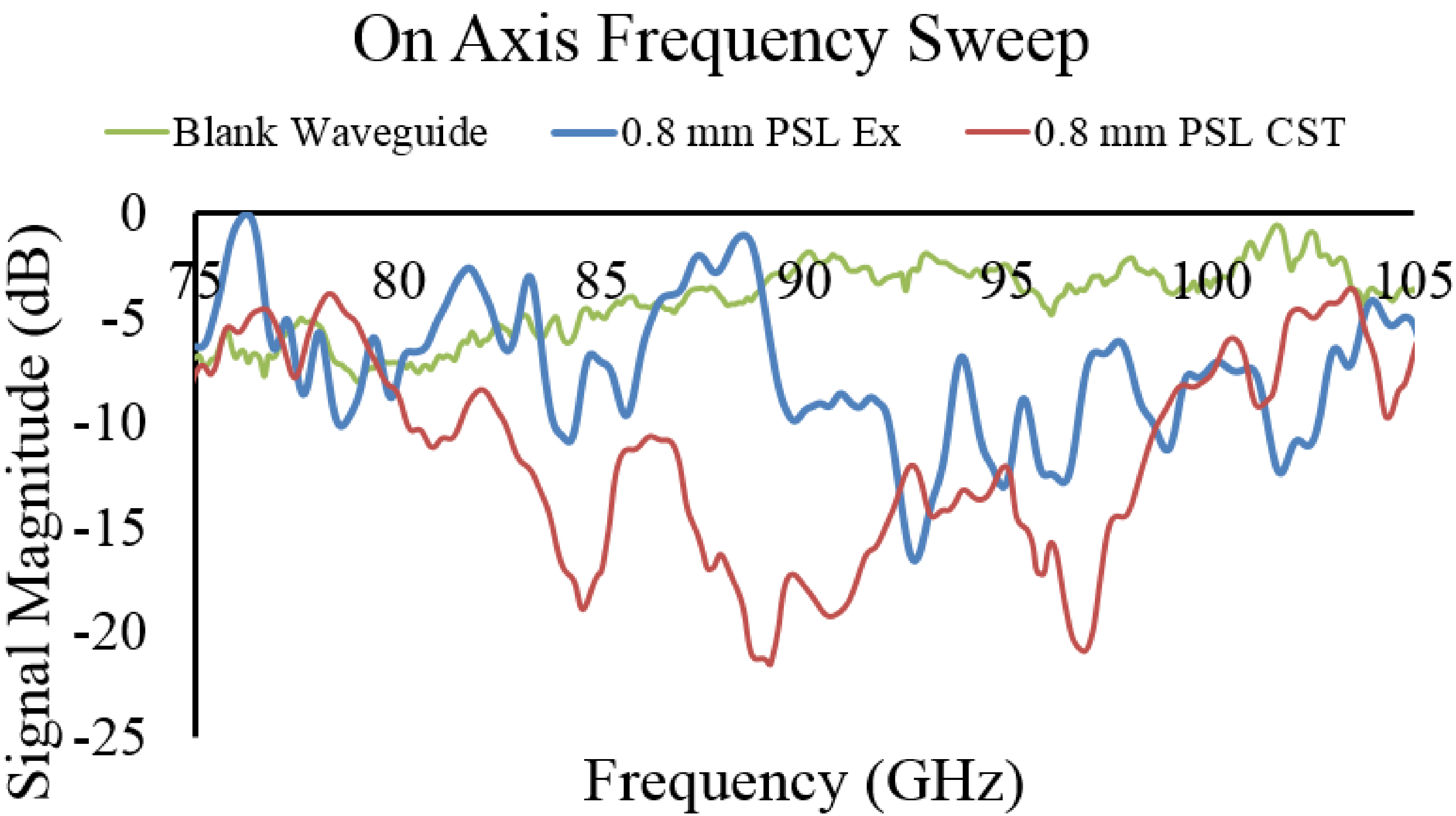


Electron beam-EM wave interaction

$$\omega = k_z v_z$$

- k_z is the wave's longitudinal wave number
- 90kV electron beam, $\gamma \sim 1.12$
- v_z is the electron beam longitudinal velocity, 0.51c
- d_z = 1.6mm

- Electrons interact with localized surface field

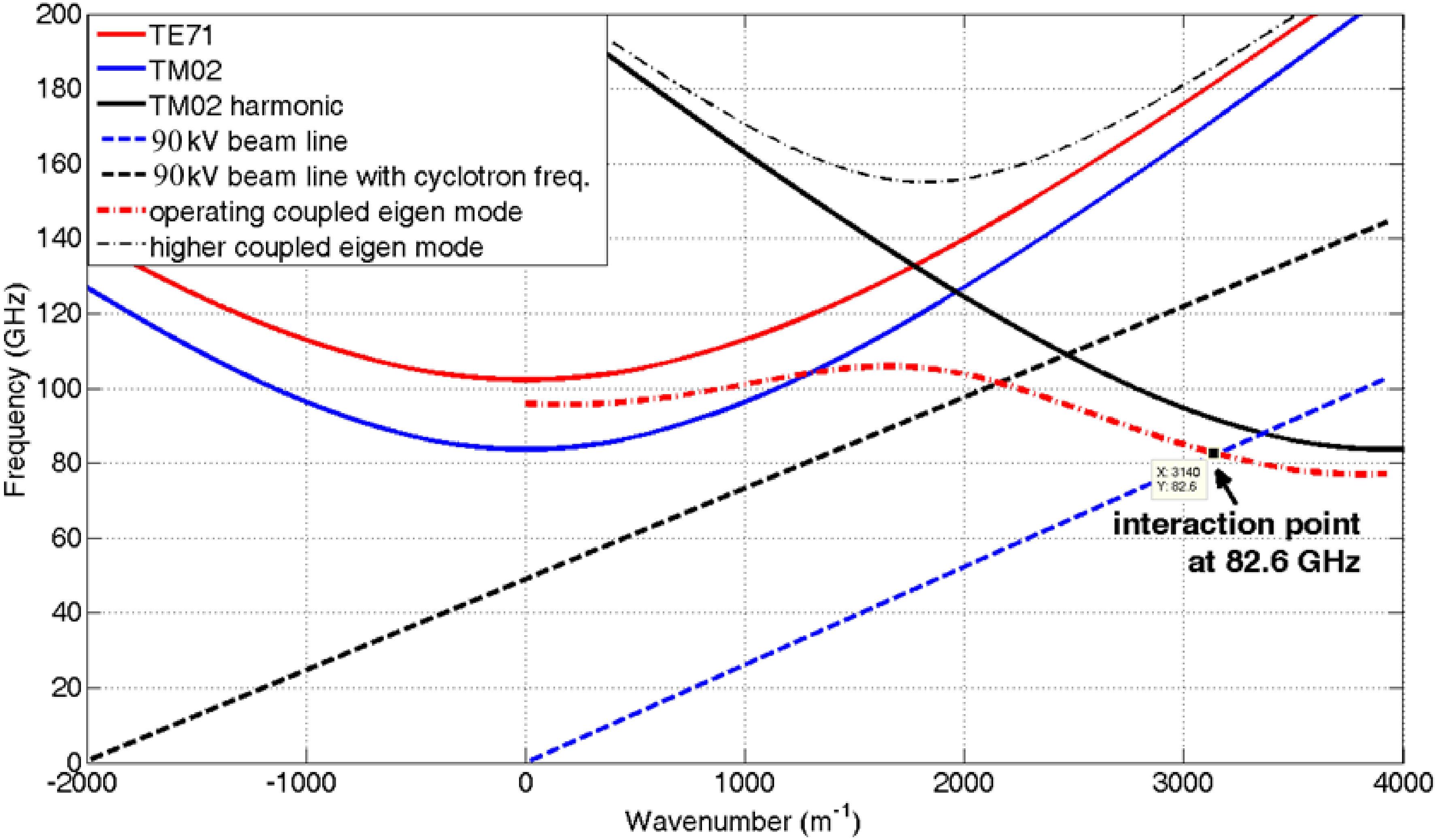
$$f = \frac{c}{d_z}\sqrt{1 - \gamma^{-2}} = 84\text{GHz}$$

- The number of lattice azimuthal variations should be larger than the number of wavelengths along the unperturbed circumference of the waveguide

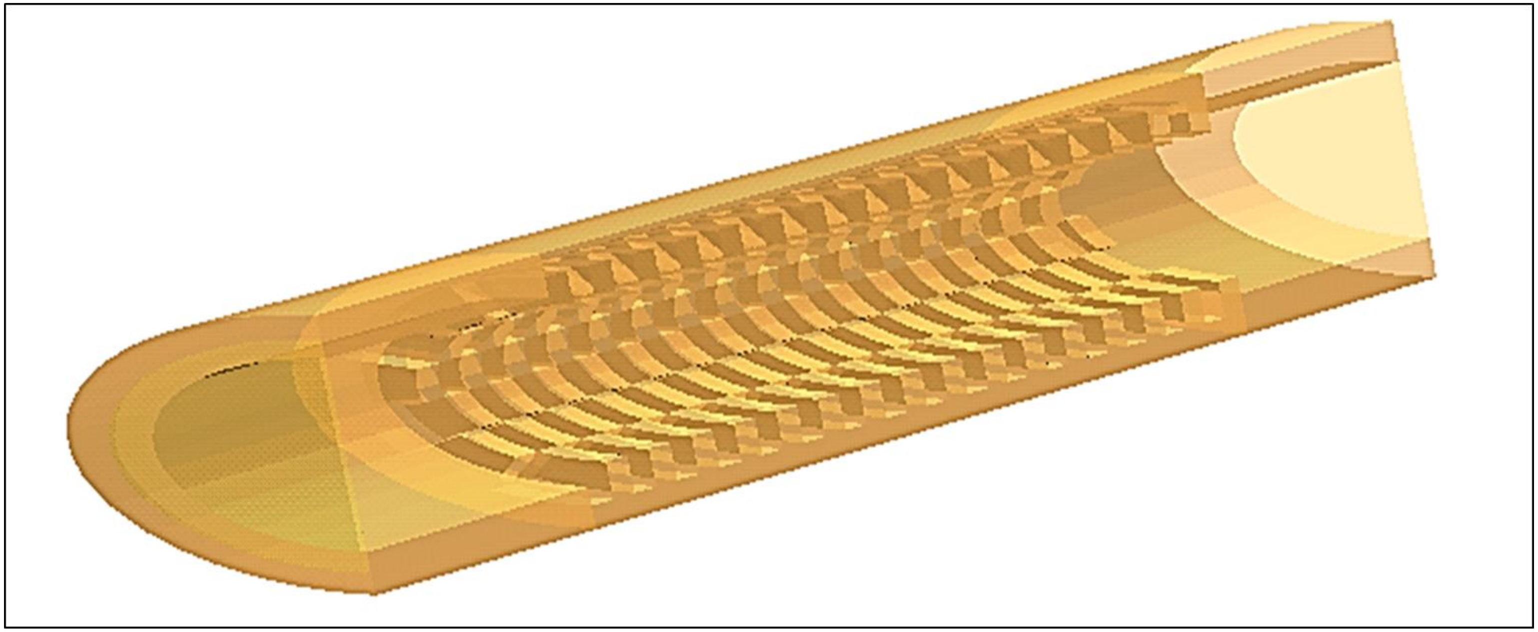
$$\frac{2\pi r_0}{\lambda\gamma} > \overline{m} \qquad \frac{2\pi r_0}{\lambda\gamma} = 8, \quad \overline{m} = 7$$

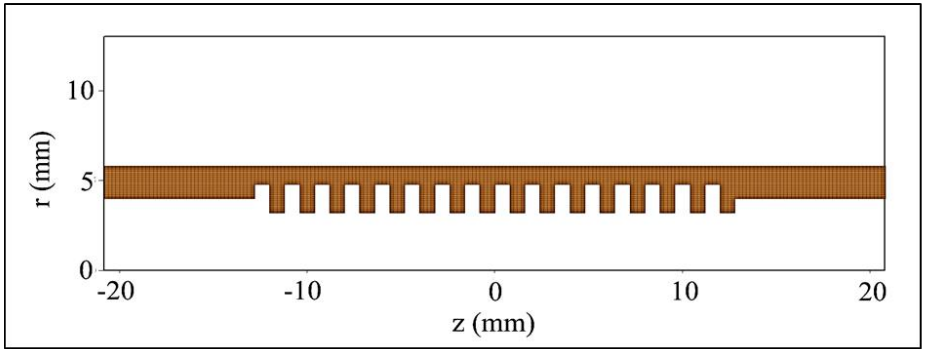
I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, et al., "Cylindrical, periodic surface lattice as a metadielectric: Concept of a surface-field Cherenkov source of coherent radiation", *Phys. Rev. A.*, **84**, 013826, 2011.

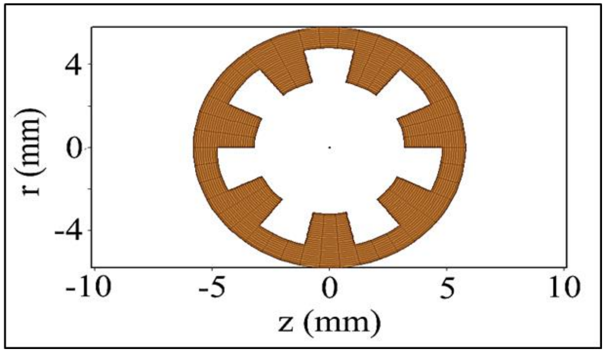
Beam – Wave Interaction Dispersion Diagram



MAGIC 3D Simulations

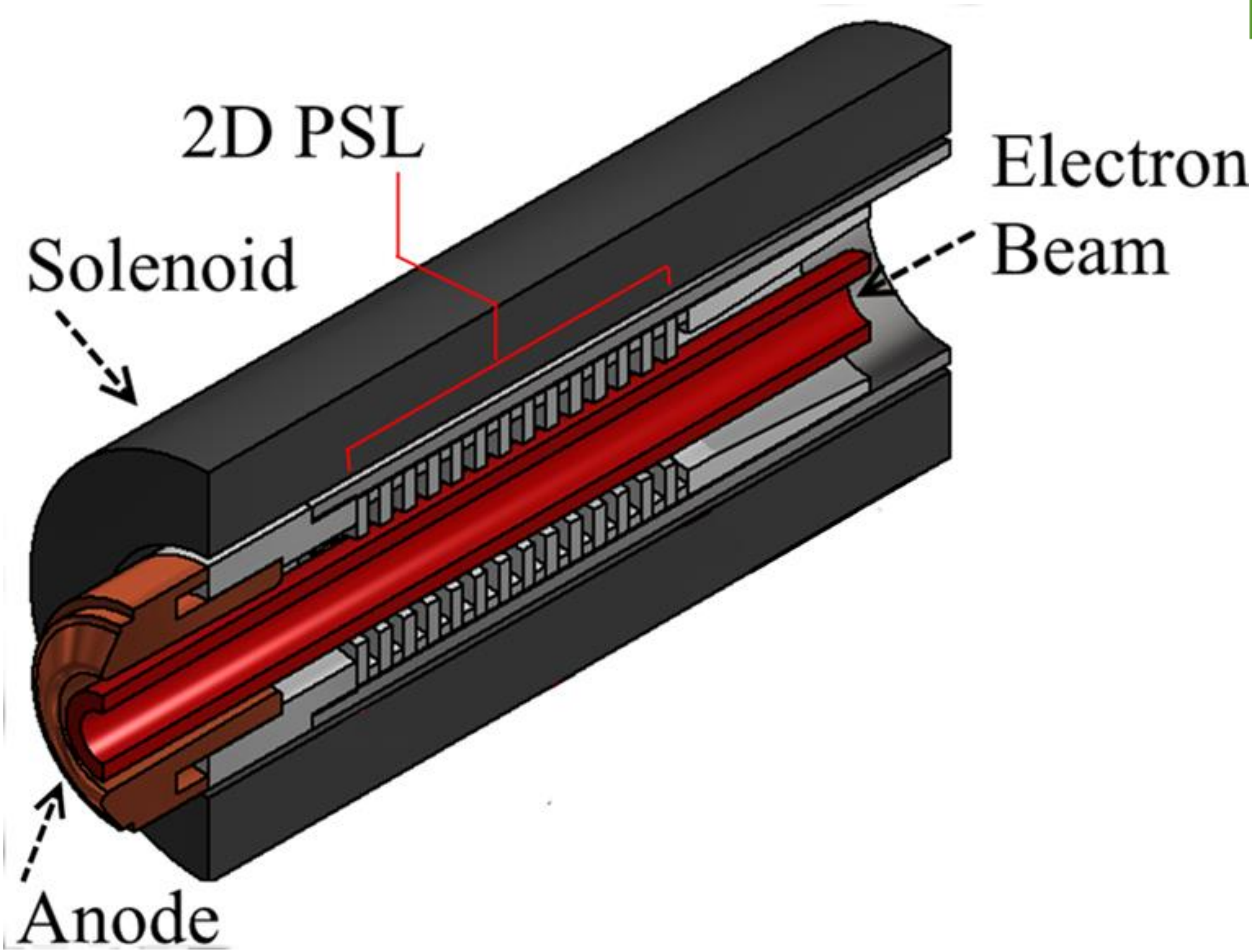






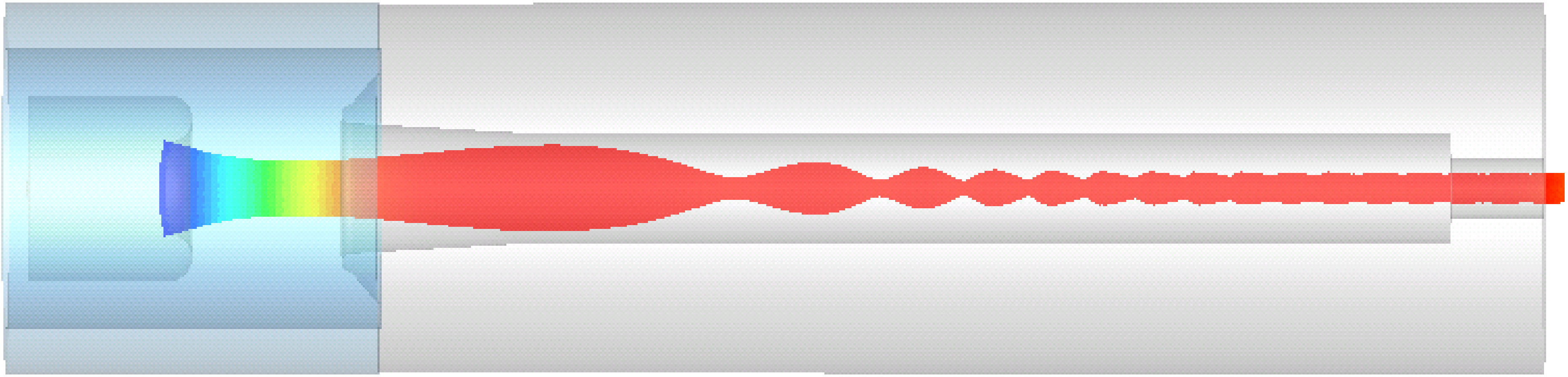
- Square perturbation to optimize simulation time
- 16 Longitudinal periods, (1.6mm)
- 7 azimuthal periods, (3.2mm)
- $B_z = 1.8$ T

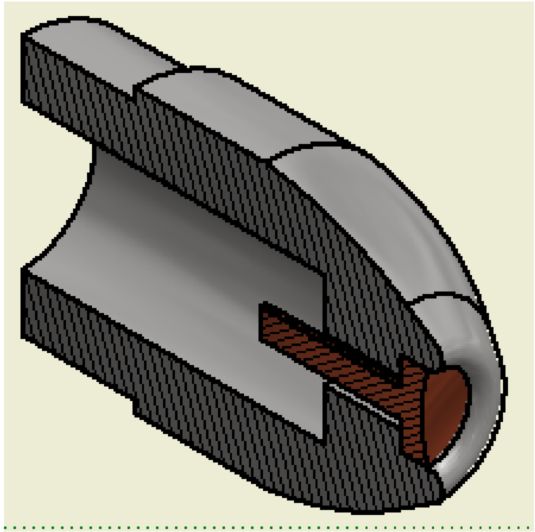
Experimental Design

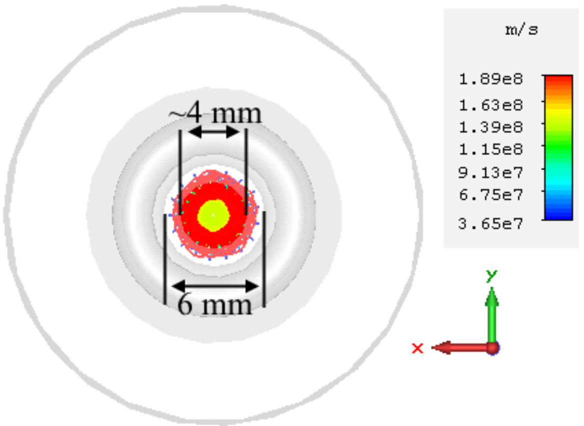


Electron beam source

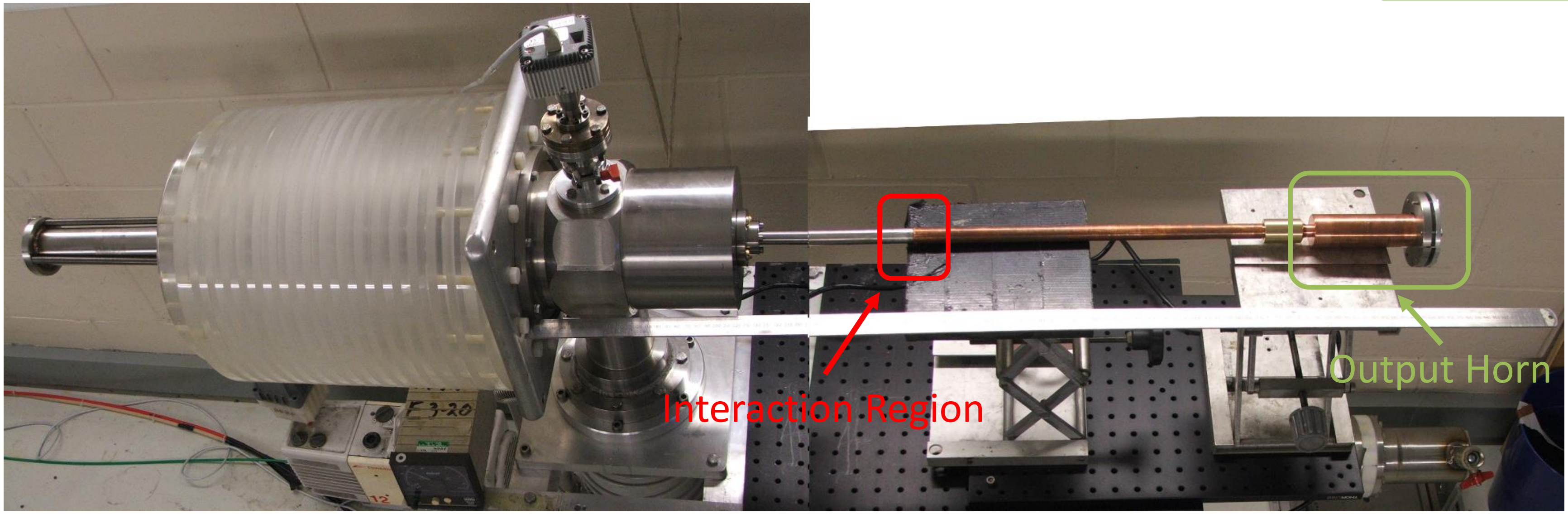
Designed using CST Particle Studio







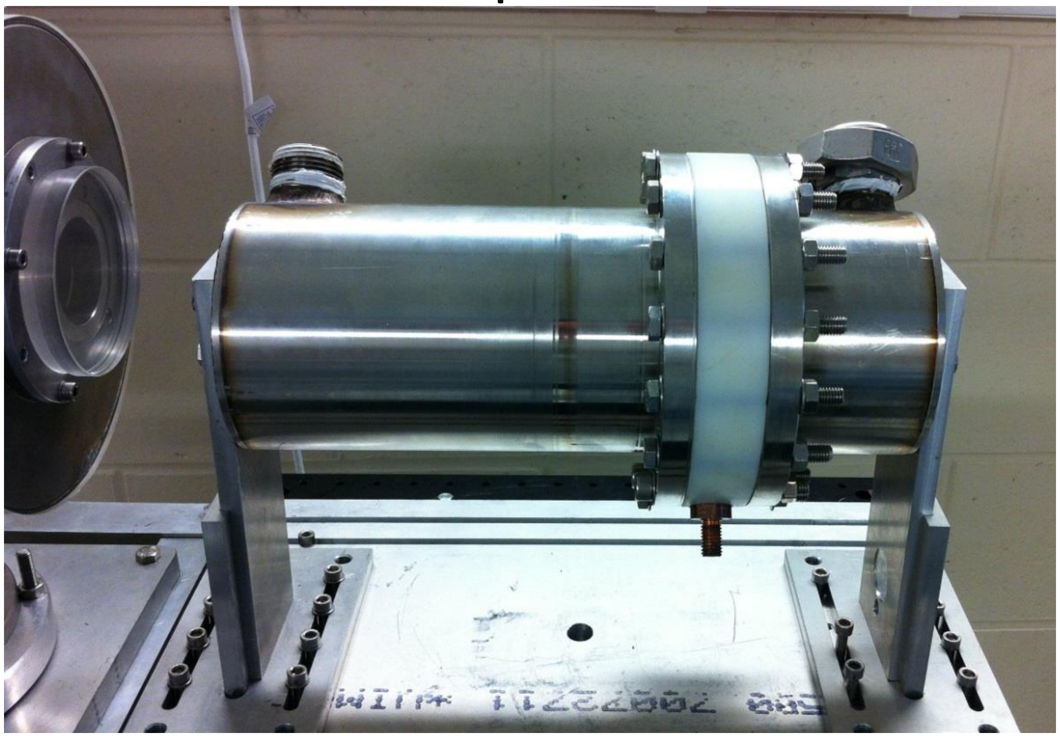
BWO source: diode\ electron gun\beam-wave interaction region

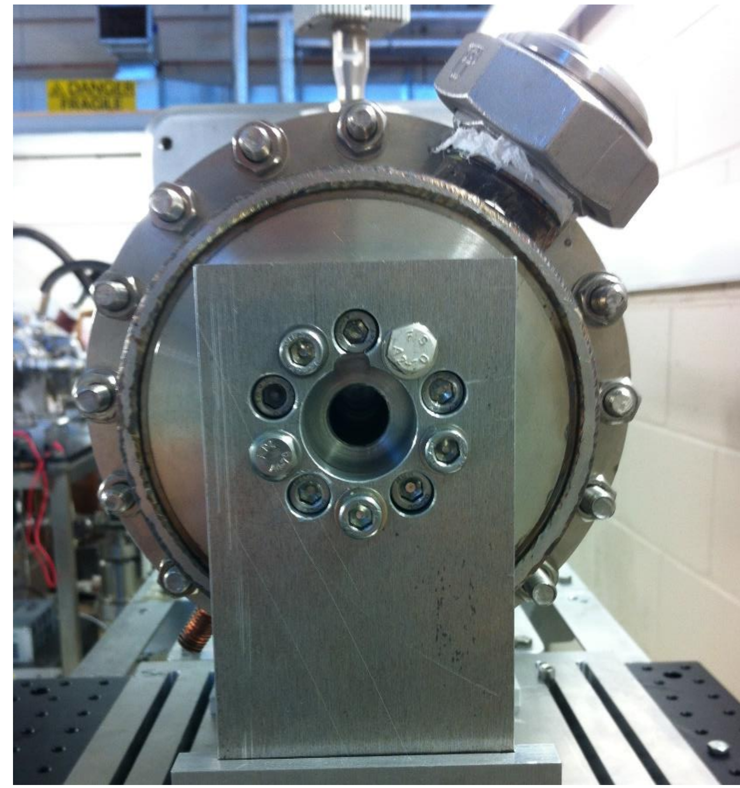


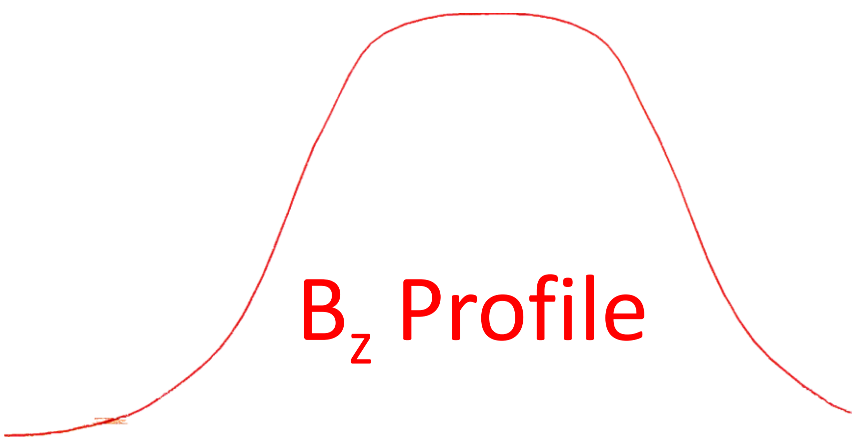
- Diode insulator, perspex
- Electron beam source, velvet
- BWO interaction region, silver 2D PSL
- Output horn and mylar window
- Vacuum jacket stainless steel and copper
  - Pressure, 5.0 x10^{-6} mbar

Solenoid & B – Field Profile

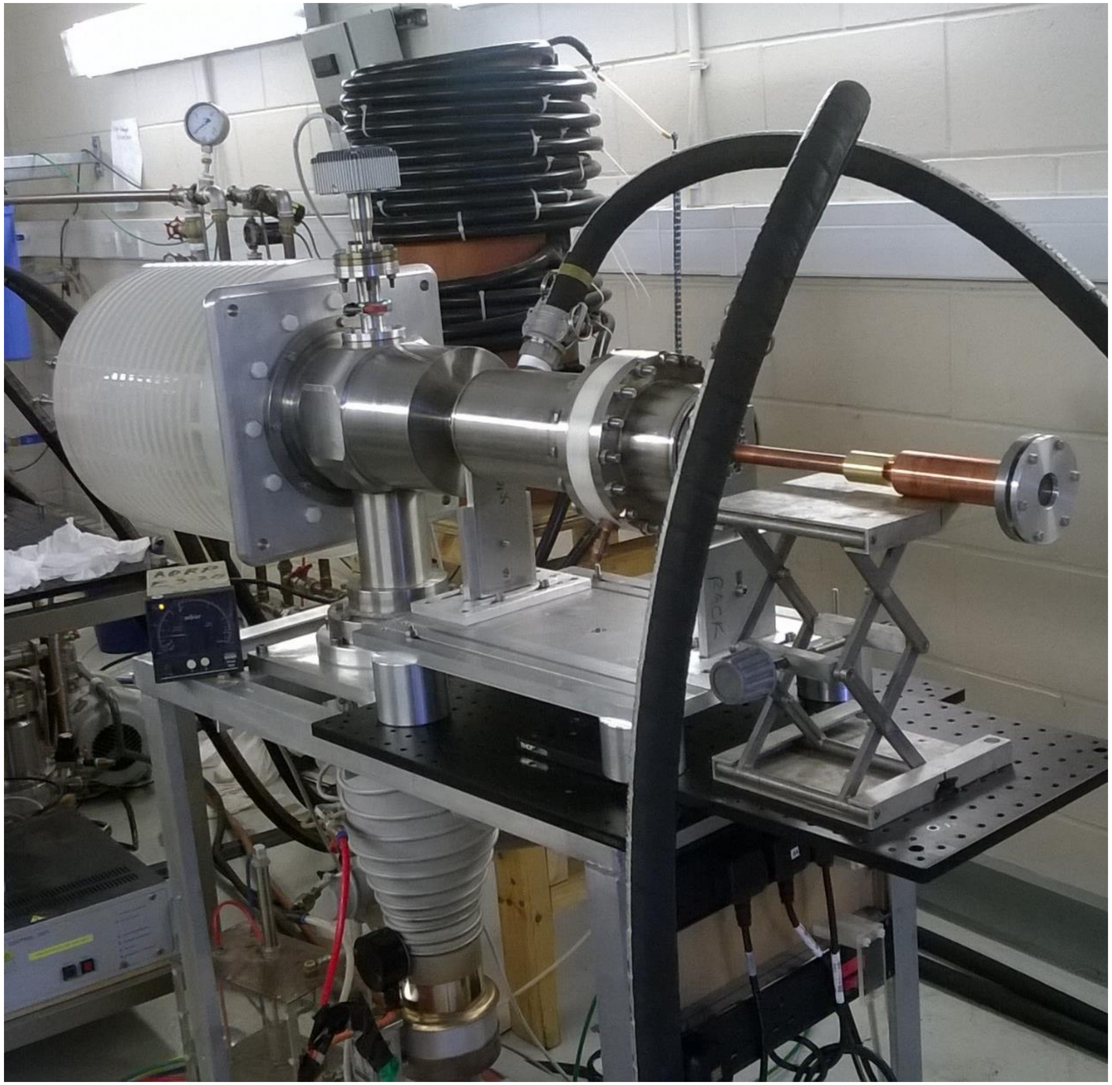
- DC conventional coil, designed, constructed and tested
    - B-field up to 2 T







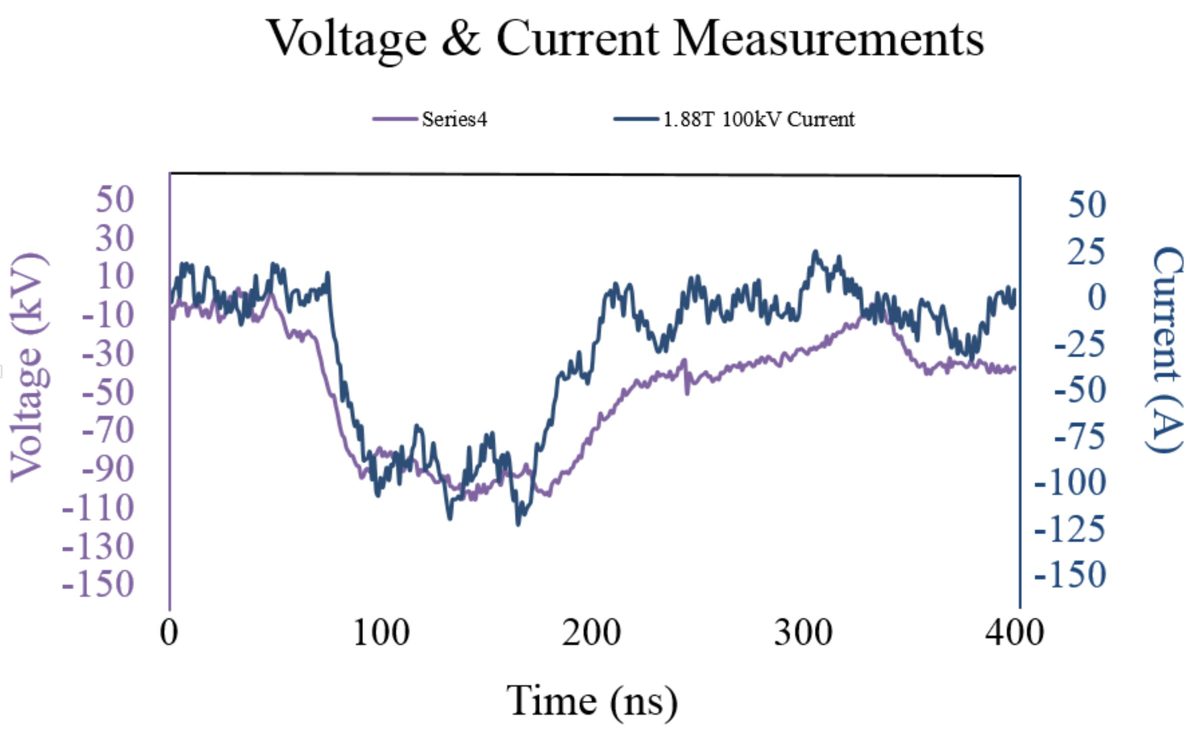
BWO experimental setup

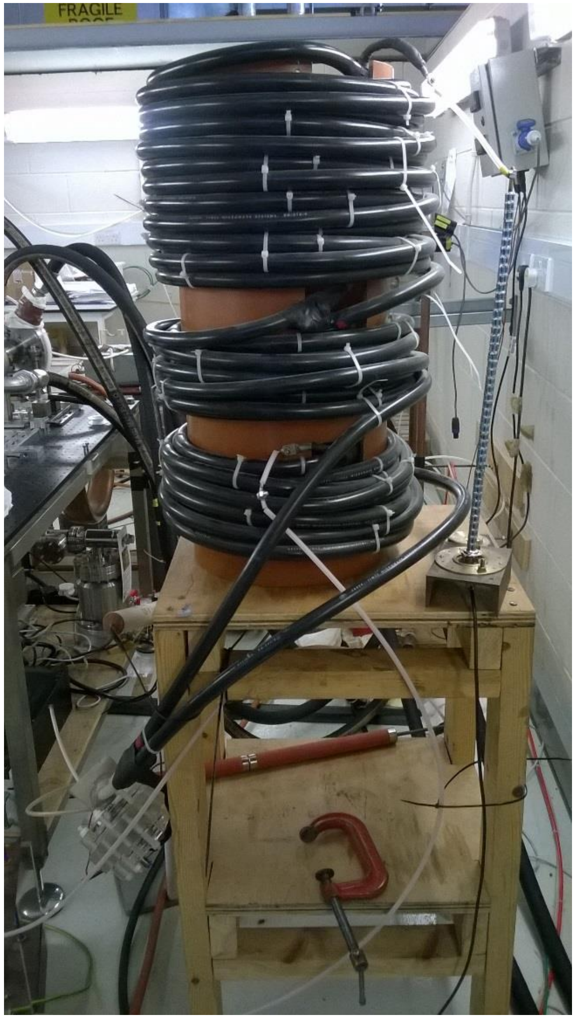


- Diode insulator
  - perspex
- Electron beam source
  - velvet
- BWO interaction region
  - silver 2D PSL
- Output horn
  - copper
- Output window
  - mylar
- Vacuum jacket, copper & stainless steel
- Vacuum system, Diffstack backed by rotary pump
  - Pressure 5 x 10^{-6} mbar

Beam Current Measurements

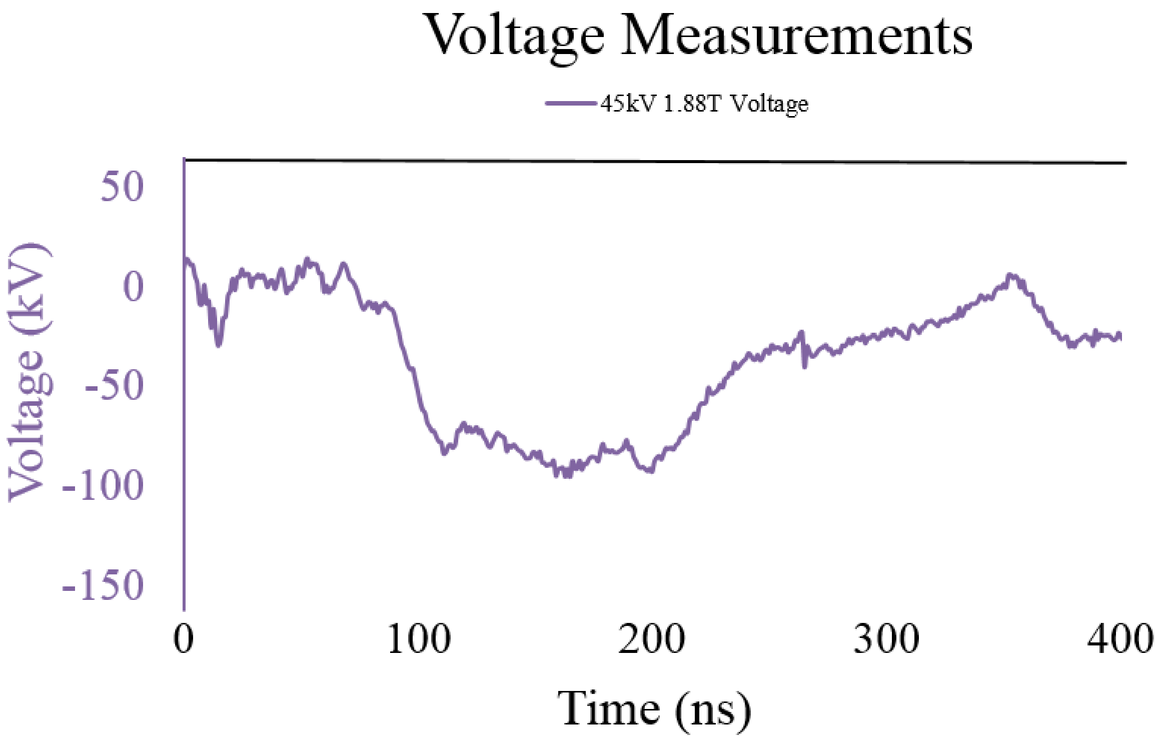
- HV power supply, cable Blumlein generator
- Cold field emission from velvet cathode
  - Beam current ~ 100 A
  - Beam voltage ~ 90 kV
  - Pulse duration 100 ns

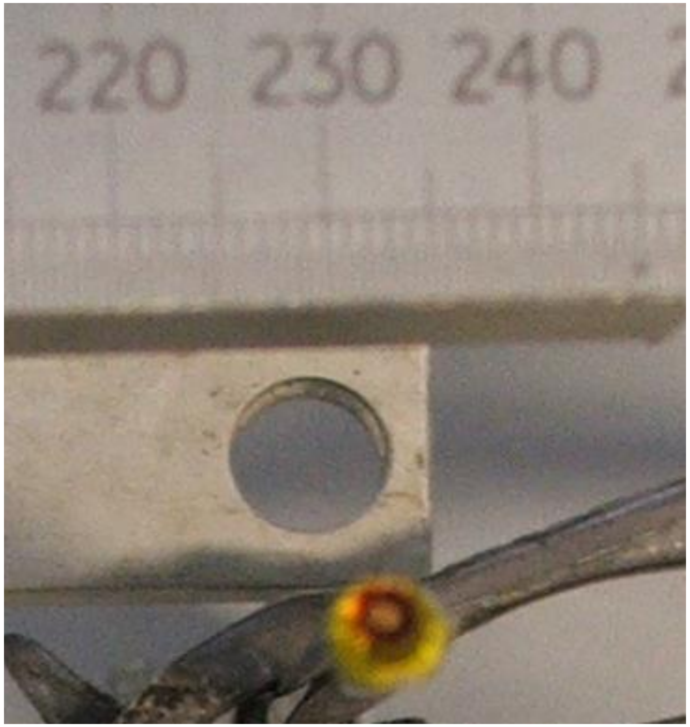




Beam Profile Measurements

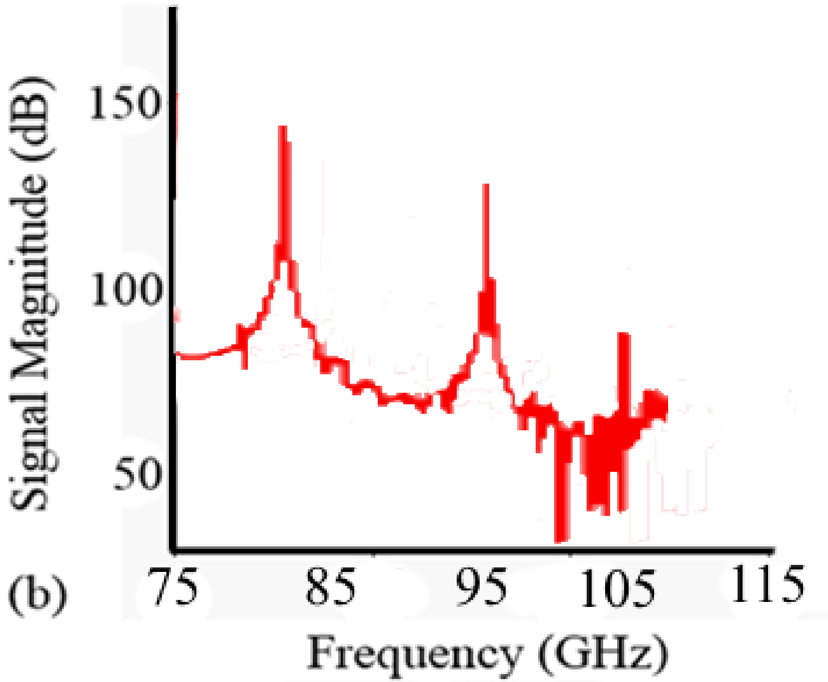
- Beam profile measured using electron sensitive film placed on the end of the Faraday cup

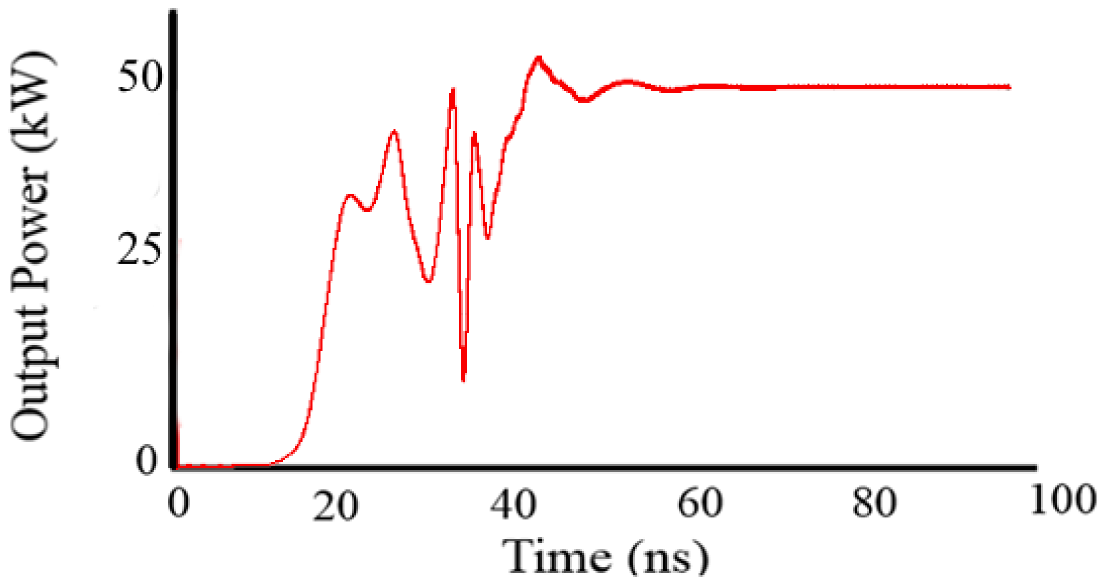




Beam profile displayed as red ring on electron sensitive film

MAGIC 3D Simulation Results

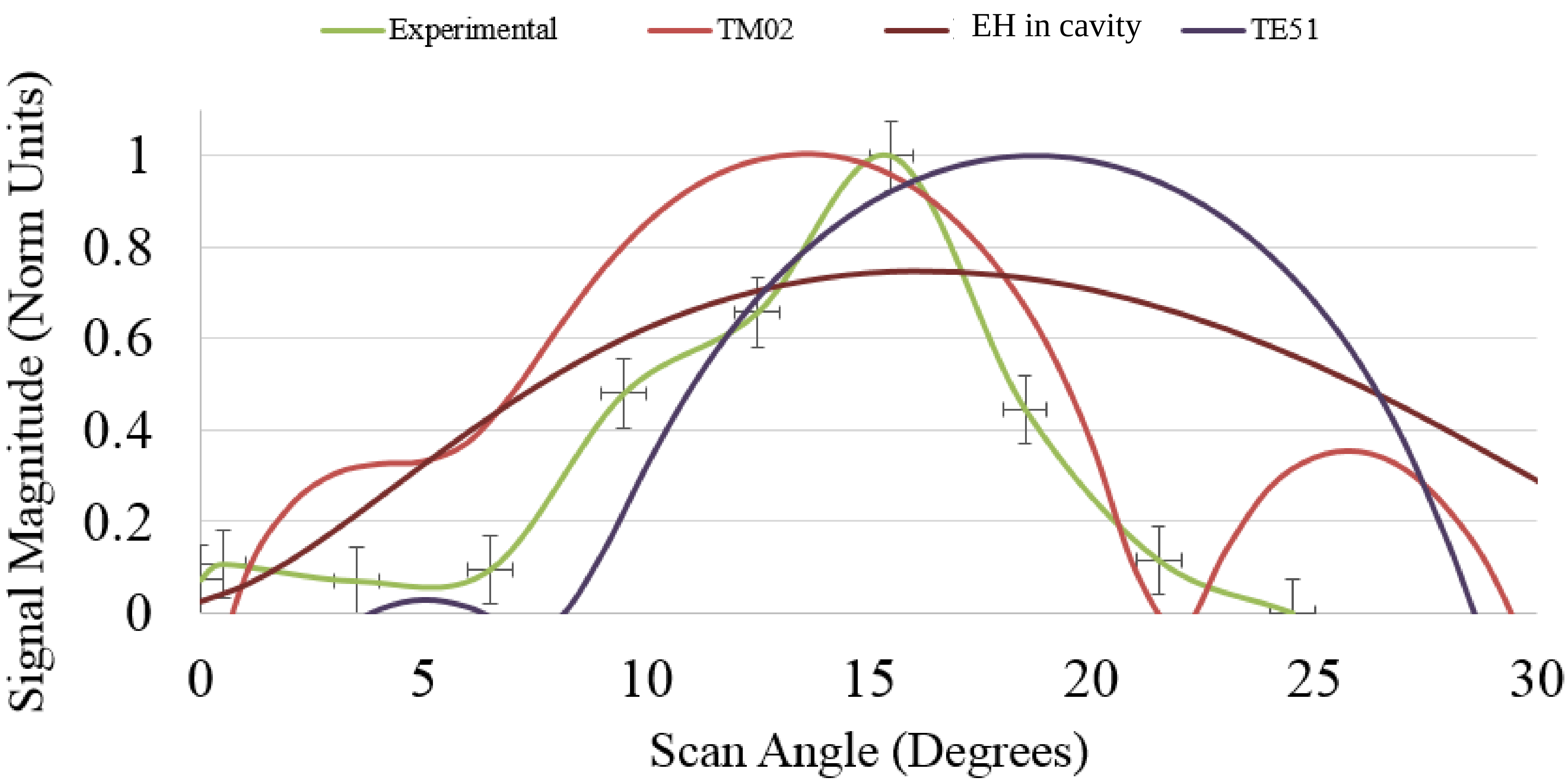




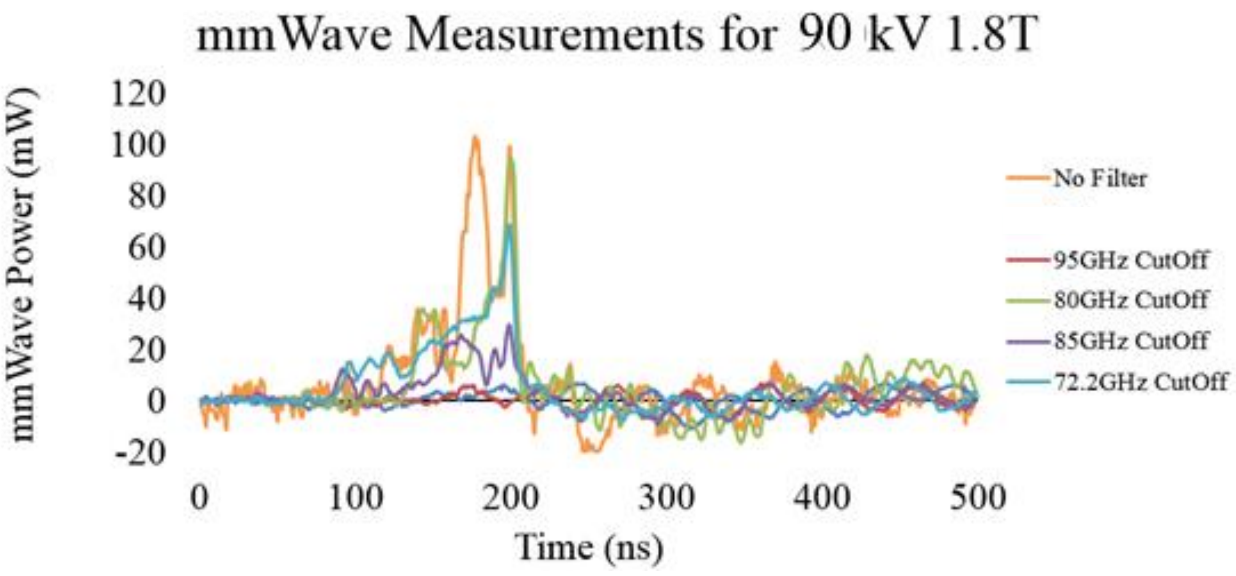
- Electron Beam
  - Accelerating voltage 90kV
  - Beam current, 100A
- Millimetre waves
  - Output power, ~50 kW
  - Frequency 83 GHz
  - Efficiency, ~0.5 %

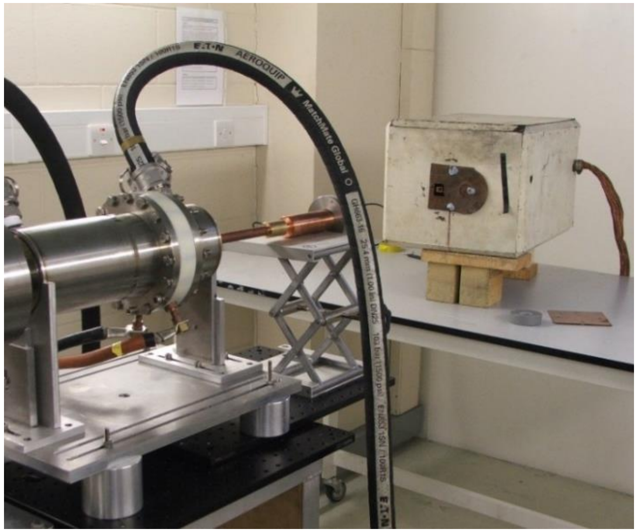
Measured Mode Pattern

Farfield mode pattern measured 60cm from output horn



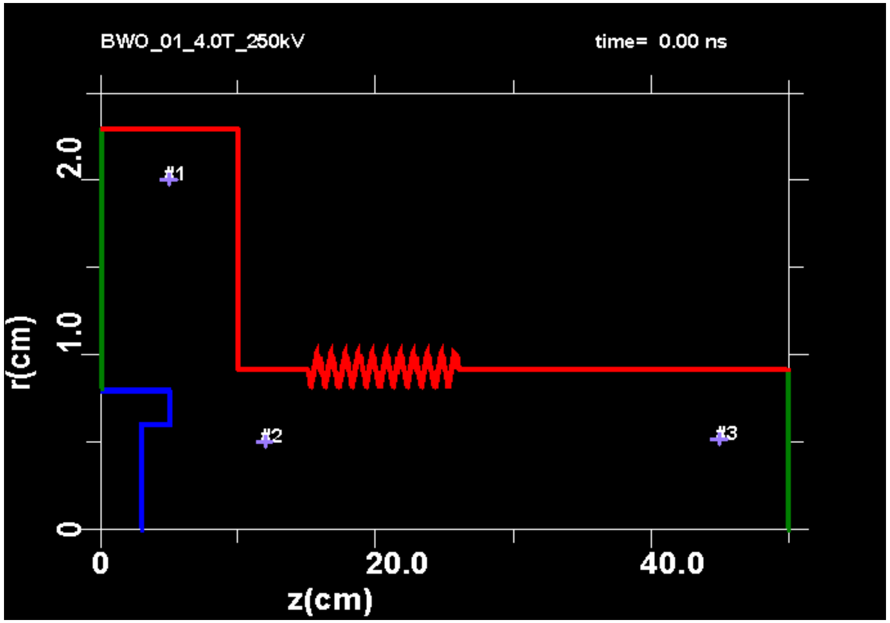
Millimetre Wave Measurements

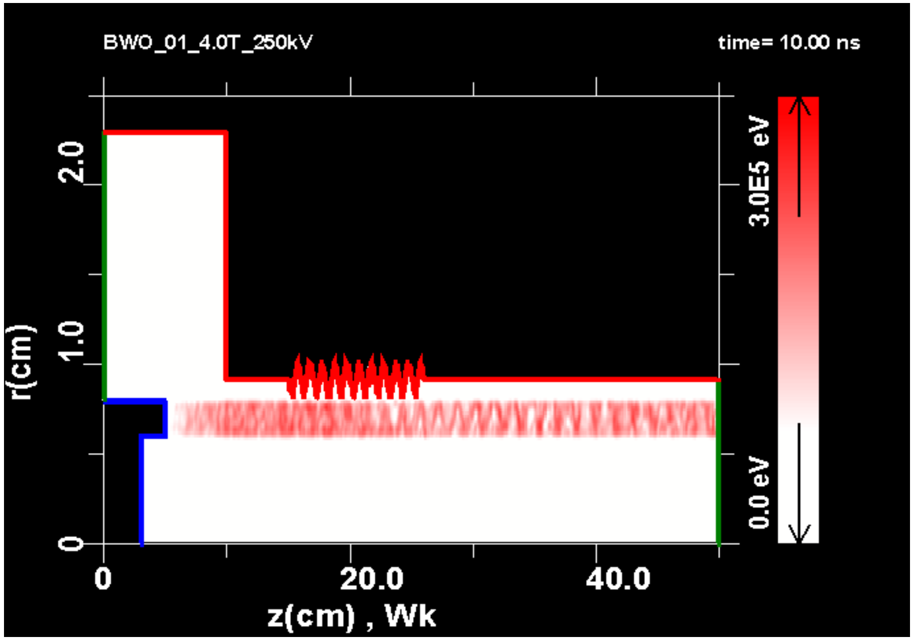




- Measured using W-band (75GHz-110GHz) rotary vane attenuator and W-band rectifying crystal detector
- Peak power measured by calibrated detector 60 cm from output horn. Integrate the power measured at detector over the mode pattern
  - Peak Power ~30kW +-10kW
- Frequency measured to be ~ 85GHz using high pass cut-off filters

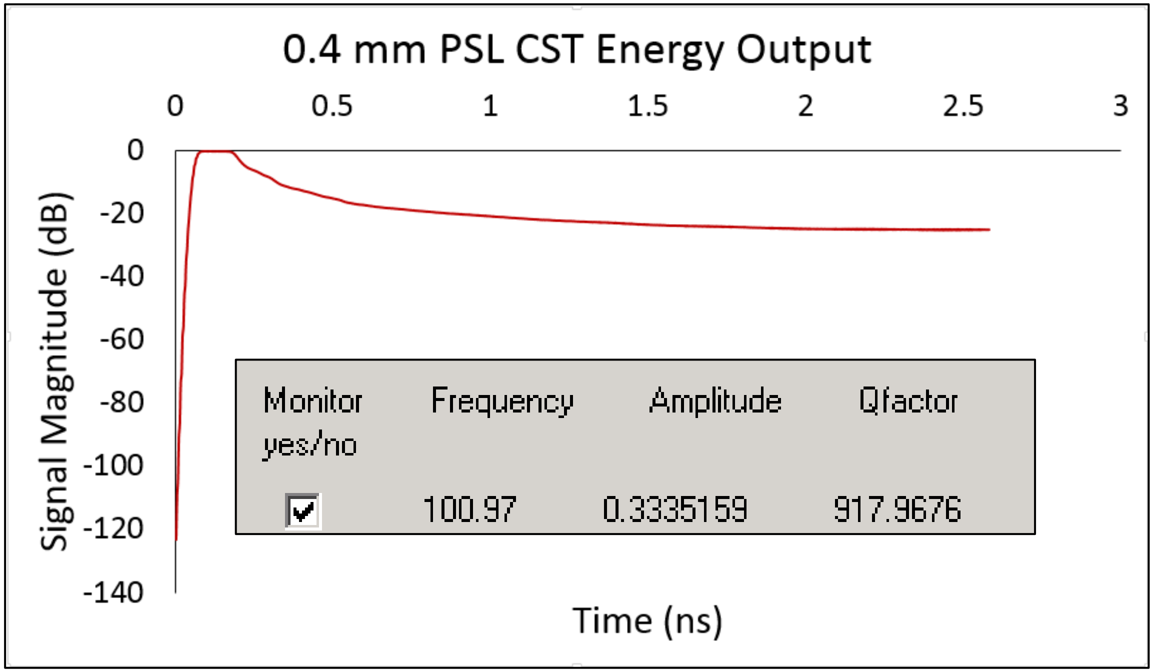
Work in Progress:-Electron Gun Design in KARAT



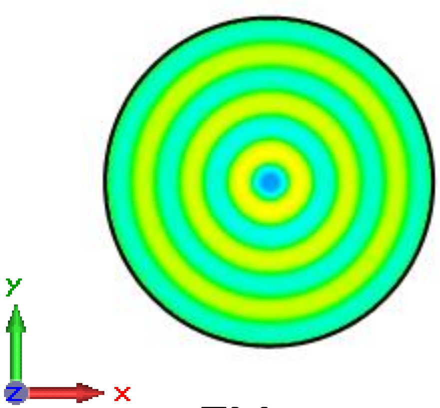


- Beam parameters:
  - Width 2 mm
  - Outer Diameter 16 mm
  - Inner Diameter 12mm
  - Current 100 A
  - Voltage 240 kV
- B-Field 4T

Work in Progress:- CST Microwave Studio Simulations

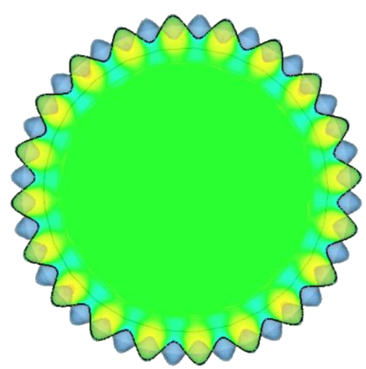


Mode Coupling



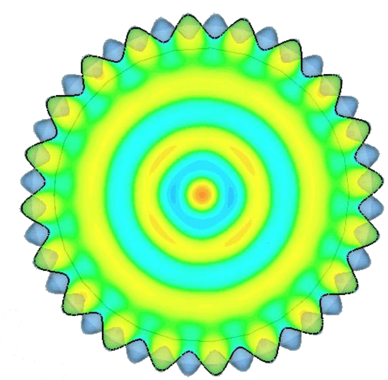
$TM_{0,7}$

+



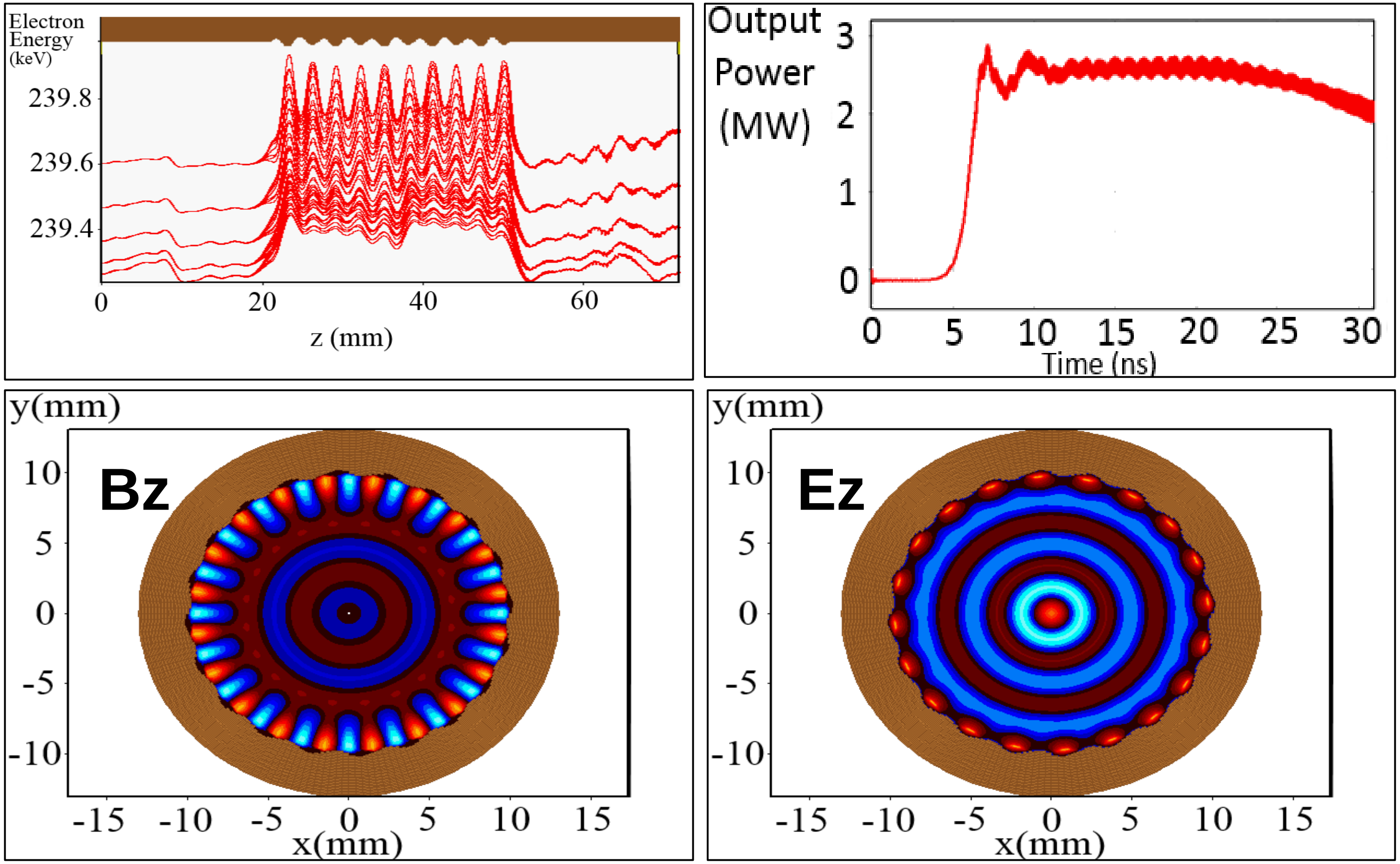
$HE_{20,1}$

=



Cavity Eigenmode

Work in Progress:- Beam/Wave Interaction in MAGIC 3D



- Beam parameters: Width 2mm, Outer Diameter 16mm, Inner diameter 12mm, Current 100 A, Voltage 240 kV
- B-Field 4T
- Microwave Output:
    - Frequency 100 GHz, Power ~2.5 MW, Efficiency ~10 %

Work in Progress:- Construction of W-band 2D PSL

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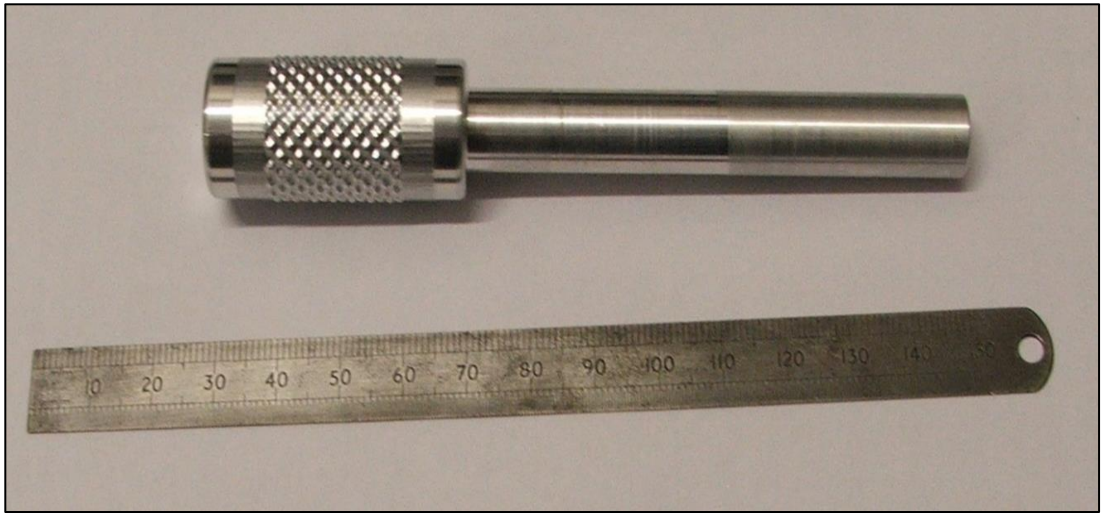
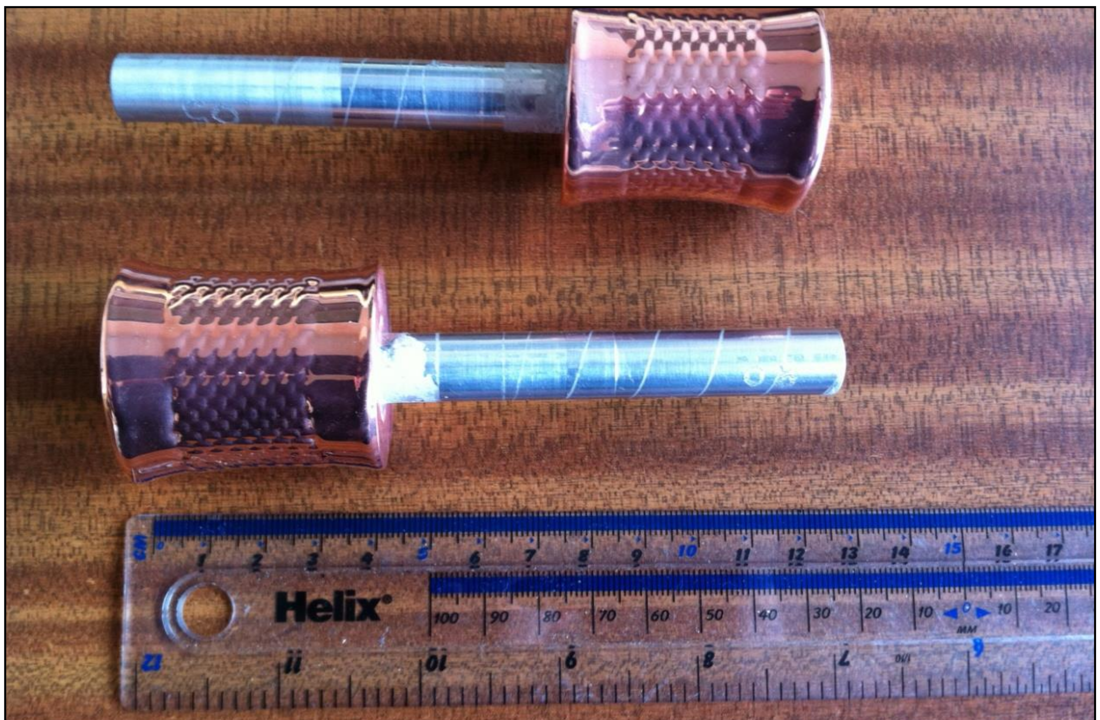
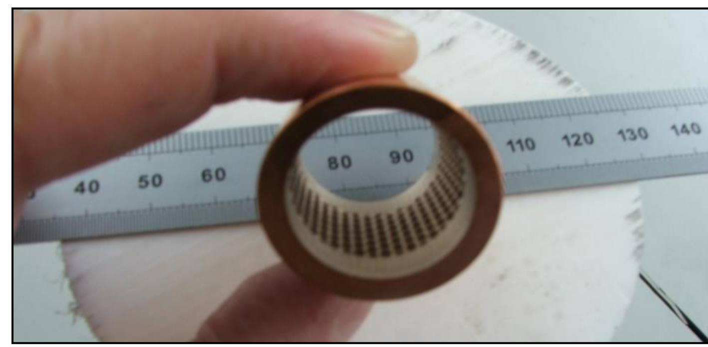




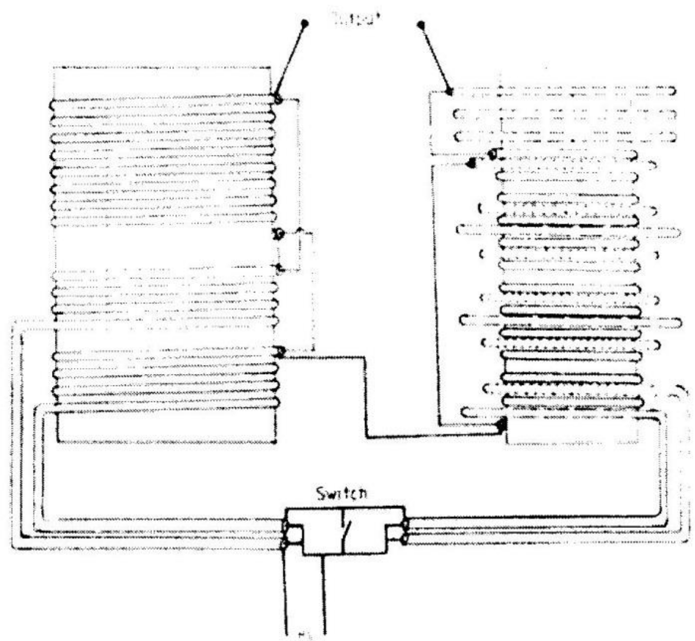
Parameters	
Unperturbed Radius	10 mm
Azimuthal Variations	20
Longitudinal Period	3 mm
Number of Periods	7
Perturbation Amplitude	0.4 mm



Work in Progress:- experiment to continue

- Investigate the effectiveness of the BWO beam\wave interaction at 100GHz with smaller depth corrugations using an annular (OD16mm, ID 12mm) electron beam, 100A, 240kV close to the wall of the 2D PSL
  - Simulations predict 2.5MW, 100GHz, 10% efficiency

- Superconducting magnet
  - B-field up to 9 T



- Double stacked cable Blumlein Generator
  - Voltage up to 300kV
  - Pulse duration 100ns

Current status

- ❑ Successful cavity formation within W-band 2D PSL structure observed
- ❑ Agreement between cavity measurements & numerical analysis
- ❑ Operating frequency and bandwidth dependent on perturbation amplitude and period of 2D PSL
- ❑ Determined range of design parameters for experimental W-band Backward Wave Oscillator
- ❑ BWO beam/wave interaction demonstrated using MAGIC 3D
  - Frequency 83 GHz, Power 50 kW and Efficiency 0.5%
- ❑ Construction completed of W-band BWO incorporating a 2D Periodic Surface Lattice: Electron gun, Solenoid, Vacuum envelope, HT power supply
- ❑ Experimental measurements
  - ❑ 90 kV, 100 A, 4 mm diameter annular electron beam
  - ❑ mm-wave pulses measured
    - ❑ Mode pattern consistent with coupling of volume field of $TM_{0,2}$ mode and surface field of $HE_{7,1}$ mode
    - ❑ Frequency ~85GHz
    - ❑ Peak power ~30kW+-10kW

Conclusion and Future Work

- Measure the frequency using an in-band mixer (Millitech MXP-10-R) and a local oscillator signal produced by a 95GHz Gunn diode (Millitech GDM-10-1013IR) with the resultant IF measured using a 20GHz deep memory digitising oscilloscope (Agilent DSX-X 92004A)
- Experiment to continue with optimisation of the electron beam source to produce a thin (2mm) annular electron beam that is close to the wall of the 2D periodic surface lattice
  - Simulations predict, 2.5MW, 100GHz and 10% efficiency
- Investigate the coupling of the volume and surface field at higher frequencies (140GHz to 220GHz) and (325GHz to 500GHz) using higher order modes in 2D PSL structures of the same diameter but with smaller periods

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University of Strathclyde – Satellite MURI Research Team
Collaborating in the Transformational Electromagnetics MURI

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