Electromagnetic Simulations of a Metamaterial Target for Applications in Particle Accelerators.

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Overview

1. Project Objectives.
2. Metamaterials.
3. Fabrication Facilities.
4. The Target.
5. Photon and Electron Beam Simulations.
6. Experimental Setup.
7. Future Work.

Project Objectives

1. Metamaterial's uses in Particle Accelerators.
   - Can any beam parameters be enhanced?

2. Bunch Length Monitor.
   - Femtosecond resolution.
     - FEL's capable of femtosecond → sub-femtosecond pulses.
   - Non-invasive.
     - Current methods with the required resolution destroy the beam during measurement.

3. Terahertz source.
   - Coherent.
   - Intense.
   - Tunable.
   - Range 0.8-1.5 THz.

Applications.

- Medical Imaging.
- Security.
- Manufacturing/Quality Testing.
- Spectroscopy.

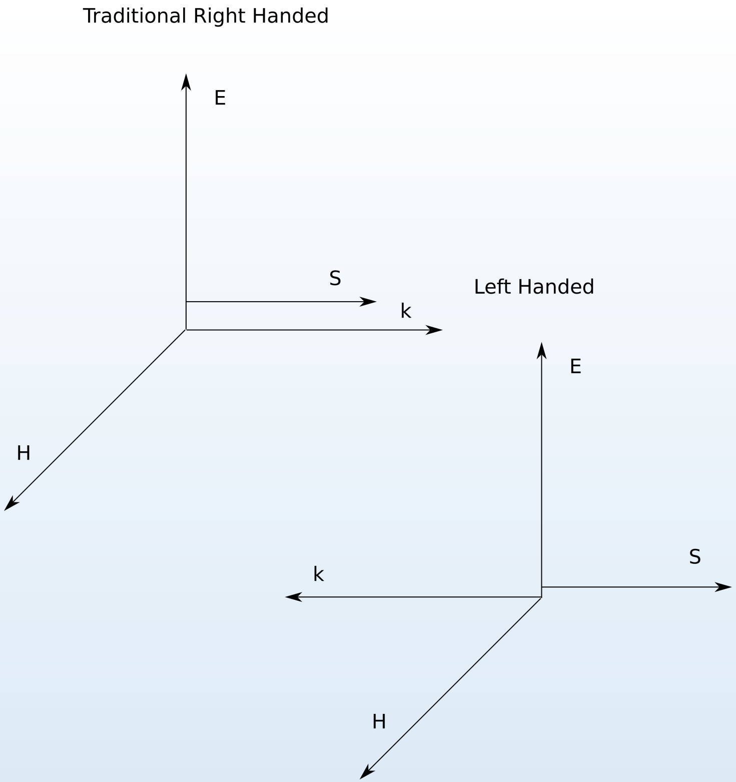
Current Technology.

- 0.1 → 1.5 THz Diodes, BWO.
- 2.5 THz – Quantum Cascade lasers.

Metamaterials

A manmade composite material that exhibits emergent properties that are not exhibited by its constituent materials.

Wave Propagation



- Poynting Vector not affected.
  $S = 1/2\ E\ x\ H$

Refractive Index

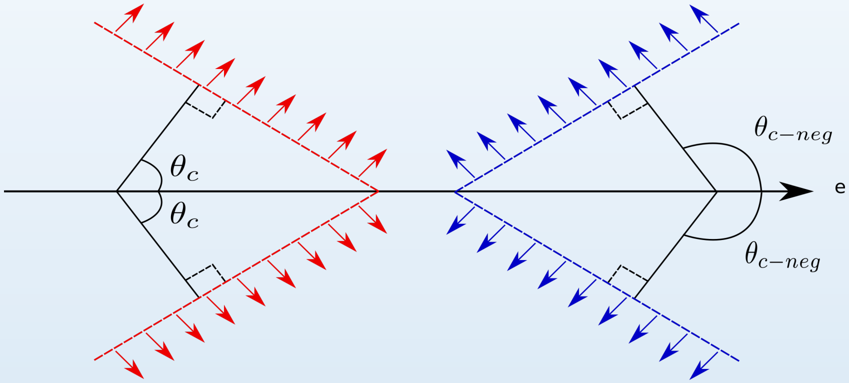
$$k\ x\ E = \omega\mu H$$

$$k\ x\ H = -\omega\epsilon E$$

$$n^2 = \epsilon\mu$$

ϵ & $\mu < 0 =>$ Negative Refraction

Cherenkov Angle



- Cherenkov Angle: $\theta_c = \cos^{-1}(1/\beta n)$

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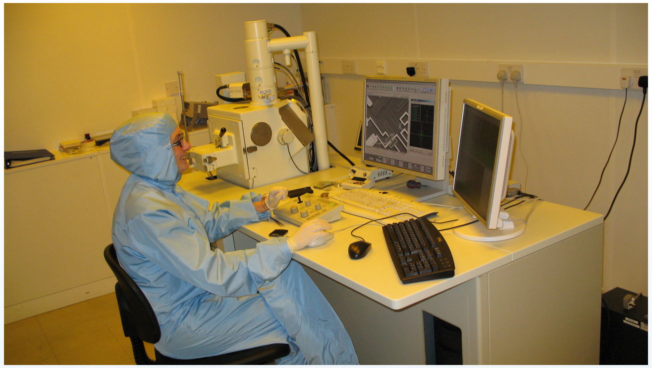
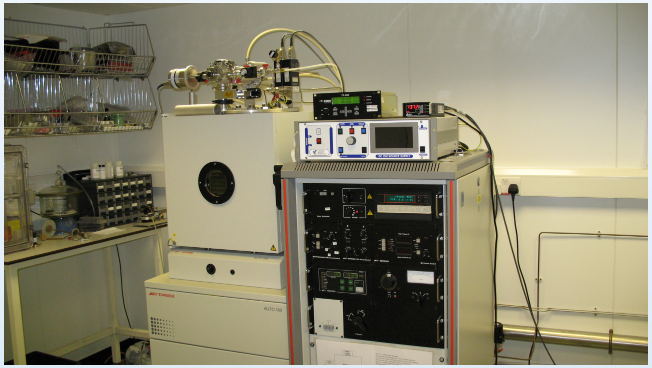
Fabrication Facilities

Royal Holloway Facilities.



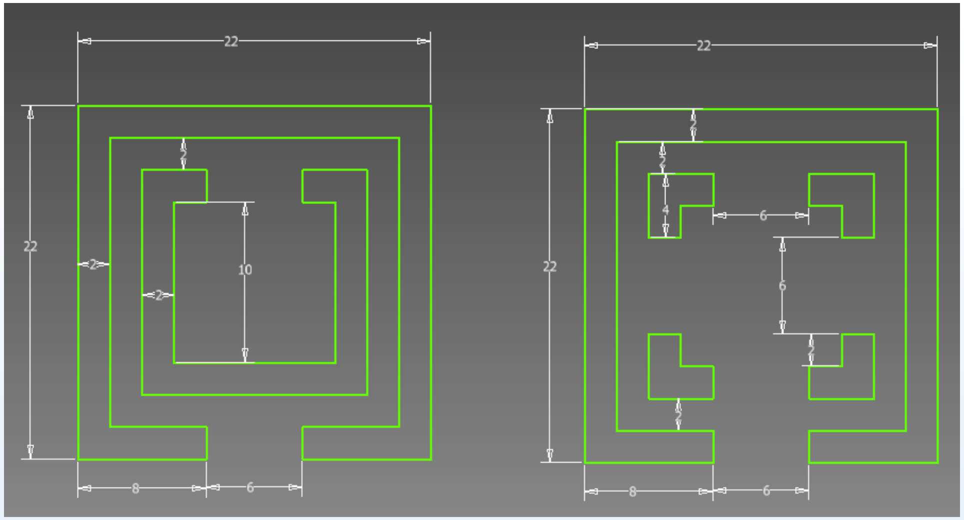


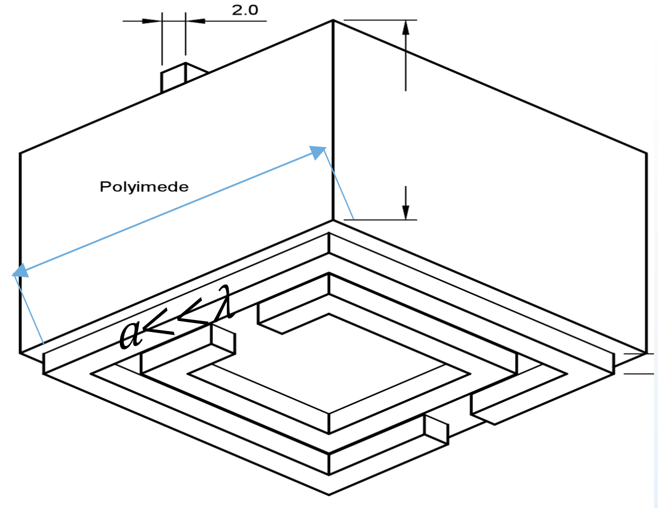
- ISO 7/ Class 10000 clean room.

The photolithographic requirement of $2\mu m$ between features determines and limits the unit cell dimension, which in turn determines the resonance frequency.

The Target

Uses design of Pendry et al. to create artificial Permittivity and Permeability. A split ring resonator (SRR) gives a negative permeability. The wire gives a negative permittivity.





Target Advantages:

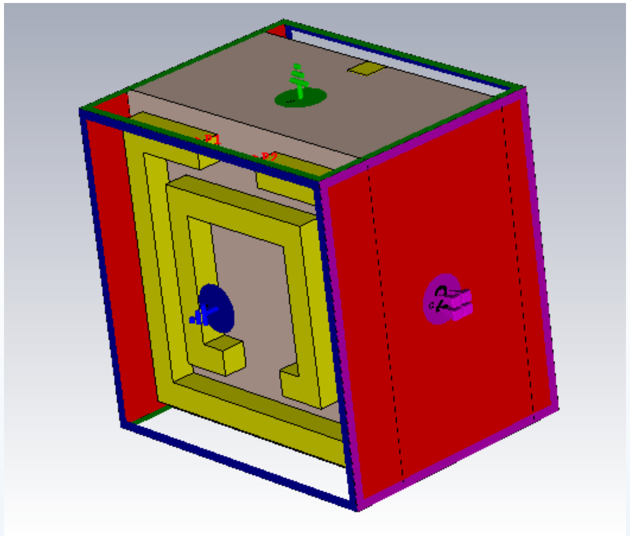
1. Extremely Tunable.
2. Can be fabricated using photolithography.

Condition for continuous media:

- $a<<\lambda$.
- 1THz = 300μm.
- a = 26μm.

Photon Beam Simulations

CST Microwave studio

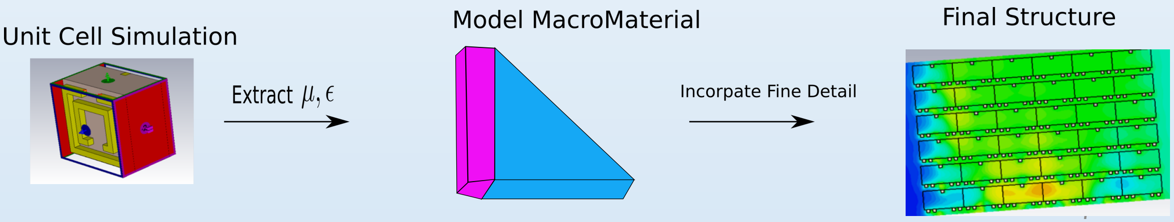


- Orientation of electric and magnetic field important.
- Optimum Meshing found by varying Cells per Minimum Wavelength (CMW) until S-Parameters do not change. 20 CWM.
- Calculate S- Parameters then convert to ϵ, μ, n.

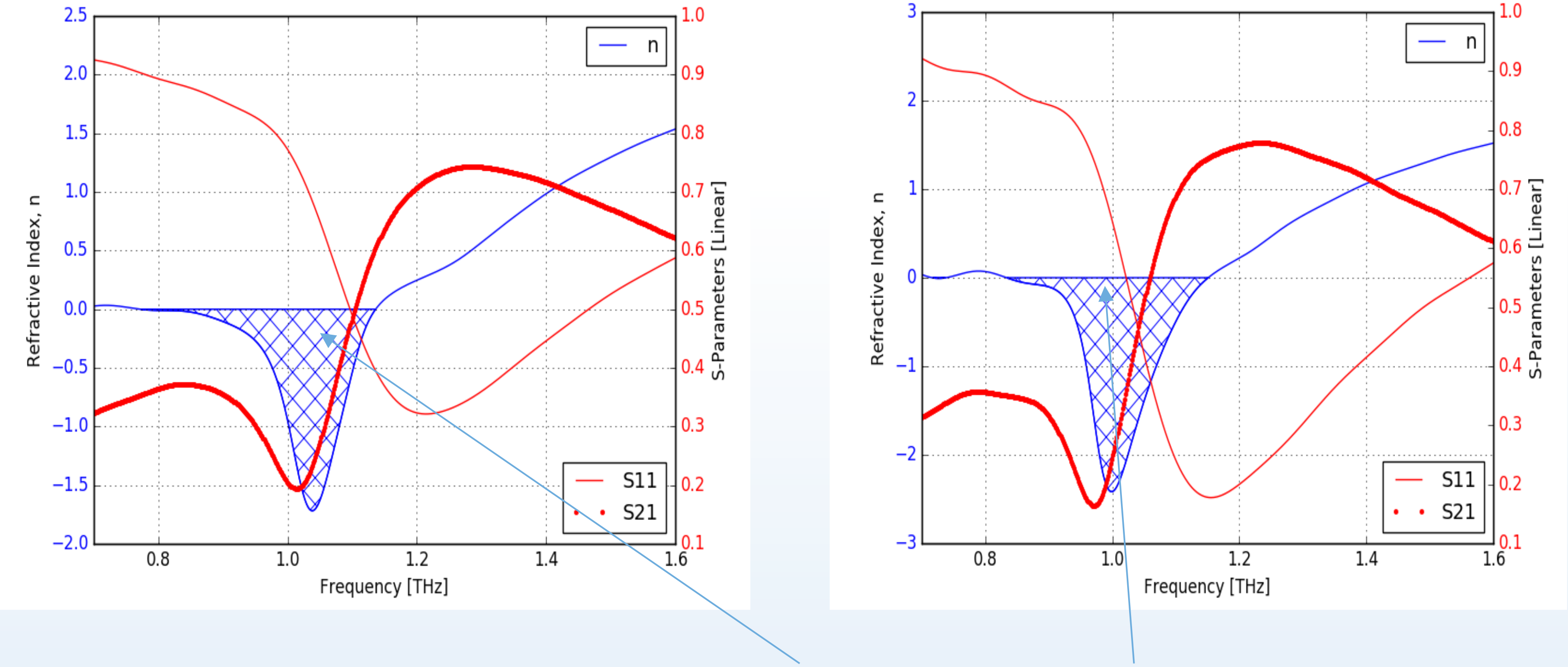
Boundary condition define photon field polarisation and unit cell dimension.

Color	Boundary Condition
Green	Electric ($E_T = 0$)
Blue	Magnetic ($H_T = 0$)
Pink/ Red	Open/Excitation Port

Calculation method



Photon Simulation Result



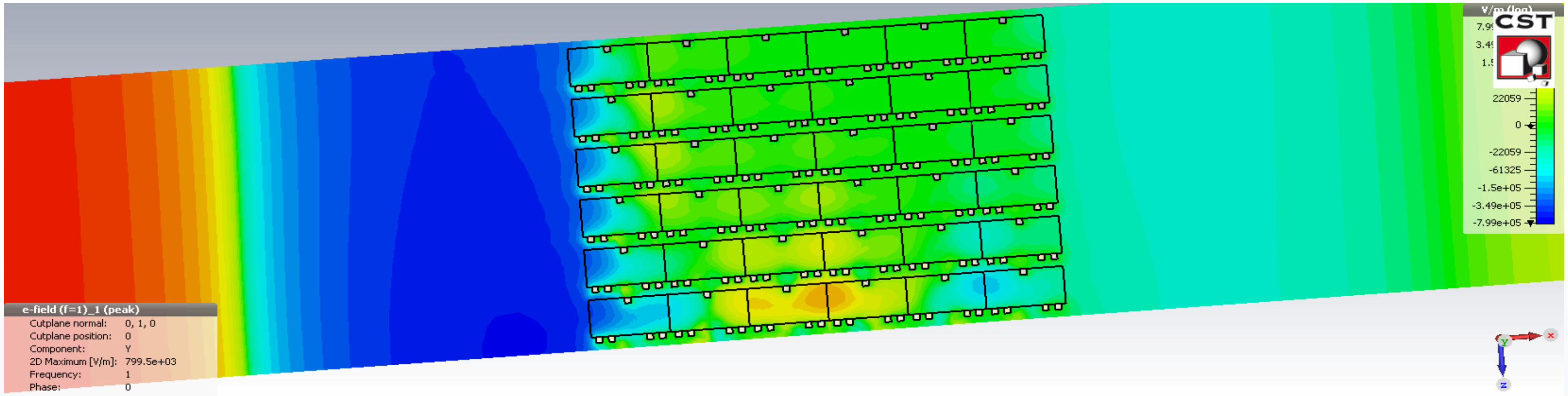
Region of negative refraction.

Material Parameter Extraction Method

Follows the method outlined in Phys Rev. E 70, 016608 (2004) by X. Chen et al. It offers a robust extraction method.

Phase Evolution Inside Bulk Material

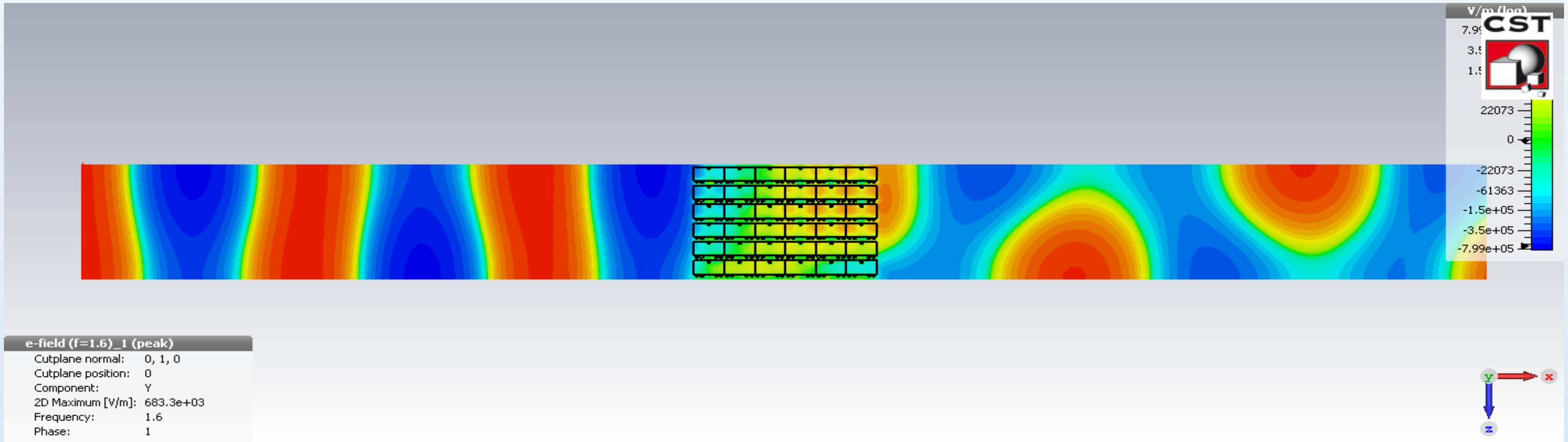
Phase Evolution at 1THz. n = -2.3



e-field (f=1)_1 (peak)

Cutplane normal: 0, 1, 0
Cutplane position: 0
Component: Y
2D Maximum [V/m]: 799.5e+03
Frequency: 1
Phase: 0

Phase Evolution at 1.6THz. n = 1.48

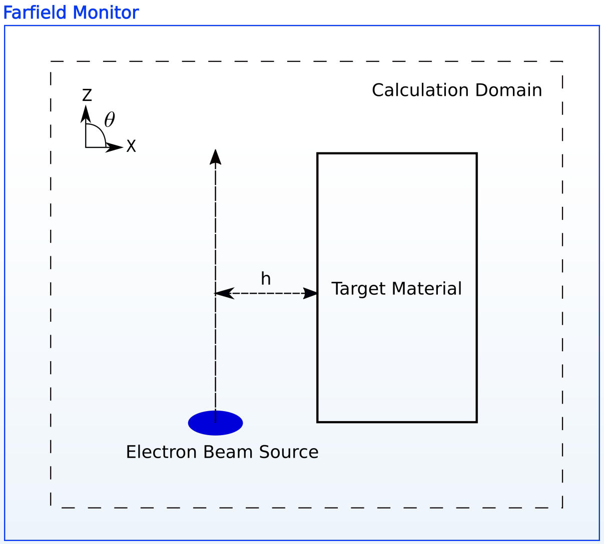


e-field (f=1.6)_1 (peak)

Cutplane normal: 0, 1, 0
Cutplane position: 0
Component: Y
2D Maximum [V/m]: 683.3e+03
Frequency: 1.6
Phase: 1

Electron Beam Simulations

Simulation Layout



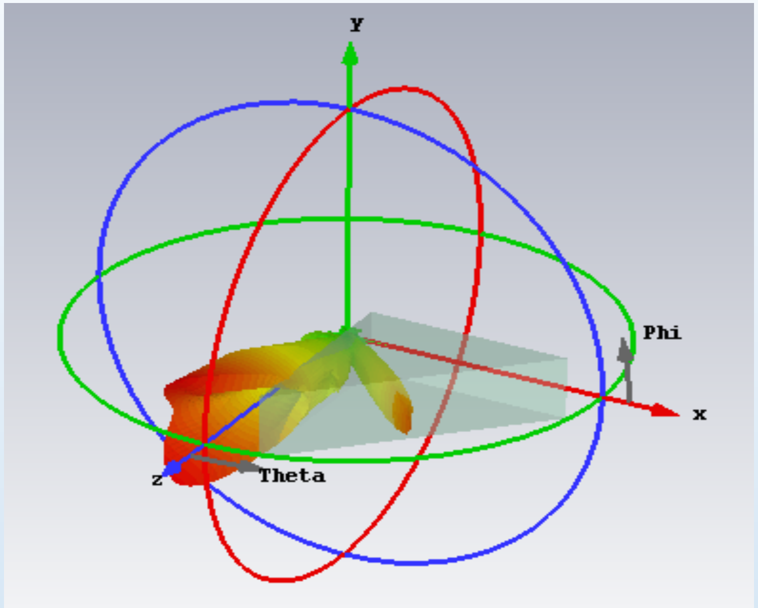
Coherency Condition:

- If $\sigma_z \ll \lambda$ then radiation is emitted coherently. Intensity proportional to N_e^2 .
- 100 fs = 3μm. Therefore, at 1THz coherent radiation.

Teflon Farfield $\gamma^2 \lambda < D$

Beam Parameters set to match CLARA facility.

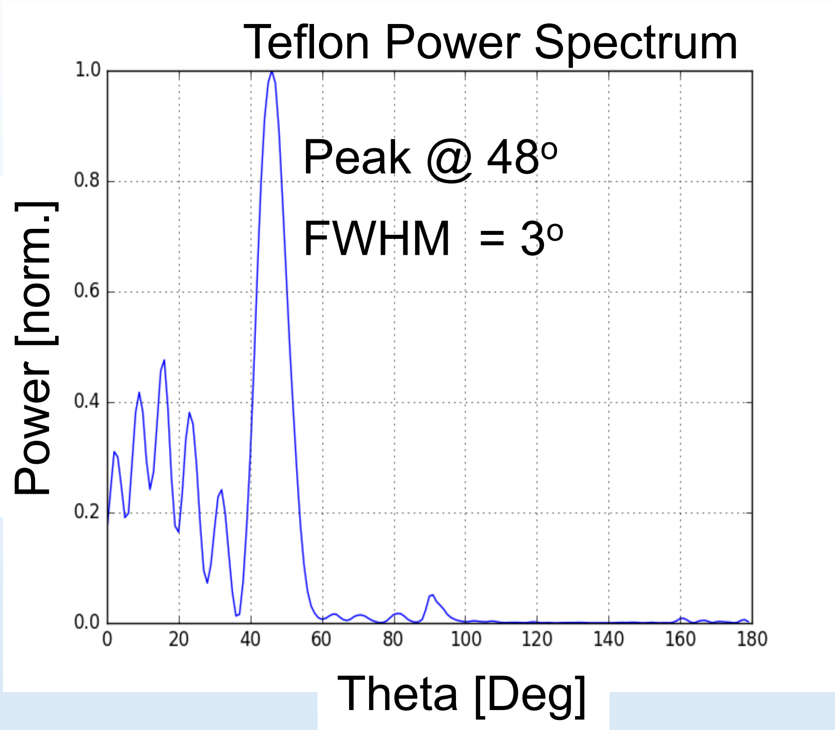
Parameter	Description	Value
h [mm]	Impact Parameter $(\gamma\lambda/2\pi)$	0.02
Target Dimension [mm]	(X,Y,Z)	3*3.16*3.41
Simulation Domain [mm]	(X,Y,Z)	10*10*10
Beam Energy [GeV]		50
Transverse Bunch [mm]		0.25
Longitudinal Bunch [fs]		10-100



Electron Simulation Results

Teflon Reference

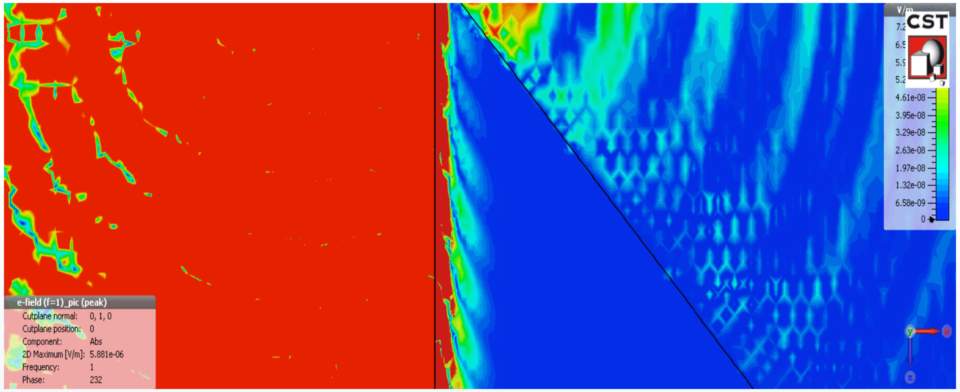
Teflon is taken as a reference as n is well defined. n = 1.44



Peak @ 48°

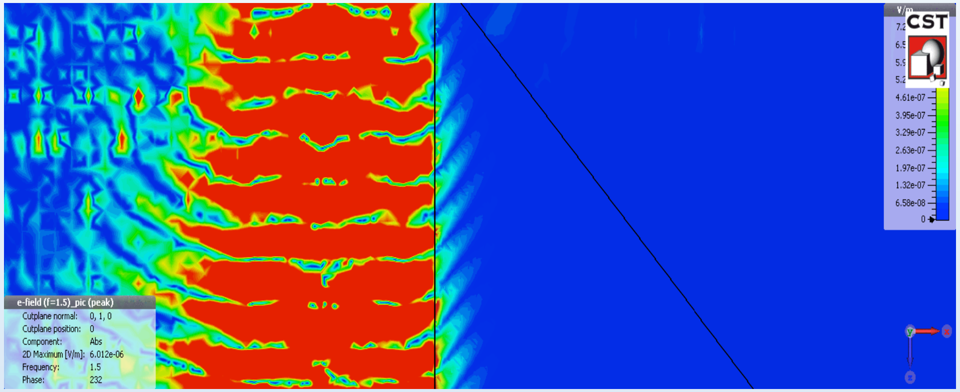
FWHM = 3°

Wave Front within the metamaterial target at 1THz



e-field (f=1)_pic (peak)
Cutplane normal: 0, 1, 0
Cutplane position: 0
Component: Abs
2D Maximum [V/m]: 5.881e-06
Frequency: 1
Phase: 232

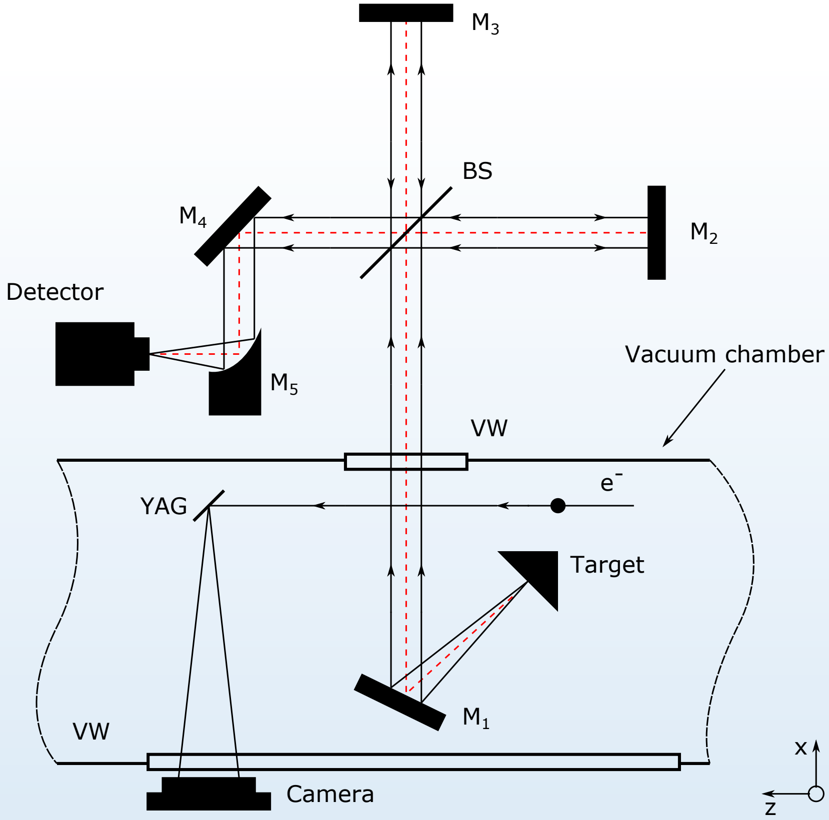
Wave Front within the Teflon target at 1THz



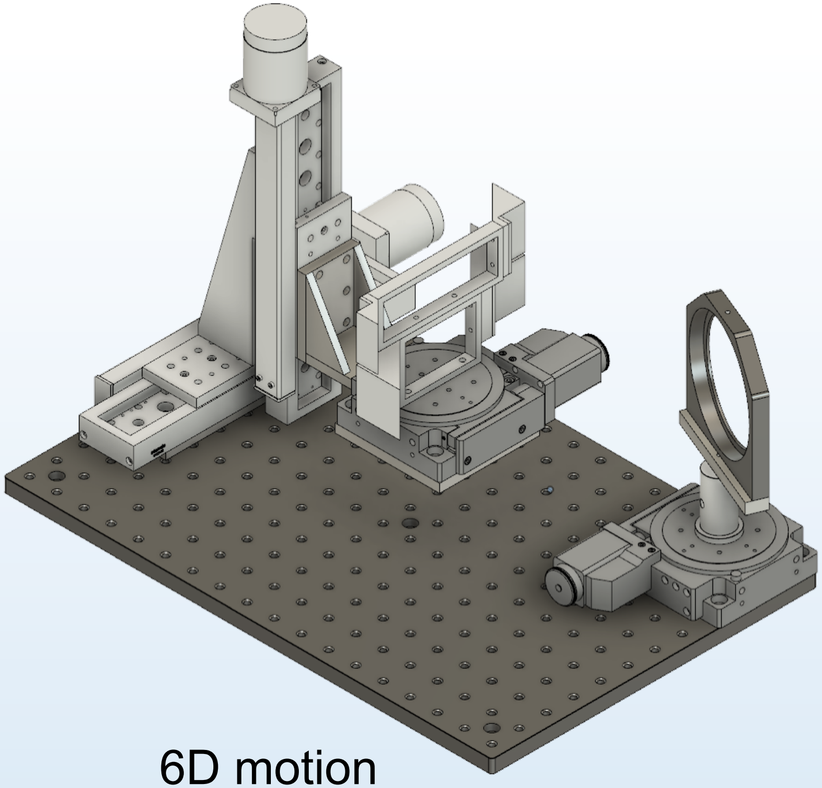
e-field (f=1.5)_pic (peak)
Cutplane normal: 0, 1, 0
Cutplane position: 0
Component: Abs
2D Maximum [V/m]: 6.012e-06
Frequency: 1.5
Phase: 232

Experimental Setup

Setup Schematic



Internal Vacuum Setup



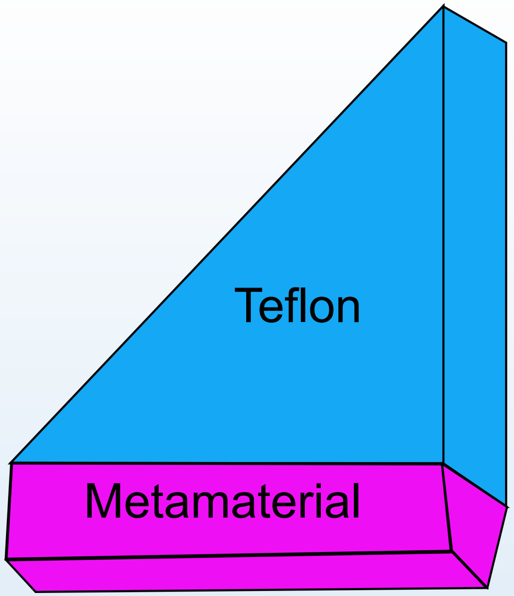
6D motion
Fully Vacuum compatible

Versatile setup to allow a full range of parameter sweeps

A Different Design

Typically metamaterial have large losses. Can they be reduced?

- Cherenkov radiation only generated up to skin depth. After material is just a medium for propagation.



How do we join Teflon to metamaterial?

How thick to make Metamaterial Layer?

<u>Advantages:</u>

1. Lower Manufacture Cost
2. Reduces Loses

The overall negative propagation is lost. However, Tunability and frequency is unchanged.

Future Work

- Further Electron Beam simulations with the added fine detail to account for not exact field alignment, and measure surface current.
- Simulate new design to see if it is a more viable idea. Cheaper and faster construction.
- Manufacture the target and test it using a THz laser to verify the simulation results.
- Manufacture a holder for the target that is compatible with current experimental setup.
- Test metamaterial and Teflon target at CLARA facility. Maybe more work on electronics need to be carried out for fast data acquisition.
- Outline a method for beam parameter extraction.
- Many more …..

Conclusions

1. A target that can be fabricated using electron lithography and emit radiation in the THz region has been developed and simulated.
2. An efficient method has been developed to simulate both the photon and electron beam interaction with the target using CST.
3. The backward wave propagation has been at least qualitatively verified.
4. A new design that will hopefully reduce the losses inherent with a totally metamaterial target has been proposed and further tests need to be carried out.
5. Experimental equipment and a DAQ program has been developed and tested at VELA facility and can be used for metamaterial tests.

Thank you for your attention.

May the channeling be with you!