Applications of Metamaterials for Particle Accelerators.

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Overview

1. Metamaterials.
2. Multibunch Resonance
3. Simulations
4. Unit and Bulk target design
5. Proposed Experiment

Metamaterials

What are they?

Man-made materials that can be engineered to have properties that do not appear in natural materials.

First theorised by Vasalago in 1959.

Reverse propagation:

$$\vec{k}\ x\ \vec{E} = \omega\mu\vec{H}$$

$$\vec{k}\ x\ \vec{H} = -\omega\epsilon\vec{E}$$

Negative Refraction:

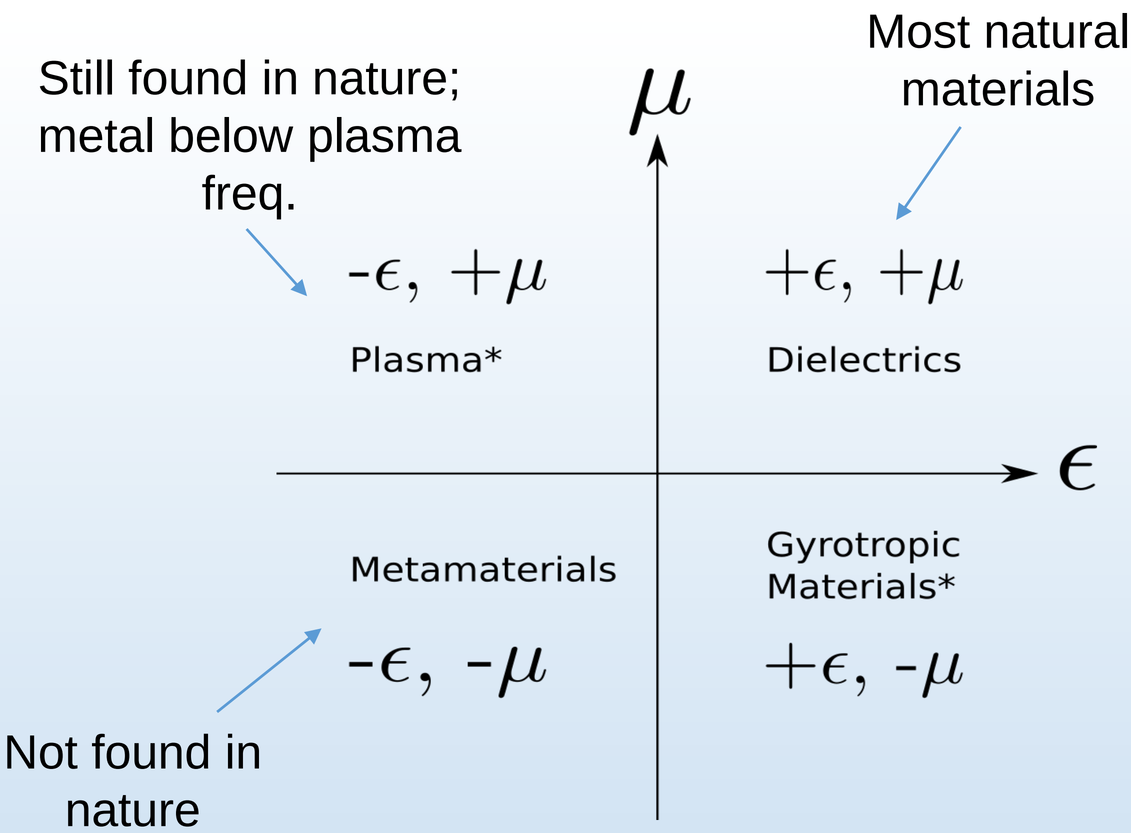
$$n^2 = \epsilon\mu$$

$\epsilon\ \&\ \mu < 0$ Neg Refraction

Momentum Check:

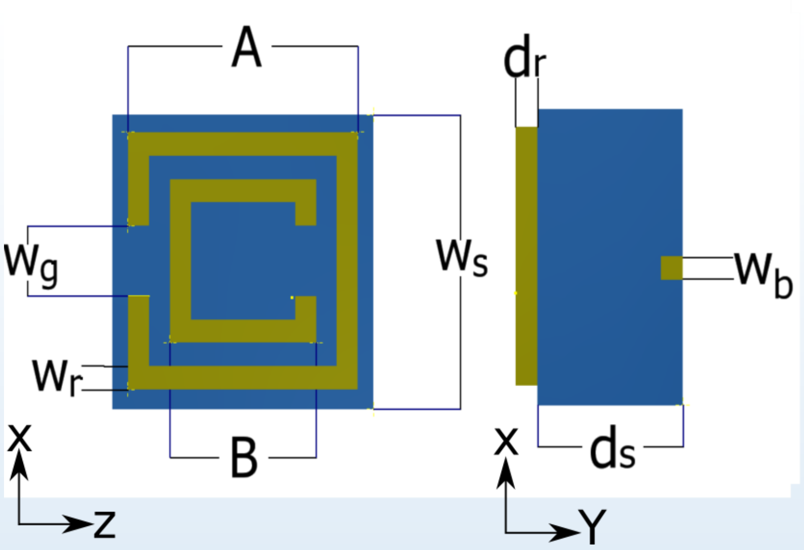
Poynting Vector unaffected:

$$S = \frac{1}{2}\ \vec{E}\ x\ \vec{H}$$



Designing a Metamaterial

Analogous to atomic material. If wavelength is larger than atomic spacing, the material is defined by μ , ϵ. If w_s is smaller than the wavelength can define effective μ_{eff} , ϵ_{eff}.



1. Using Lorentz model, that views atoms as resonators.

2. Rings work as LC resonance circuit. The metal provides inductance and the gap W_g provides a capacitance. Overall, resulting in a negative μ.

3. A network of wires works like an electric dipole providing a negative ϵ.

<u>Advantages</u>

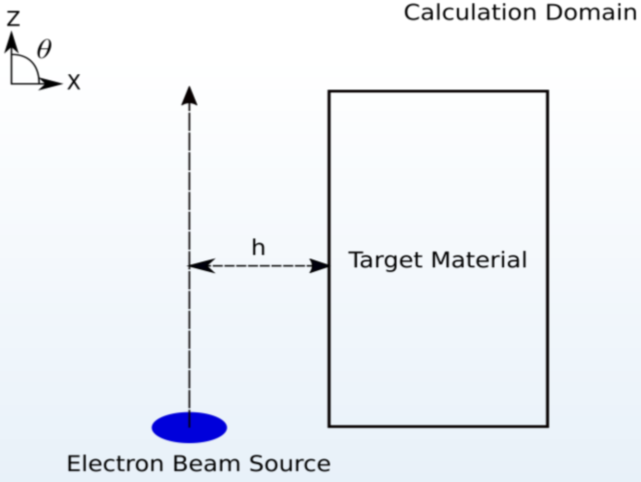
- Extremely tunable
- Negative refraction
- Pos better noise

<u>Disadvantages</u>

- Manufacturing
- Extremely Sensitive

Diagnostics – Cherenkov Radiation

To be used as a diagnostics tool ideally we want to be non invasive.

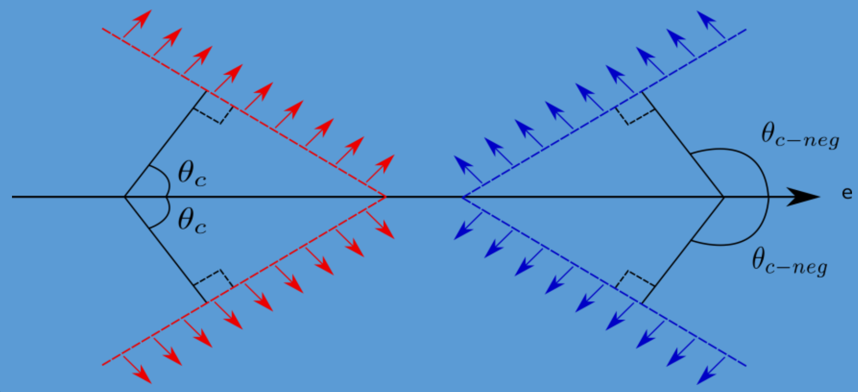


Beam doesn't have to pass through the material, it just has to be in the vicinity so that beam E-field can interact with target.

Cherenkov radiation

If the beam moves faster than speed of light In the material Cherenkov radiation is generated:

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



Multibunch Resonance

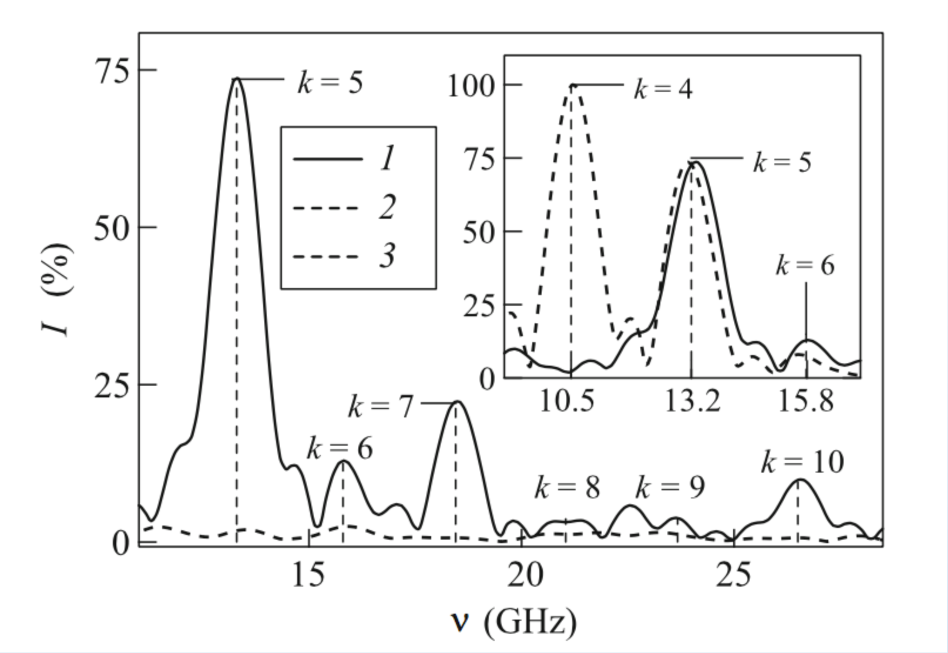
A single bunch of N_e electron will radiate power according to:

$$\frac{d^2W}{d\omega d\Omega} = \frac{d^2W_e}{d\omega d\Omega}\left(\underbrace{\boxed{N_e}}_{\text{Incoherent}} + \underbrace{\boxed{N_e(N_e}}_{\text{Coherent}} - 1)|f_z|^2\right)$$

If the radiation wavelength is larger than bunch length, σ_z, then power $\alpha\ N_e^2$ instead of N_e.

For a train of bunches, with bunch separation A, the coherent part of the spectrum is modified by a factor:

$$F_{Train} = \sin\left(\frac{N_b \omega A}{2c}\right) \Big/ \sin\left(\frac{\omega A}{2c}\right)$$



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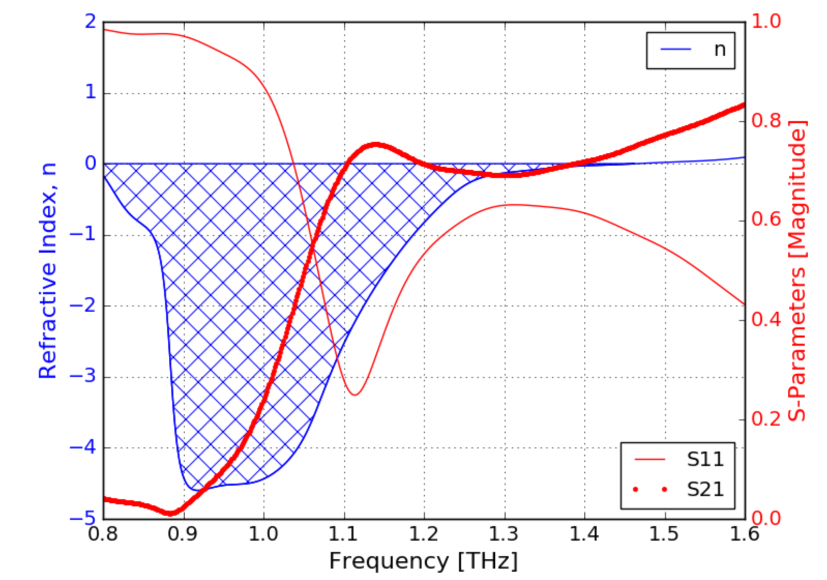
This extra factor gives rise to a series of harmonic peaks whose fundamental frequency is determined by the RF freqeuncy.

Target around 1THz

A target that will operate around 1THz has been designed and optimised using CST Microwave Studio.



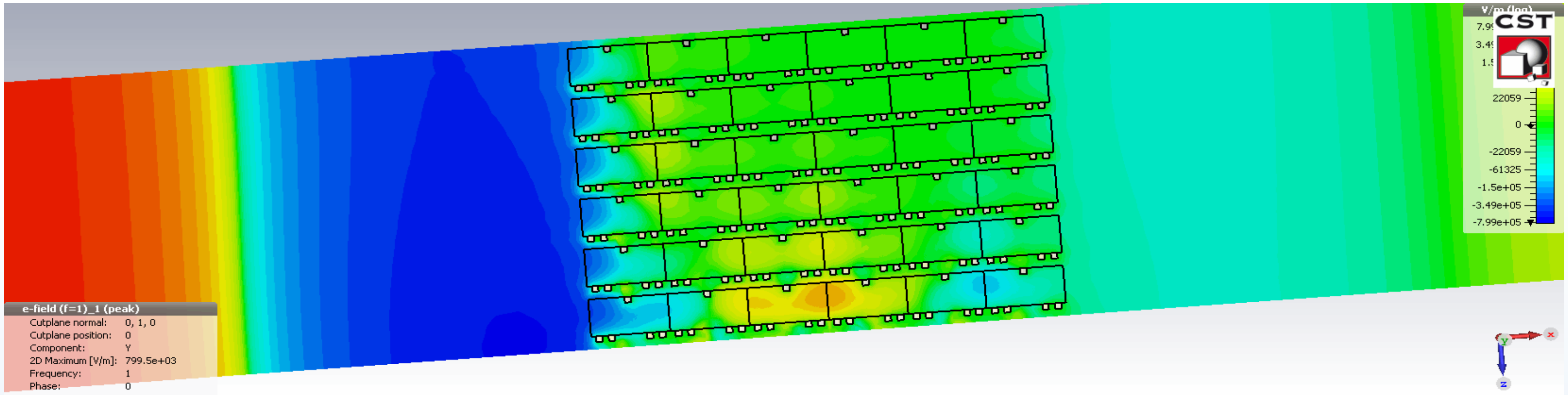
Parameter	Value (μm)	Description
A	22	Outer Ring Side
B	14	Inner Ring Side
d_s	20	Depth of Substrate
d_r	2	Depth of Rings
w_b	2	Width of Bar
w_r	2	Width of Rings
w_g	6	Width of gap
w_s	24	Width of Substrate
s_l	2	Bulk Layer Spacing

The grey area represents the range of frequency over which the refractive index is negative. The red points show the values of the minimum refractive index. The blue points represent the value of frequency at which the minimum refractive index occurs.

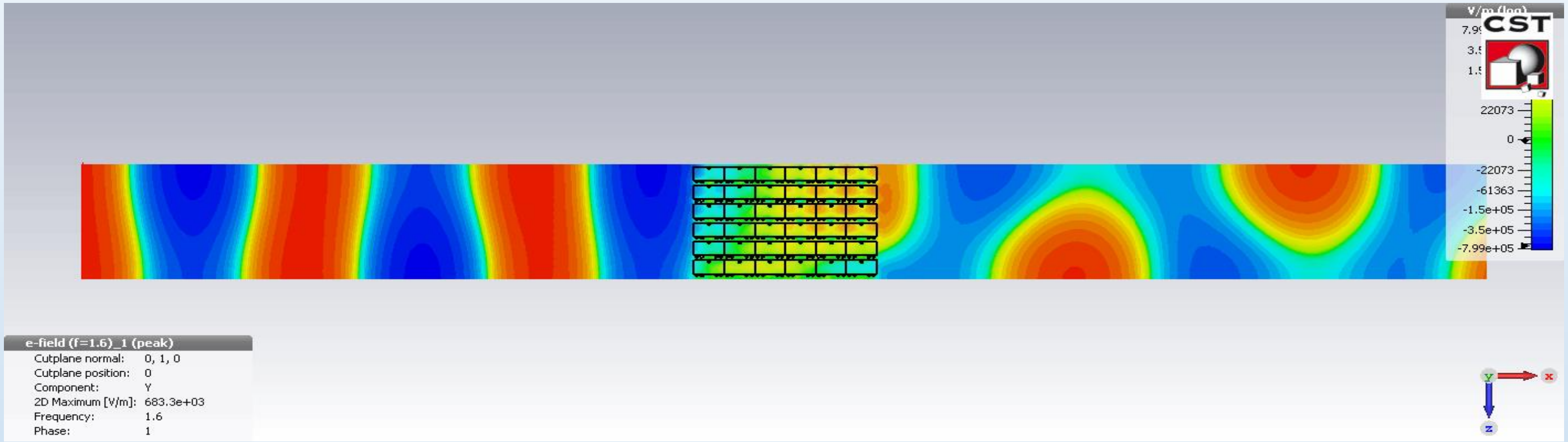
Optimise unit cell to have:
1. Negative refractive index in the 1THz region.
2. Greater than 50% transmission through the target.
3. Bulk target to avoid total internal reflection.

Reverse Propagation

Phase Evolution at 1THz. n = -2.3



Phase Evolution at 1.6THz. n = 1.48



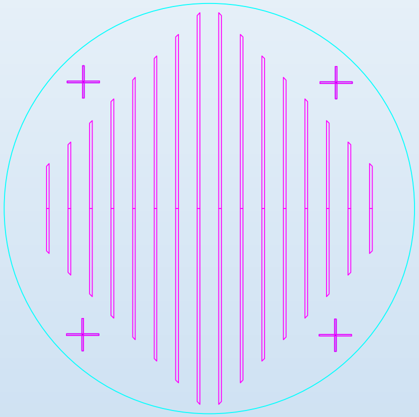
Lower Frequency Target

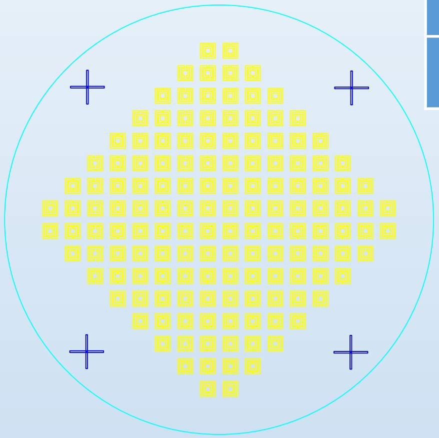
The detector response and the manufacture is much easier for a lower frequency as the dimension of the structures is larger. Therefore, we would like to do a proof of principle first at lower frequency.

Manufacturing

- A mask is created from 50um thick stainless steel with the pattern laser cut.
- 100nm of conducting metal is then deposited onto Si wafer
- The wafer is cracked and layers can be aligned.

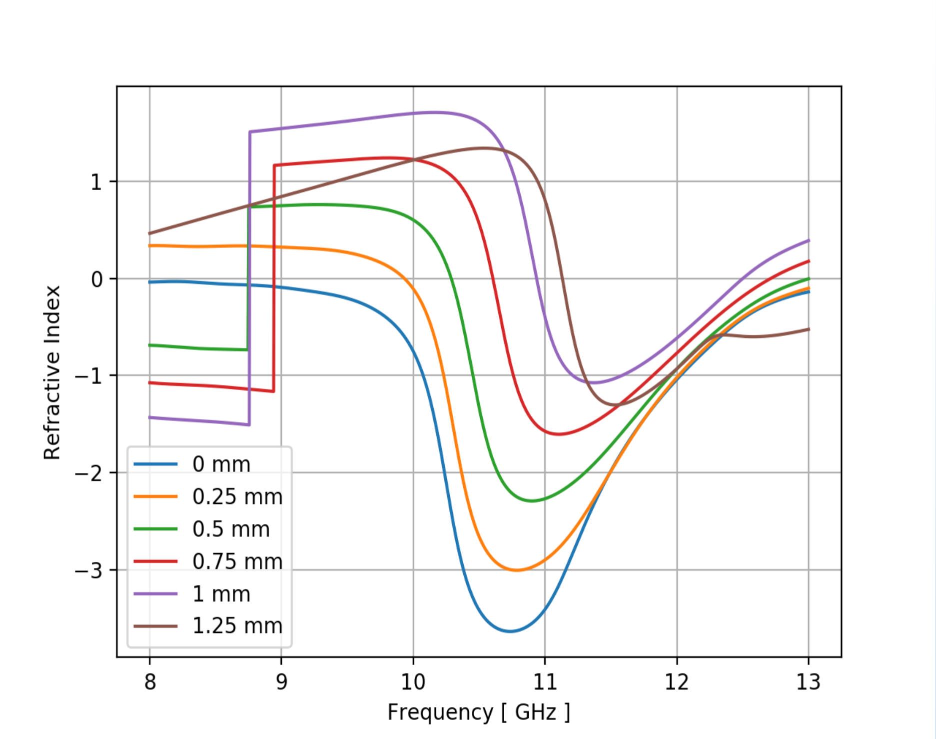
Parameter	Value (mm)	Description
A	2.64	Outer Ring Side
B	1.50	Inner Ring Side
d_s	0.4	Depth of Substrate
d_r	0.001	Depth of Rings
w_b	0.25	Width of Bar
w_r	0.5	Width of Rings
w_g	0.25	Width of gap
w_s	3.5	Width of Substrate
s_l	4.8	Bulk Layer Spacing





Ring – Bar Alignment

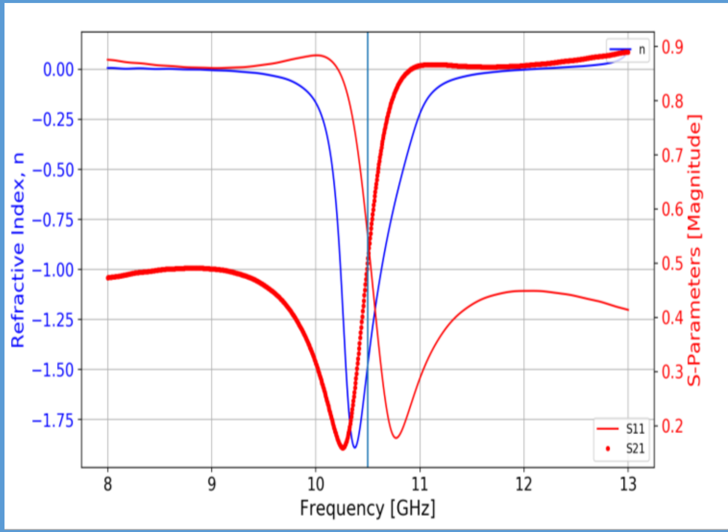
We were interested to see how much of an effect the alignment between the pattern on the front and back of the wafer has on the refractive index!



- 0mm is when the center of the bar is perfectly aligned with the center of the rings.
- This effect may not seem very large, however, the wafer is not see through and we have no infrared aligner.
- Solution! – Each wafer is drilled using the alignment marks on the masks to get the best possible alignment.

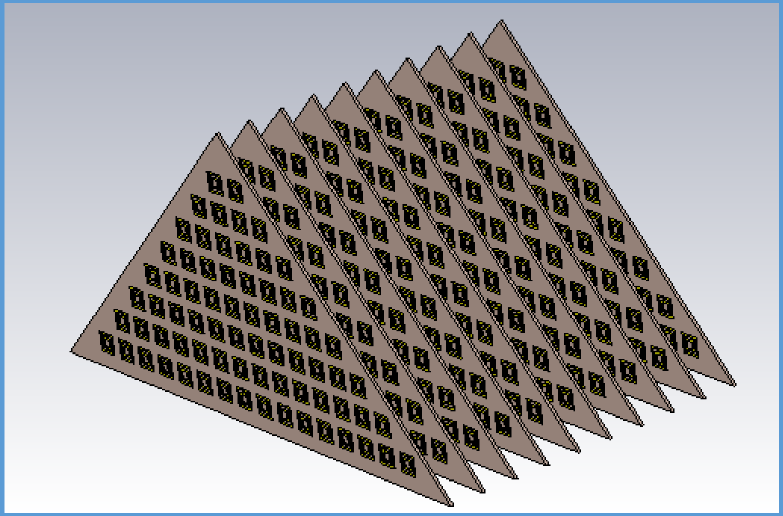
Final Design Result

Final unit cell plot



- The lines represent the same as the previous plot.
- For n >-1, there will be no Cherenkov radiation as it is unphysical.

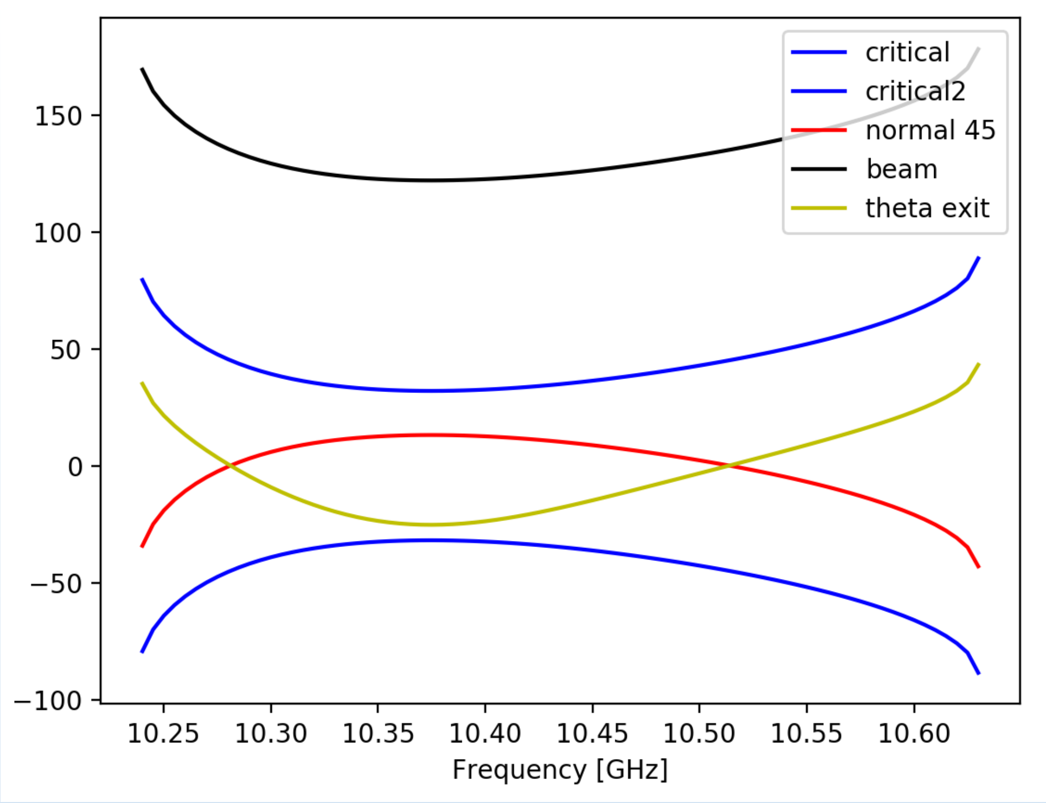
Bulk Structure



The unit cell are then arranged into a a prism shape target. The length along the beam line must be larger than the wavelength to avoid it just being a diffraction target.

Bulk Target angle

To ensure that Total Internal Reflection (TIR) does not occur at the boundary of the bulk target, we used the refractive index spectrum on the previous slide along with Snell's law, which still holds for metamaterials, to calculate the critical angle and the actual angle.



Snell's Law:

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

Critical Angle:

$$\theta_{critical} = \sin^{-1}\frac{n_1}{n_2}$$

Blue curves show critical angle. The red curve must be neither above nor below to not get TIR. The black curve shows the Cherenkov angle with respect to the forward direction.

CLEAR Experiment

For example, the CLEAR facility if a 150ns long train with 225 bunches per train, has a 666ps bunch spacing, the first harmonic will be around 1.5 GHz. The 7th harmonic would then be around 10.5 GHz, the same as the 4th harmonic for the Tomsk Micron configuration.

We would like to test the feasibility of using the metamaterial to select a certain frequency band within the spectrum. Although not a THz, could be modified if initial experiment proves theory.

- The measurement that we would like to carry out can be carried out in air.
- Collect radiation with horn antenna and analyse with spectrum analyser or Michelson interferometer
- To get signal from tunnel, maybe a cable that transmits around 10.5 GHz?, or we can down mix the signal if easier.
- Compare to Teflon target of the same dimensions.
- Has many potential application; filter, bunch length monitor, arrival time.

Conclusions

- Metamaterials offer advantages compared to traditional materials due to there tunability and reverse wave propagation. However, they can be difficult to manufacture and high precision required
- A metamaterial target can be used in a non-destructive manner as a diagnostics tool.
- A negative refractive index leads to a reversed Cherenkov angle which may reduce noise on a signal.
- There are many FUN things that we would like to try; maybe having each layer a slightly different response to see if we can get an overall broadband response, or try different designs to get a more narrow band response or try 3D printing the pattern onto the wafer.