Metamaterials and dispersion engineering for accelerators

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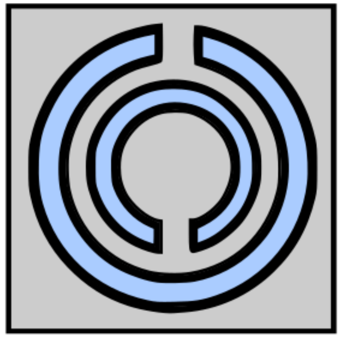
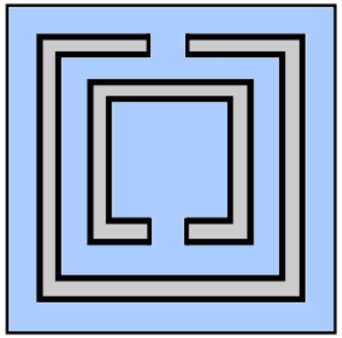
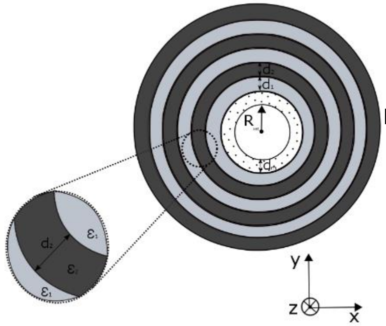
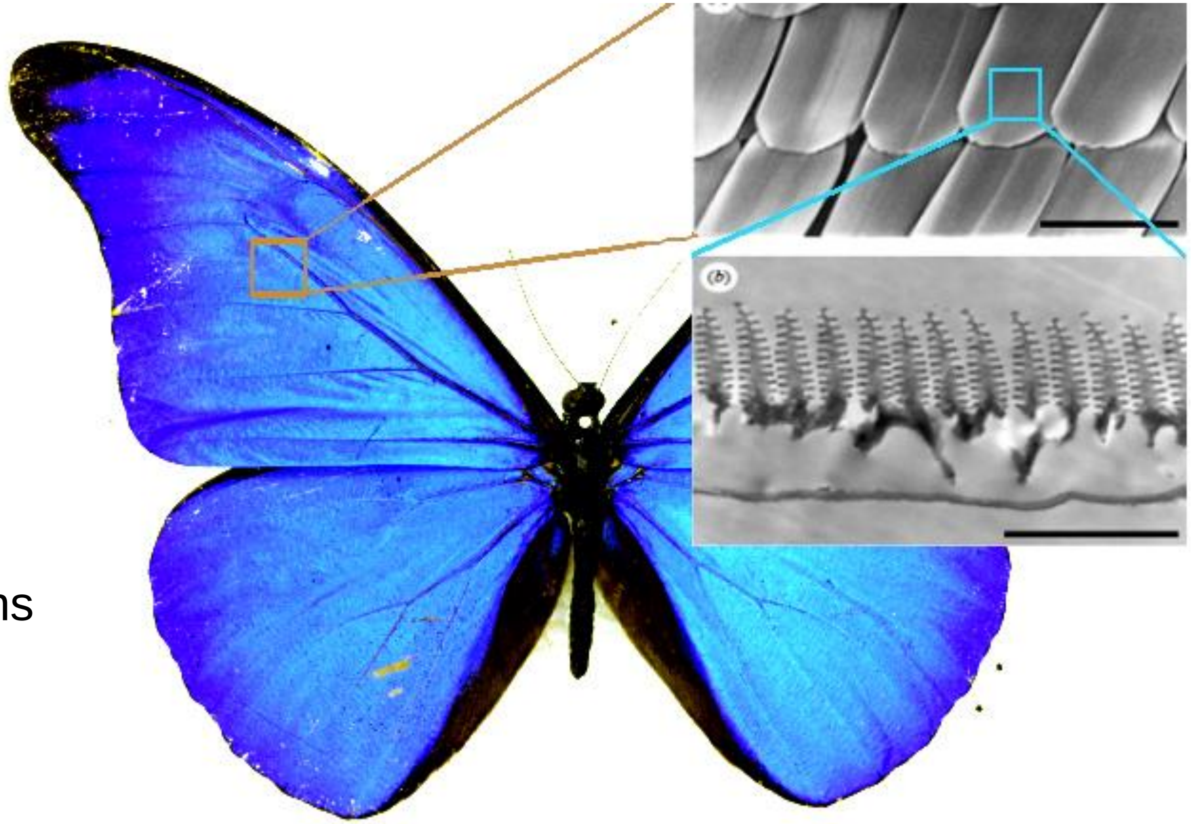
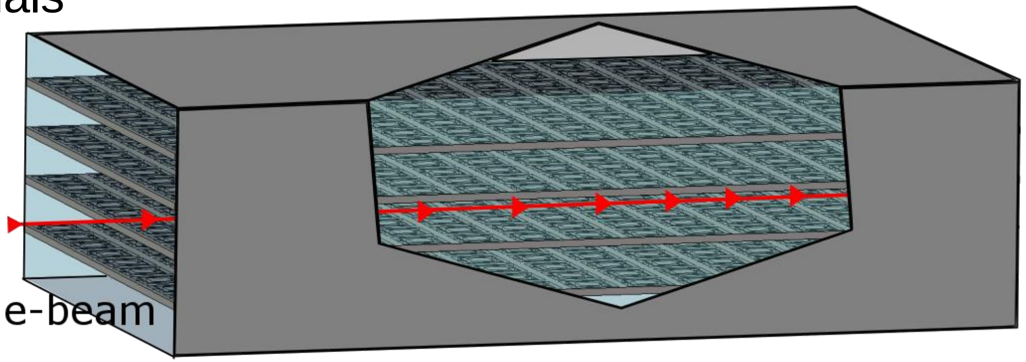
Presenting work done at the Cockcroft institute and Lancaster University

2nd workshop on Microwave Cavities and Detectors for Axion research

Talk outline

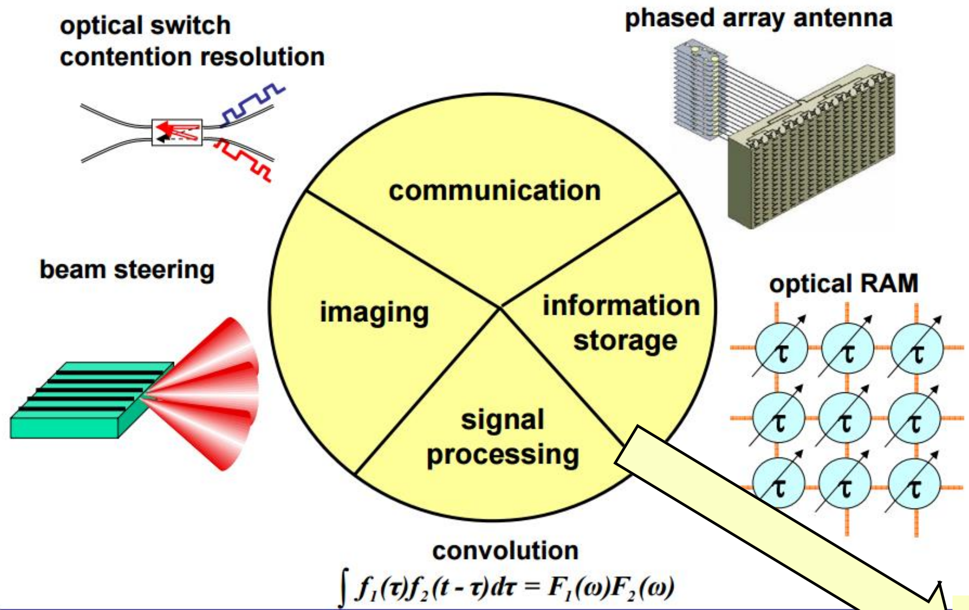
- Dispersion engineering
  - What is dispersion engineering
    - Applications in accelerators
- New Plasmonic materials
  - What are new plasmonic materials
- Introduction to metamaterials
  - Basic principles
    - Common forms
      - Unique effects
        - Interesting applications
- Metamaterials in accelerators
  - Existing schemes
    - Challenges and drawbacks
      - New plasmonics and metamaterials
- The CSRR loaded waveguide
  - Design considerations
    - Wakefield analysis
      - Particle in cell simulations
- Summary

Dispersion Engineering

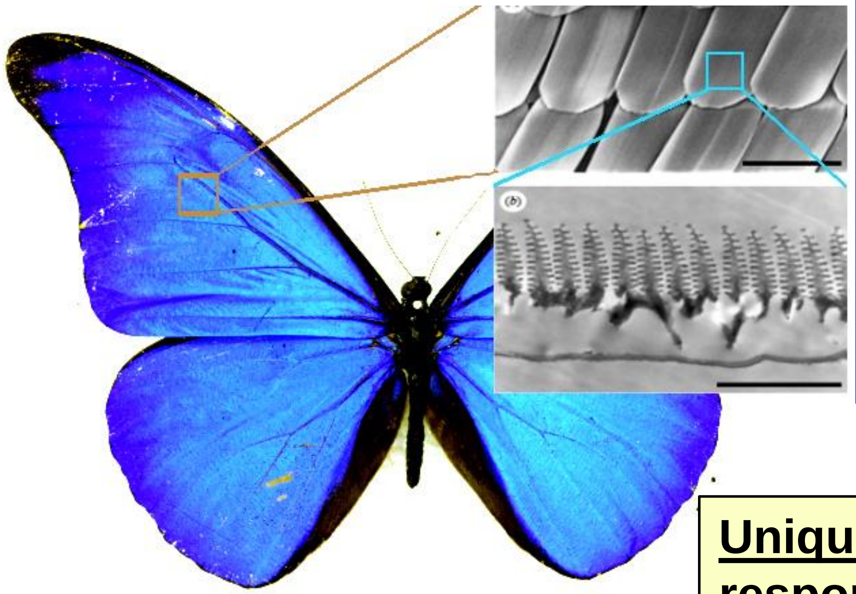
"Controlling the dispersion of a material to control the group velocity of radiation in that medium"

Applications of slow light

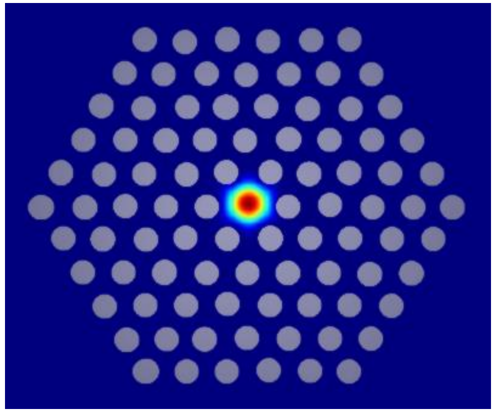


EECS 598-002 Nanophotonics and Nanoscale Fabrication by P.C.Ku

Accelerators!



FAU university physics soft matter http://www.theorie1.physik.uni-erlangen.de/gerd/teaching/2013-softmat-seminar/2013-softmatter-seminar.html



Unique electromagnetic response
Epsilon near zero
Negative index effects

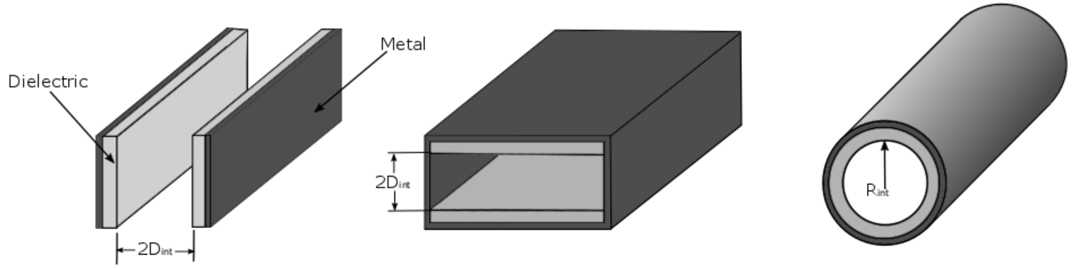
Wavelength scale:
Bragg gratings and Photonic crystals.
Pros: Simple fabrication and robust.
Cons: Frequency limitations and a limited range of responses.

VS

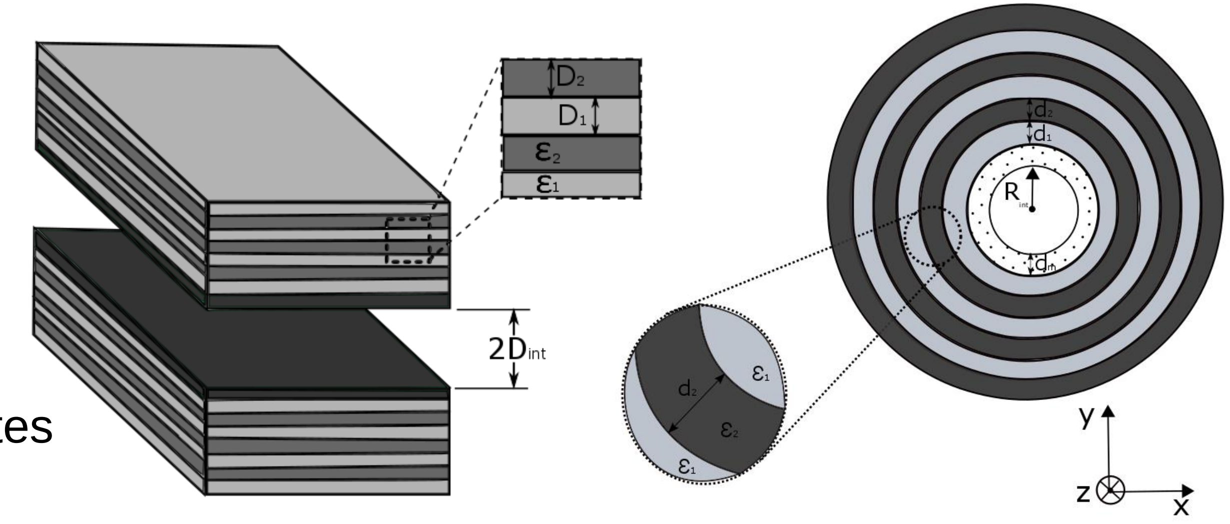
Subwavelength scale:
Metamaterials
Pros: greater control over the permittivity and permeability, more unique responses.
Cons: Hard to fabricate, susceptible to damage, power limitations

Dispersion Engineering in accelerators

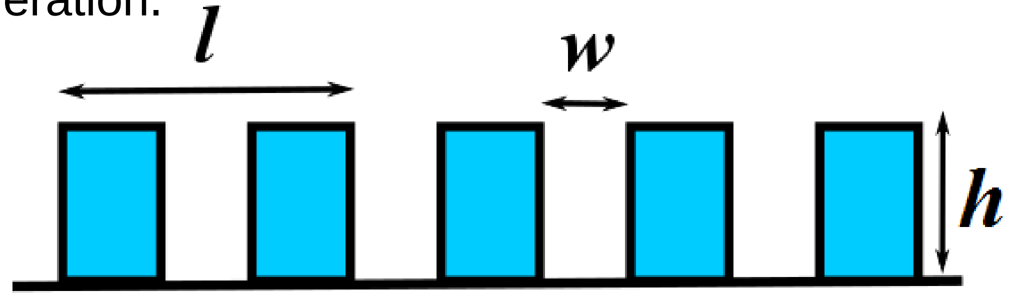
Dielectric lined waveguides



Dielectric Bragg waveguides

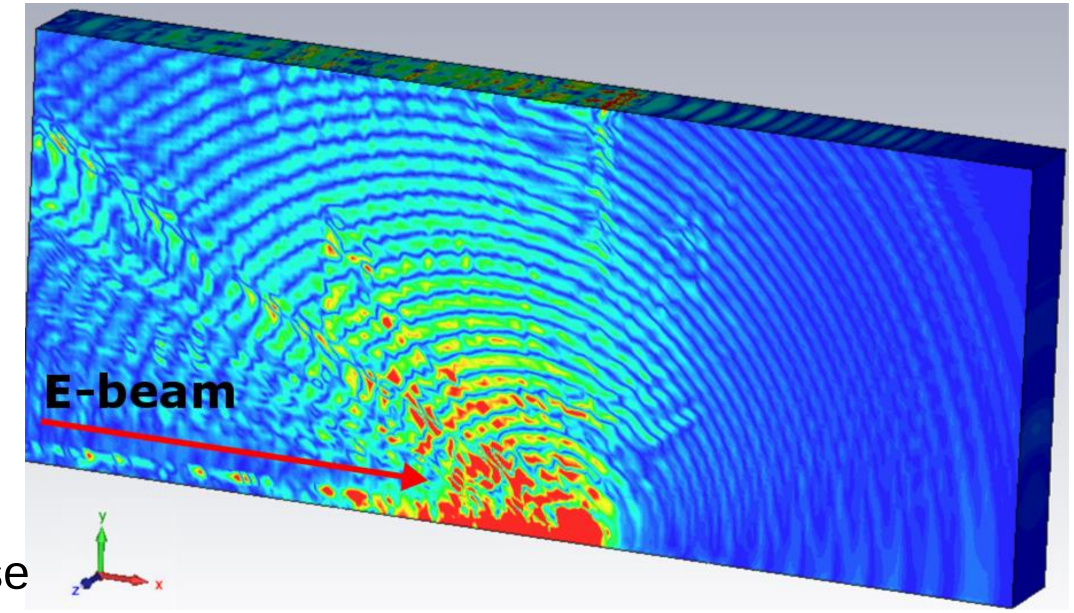


Can be used as small scale accelerators, the dielectric coating slows propagating EM waves so the beam propagates at a higher phase velocity than the EM radiation generating Cherenkov radiation which can be used for wakefield acceleration.



Smith Purcell gratings

When an electron passes close to the surface of the grating, it generates Smith-Purcell radiation which is emitted in crescent shaped waveforms for every period of the grating passed. These can be used for detection applications.



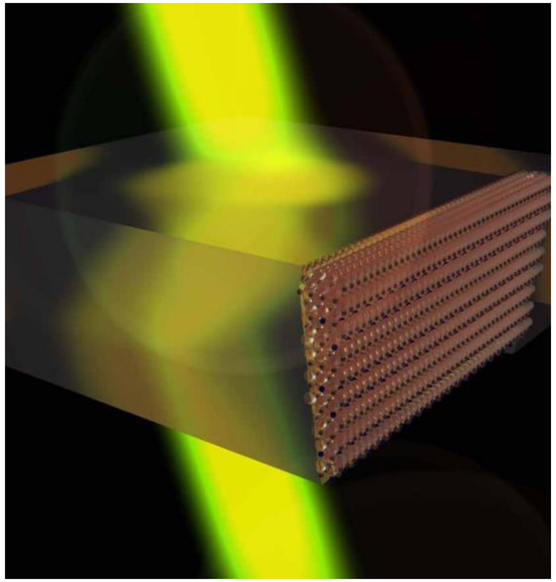
New Plasmonic materials

Metals
'too metallic', the high carrier concentration leads to large plasma frequencies and large losses.

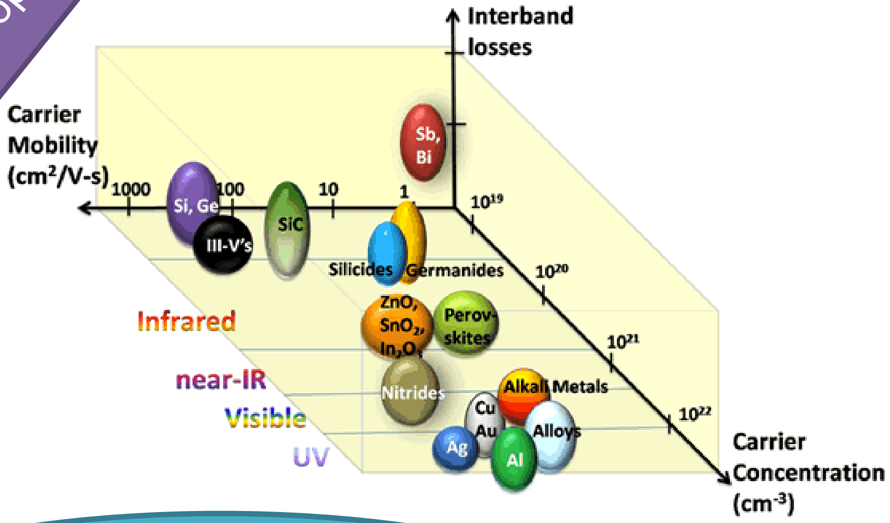
Semiconductors
Compatible with conventional fabrication but reaching limits at small length scales.

Reducing carrier concentration by mixing with non-metals

Carrier concentration is increased by doping



New Plasmonic Materials
Compatible with CMOS fabrication



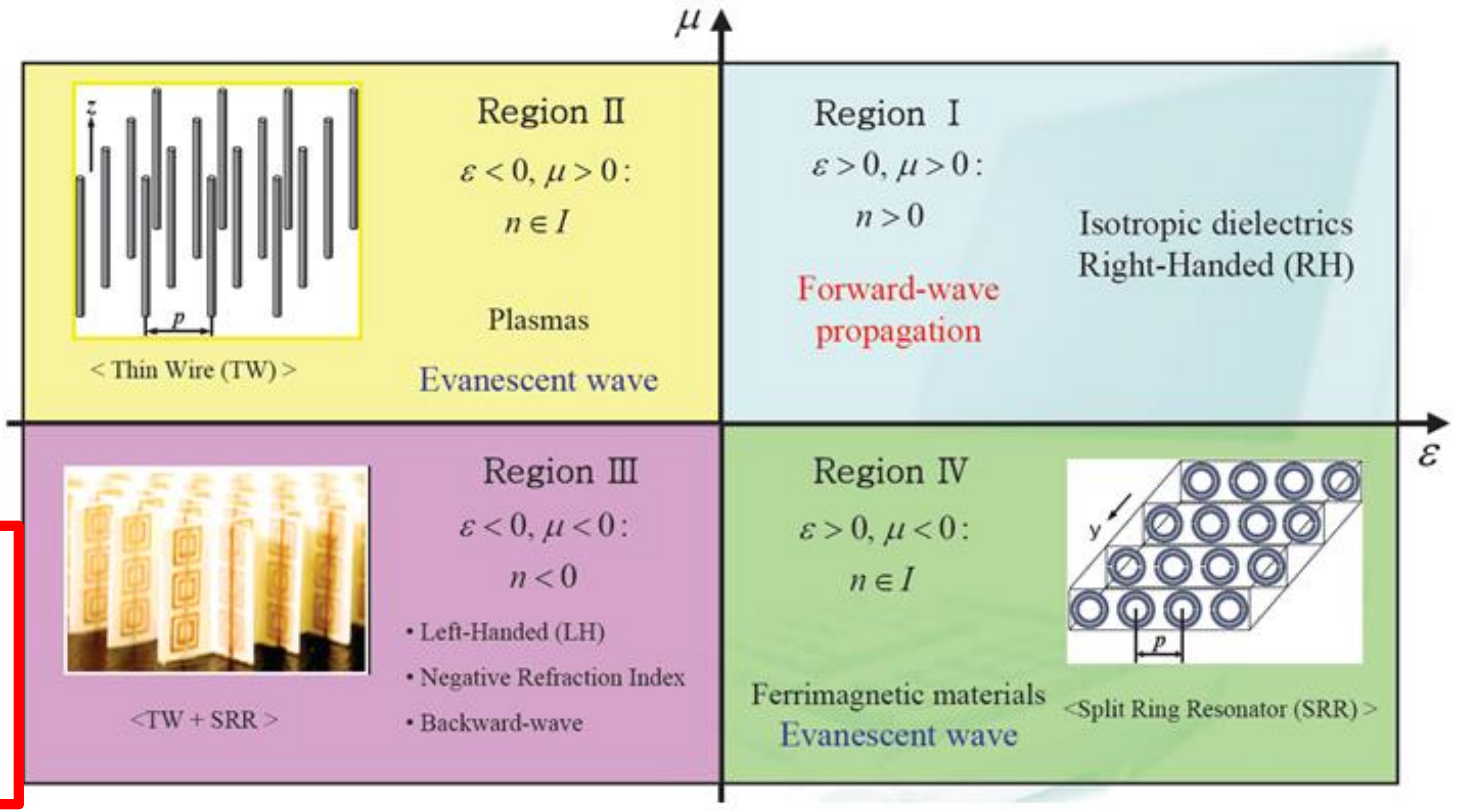
Intermettallics
Effective at visible frequency. Example Titanium Nitride (TIN).

Transparent conducting oxides
Effective in IR. Examples: Indium Tin Oxide (ITO) and Gallium doped Zinc Oxide (GZO).

For more information see Alexandra Boltasseva's group at Purdue University https://engineering.purdue.edu/~aeb/projects.shtml

Metamaterial definition

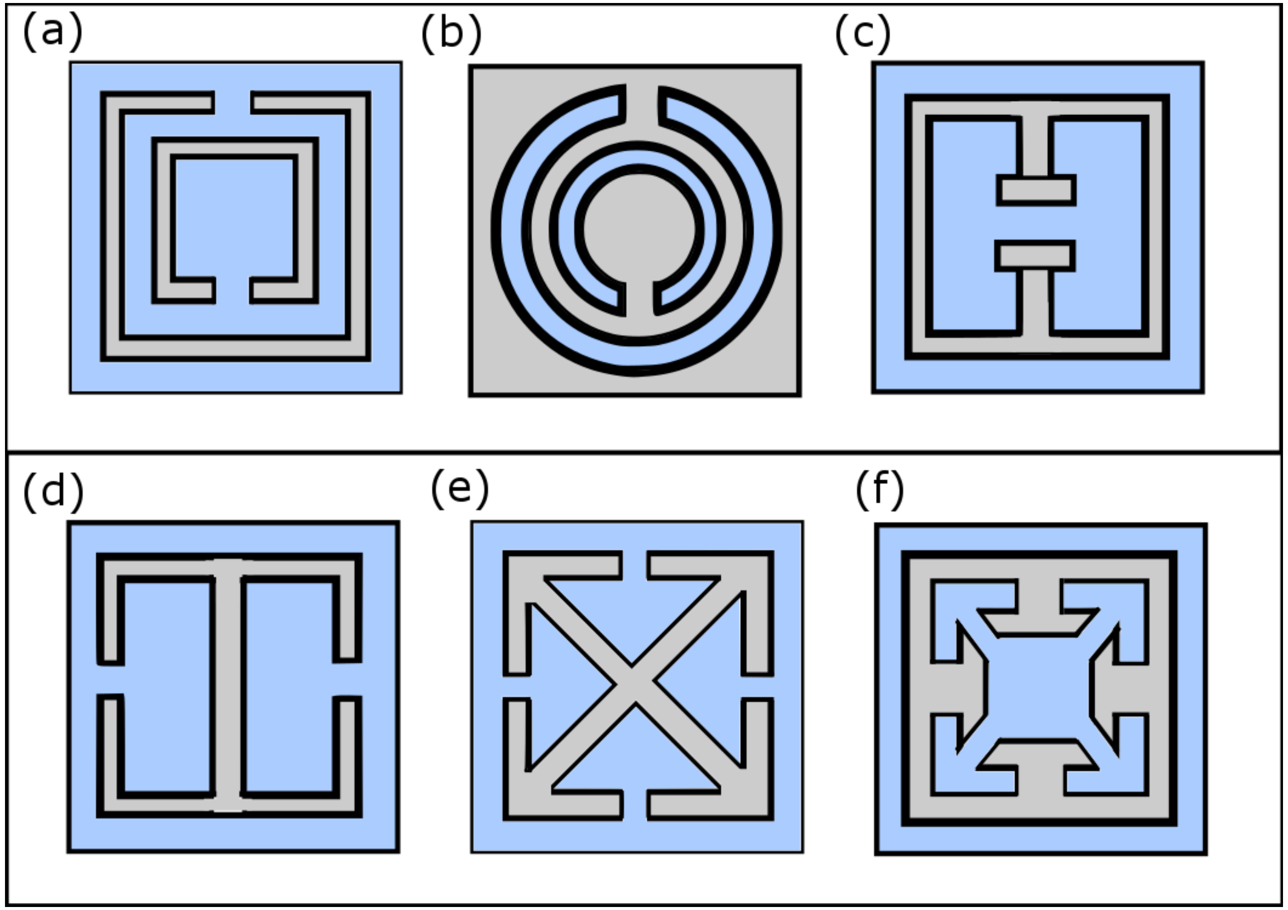
“An artificially engineered material comprising of periodic elements, the period of which is subwavelength (p<<λ/10), that when excited by external radiation gives rise to unique electromagnetic effects.”



Left handed Media

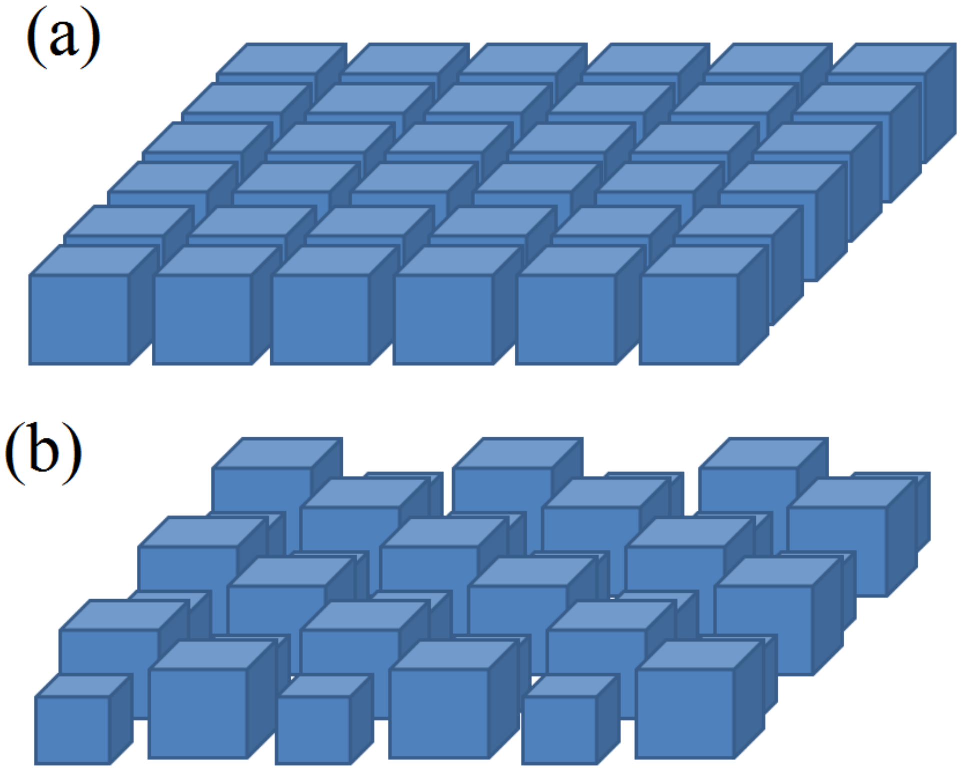
Common forms

LC resonant metamaterials



Rely on inductance and capacitance to drive a unique electromagnetic response just after the resonant frequency. These can be combined to form materials with simultaneously negative permittivity and permeability.

Mie resonant metamaterials

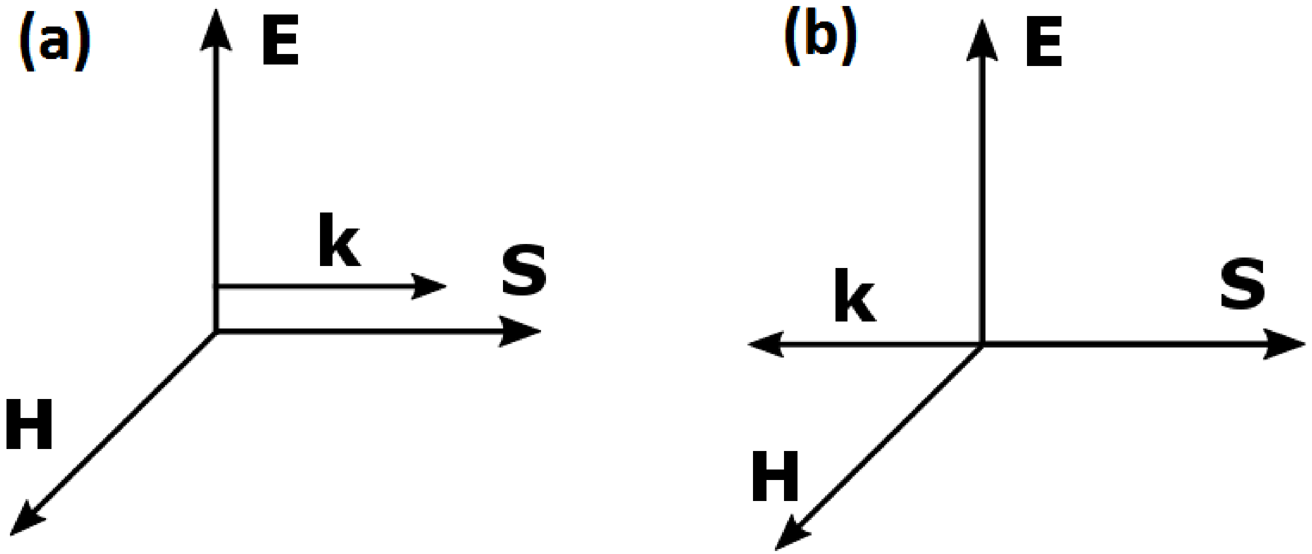


Uses an array of dielectric elements to obtain $\varepsilon < 0$ and $\mu < 0$. The 1st resonance => $\varepsilon < 0$ and the 2nd resonance => $\mu < 0$.

It is possible to obtain simultaneously negative ε and μ dielectric elements of different sizes.

Left handed Media

Materials in which permittivity ε and permeability μ are both negative are often called **Left handed media (LHM)**



$$\mathbf{k} \times \mathbf{E} = \frac{\omega}{c} \mu \mathbf{H}$$

$$\mathbf{k} \times \mathbf{H} = \frac{\omega}{c} \varepsilon \boldsymbol{E}$$

- Wave vector and poynting vector antiparallel => wave packets and wave fronts move in opposite directions
- Phase velocity and group velocity have opposite signs

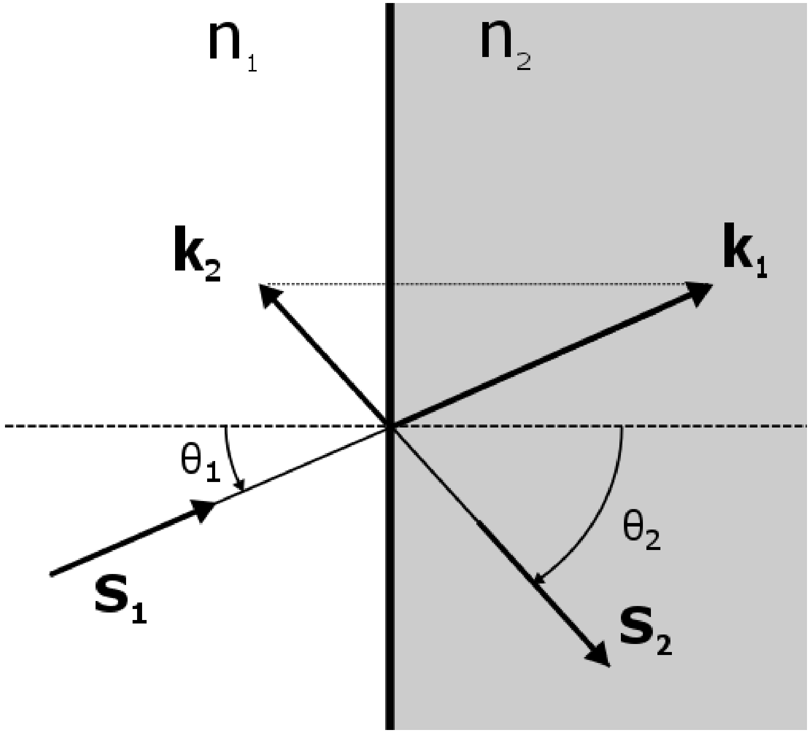
Applications: Negative refraction, cloaking, super lenses, backward propagating Cherenkov.

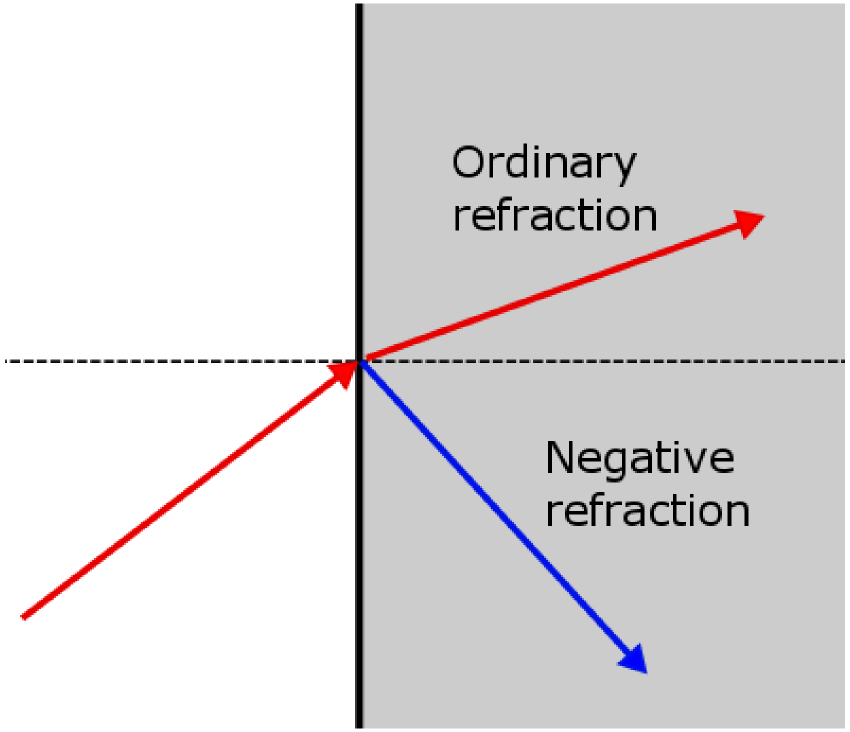
Negative refraction

Snells law in a Left handed media

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{-|\mathbf{k}_2|}{|\mathbf{k}_1|} \equiv \frac{n_2}{n_1} < 0$$

$$\text{if } n_1 > 0 \quad \text{then } n_2 < 0$$

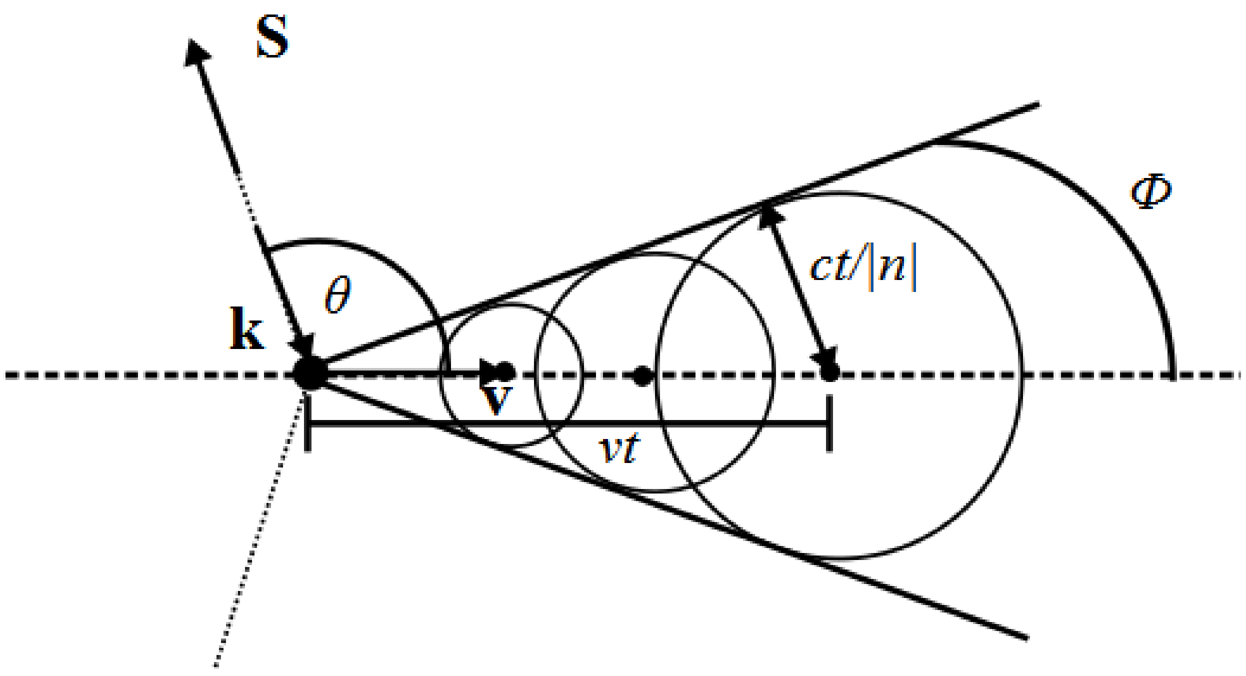




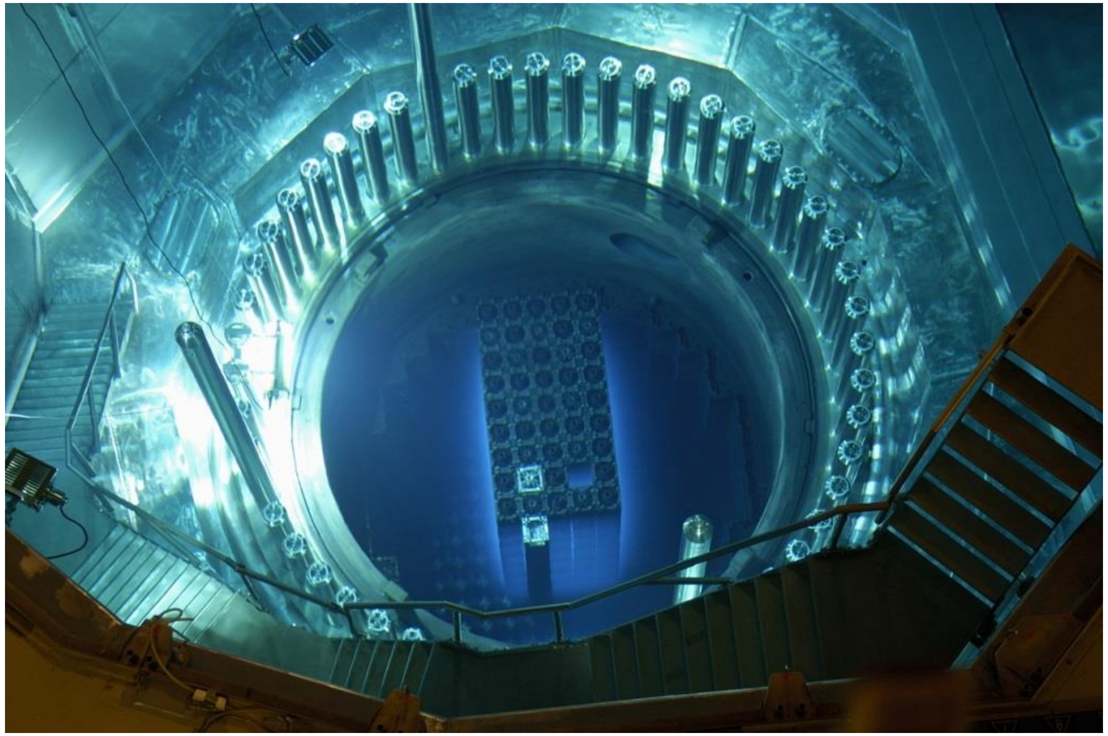
The path of wave vector **k** and Poynting vector **S** as an EM wave moves from an RHM to an LHM, the rays propagate along the direction of energy flow.

Key applications: Cloaking, hyper lenses, the backward propagation of electromagnetic effects.

Reverse Cherenkov radiation



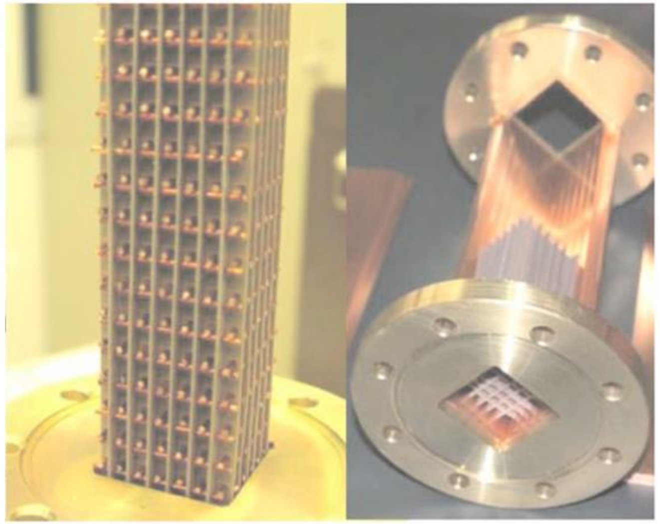
- Backward wave propagation => the spherical wave-fronts move inwards towards the source.
- Wave-fronts collapse when they reach the particle
- Shockwave propagates backwards



Applications:

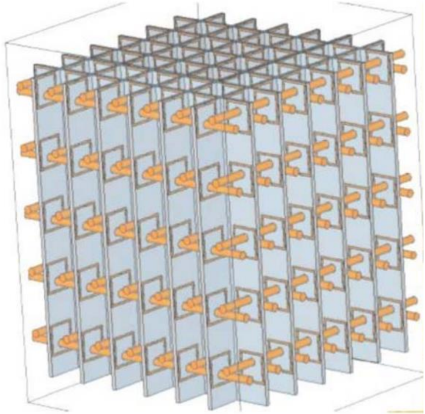
- Non-destructive particle detectors
- Coherent radiation sources
- Wakefield acceleration.

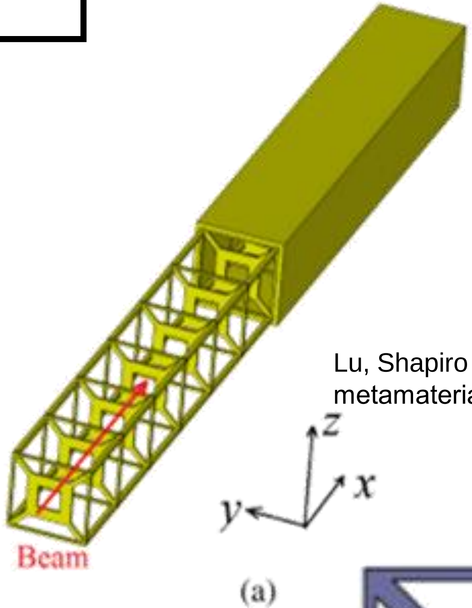
Metamaterials in accelerators

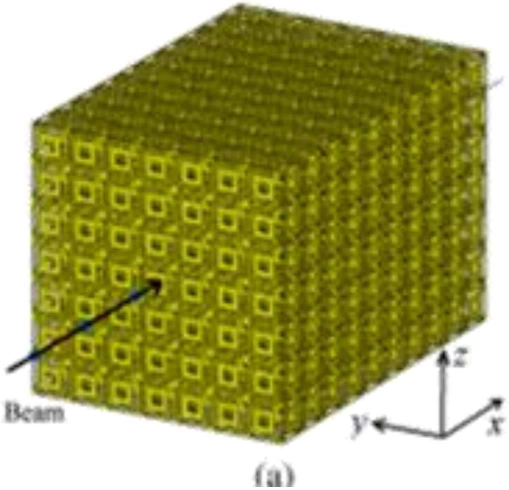


Antipov et al " Observation of wakefield generation in left-handed band of metamaterial-loaded waveguide", 2008

Split ring resonator and split wire loaded waveguide

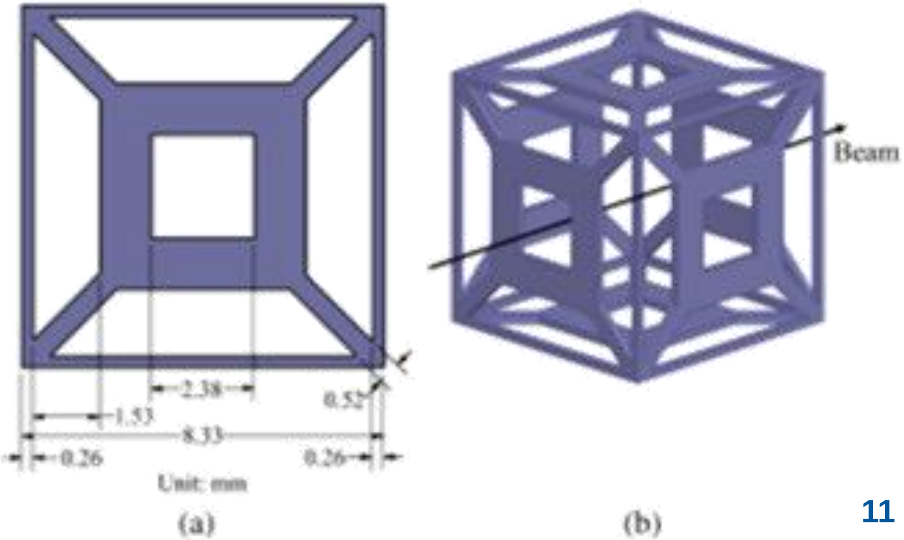




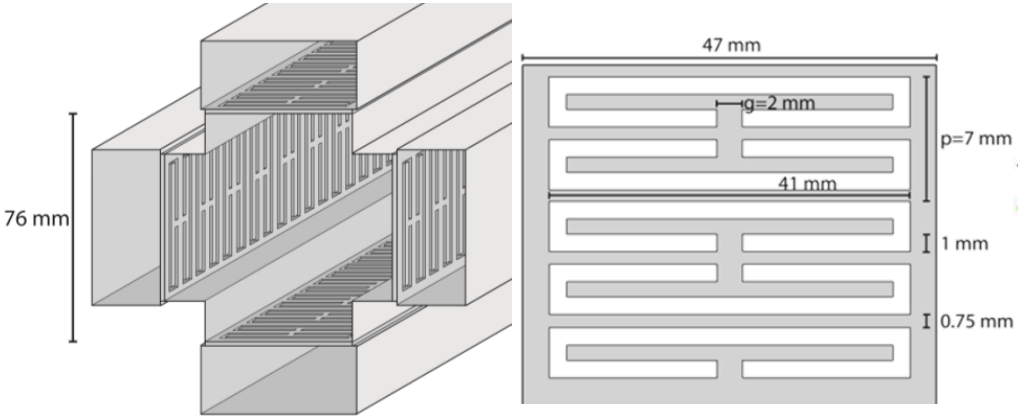


Lu, Shapiro and Temkin. "Modeling of the interaction of a volumetric metallic metamaterial structure with a relativistic electron beam" 2015

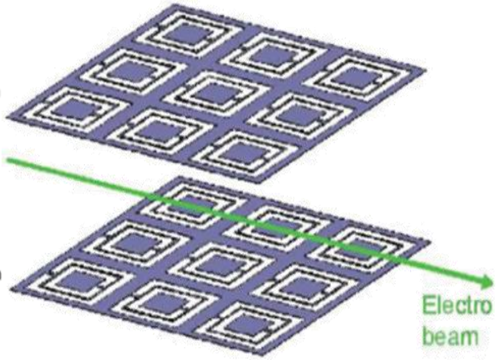
Volumetric metallic metamaterials



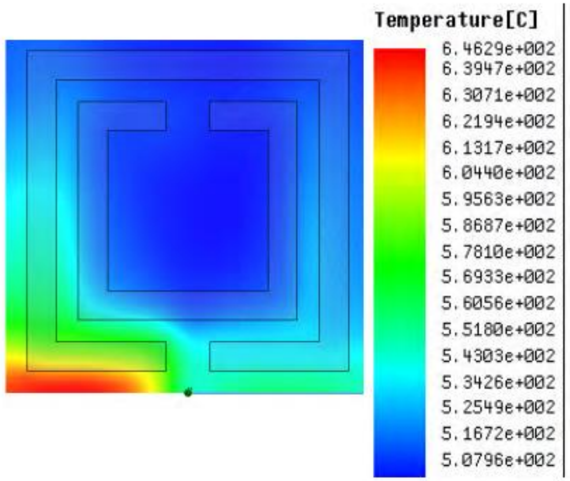
Complementary split ring resonator (CSRR) loaded waveguides

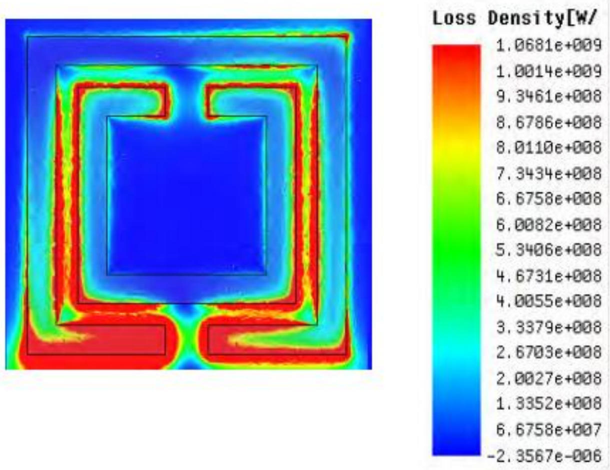


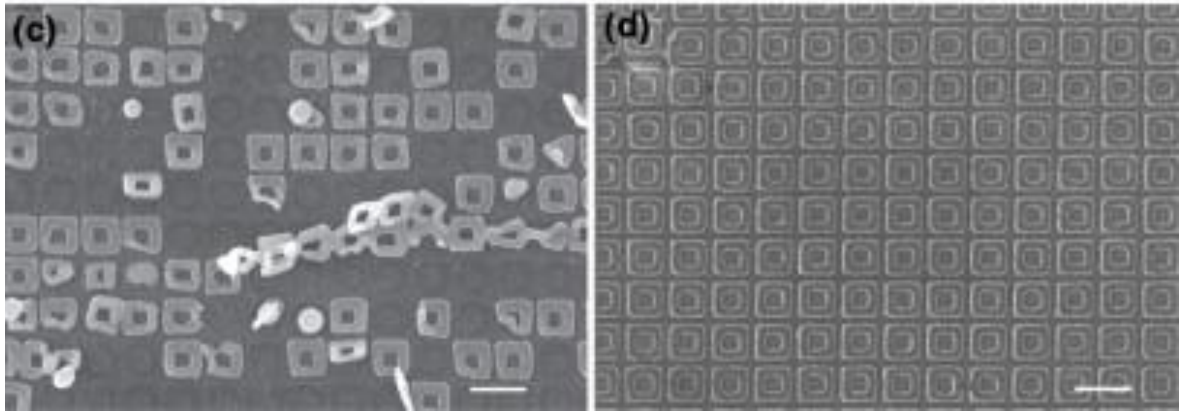
Hummelt, et. Al. " Simulation of wakefields from an electron bunch in a metamaterial waveguide" 2014



Shapiro, et. Al. " Metamaterial-based linear accelerator structure" 2012



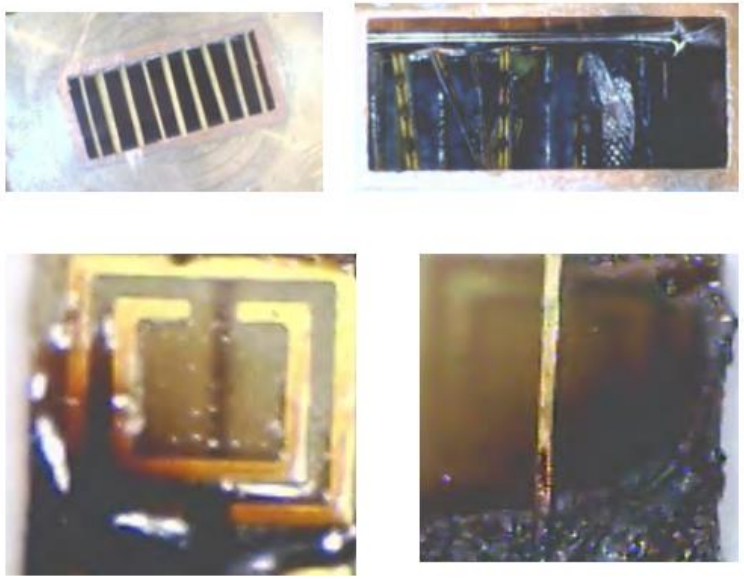




U. Guler, V.M. Shalaev and A. Boltasseva "Nanoparticle plasmonics: Going practical with transition metal nitrides", Materials Today 18(4) · November 2014 DOI: 10.1016/j.mattod.2014.10.039

D. Shiffer, R. Seviour, E. Luchinskaya, E. Stranford, W. Tang & D. French. Plasma Science, IEEE Transactions on, 41, 6 (2013) 1679-1685. ISSN 0093-3813.

The key issue: susceptibility to damage and deformation as a result of resistive heating at high power.

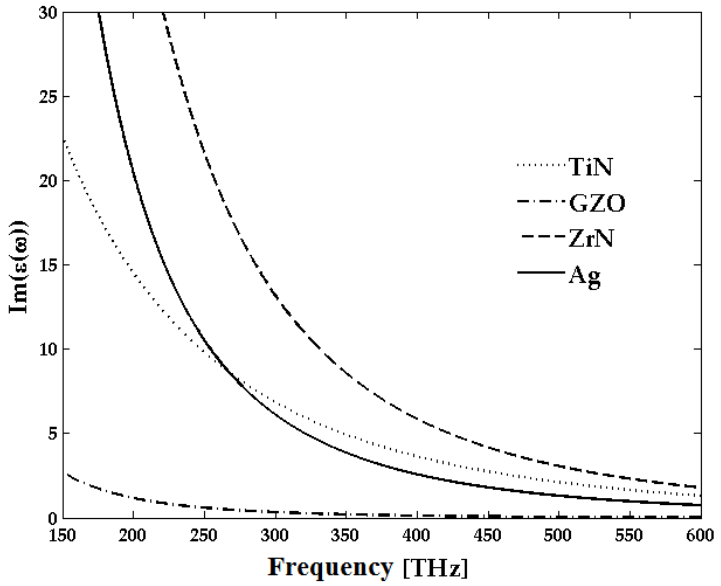


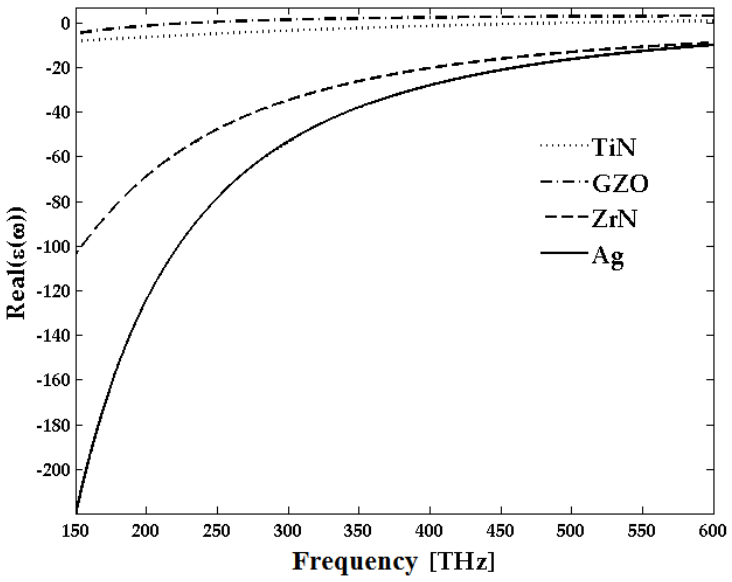
Final issue: Losses of common materials at high frequency.

One big challenge is that these designs are **not realistically suitable for fabrication.** They suffer from;

- Poor beam clearance.
- Inability to self support in a waveguide.
- Cannot stand up to machine tolerances.
- Lack of vacuum compatibility.

New Plasmonic metamaterials



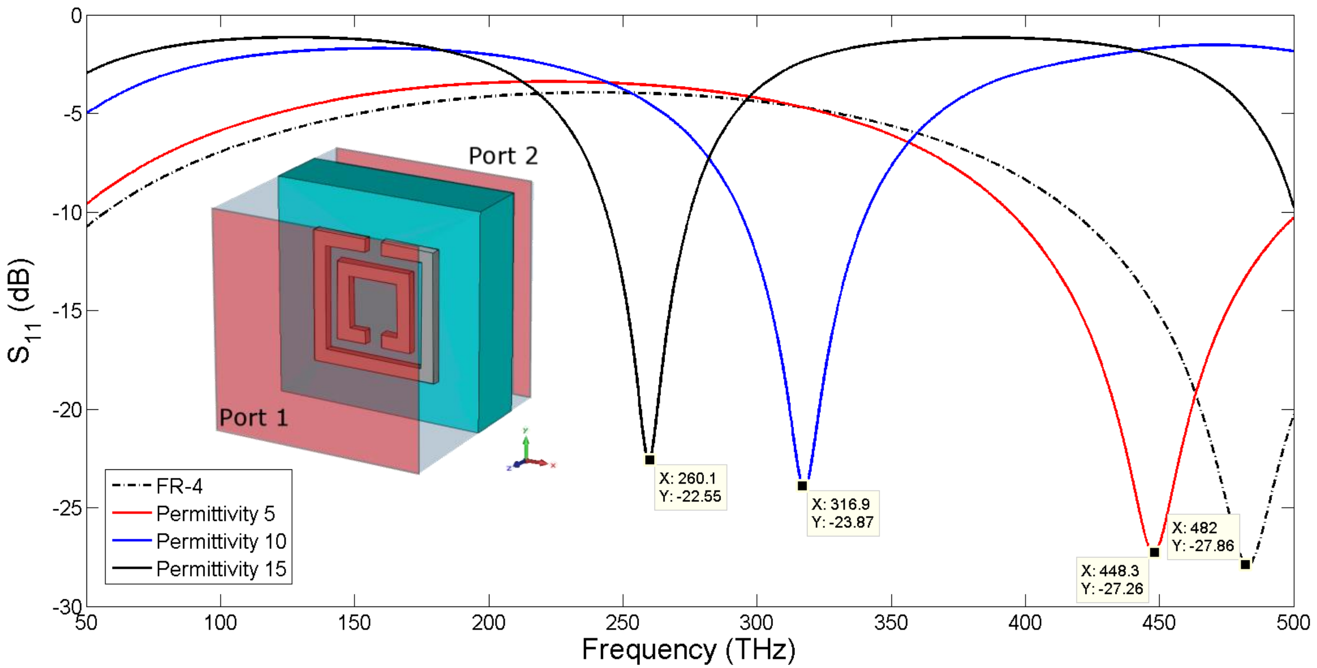


Over coming the limitations of metals at high frequencies.

Plasmonics vs Metals

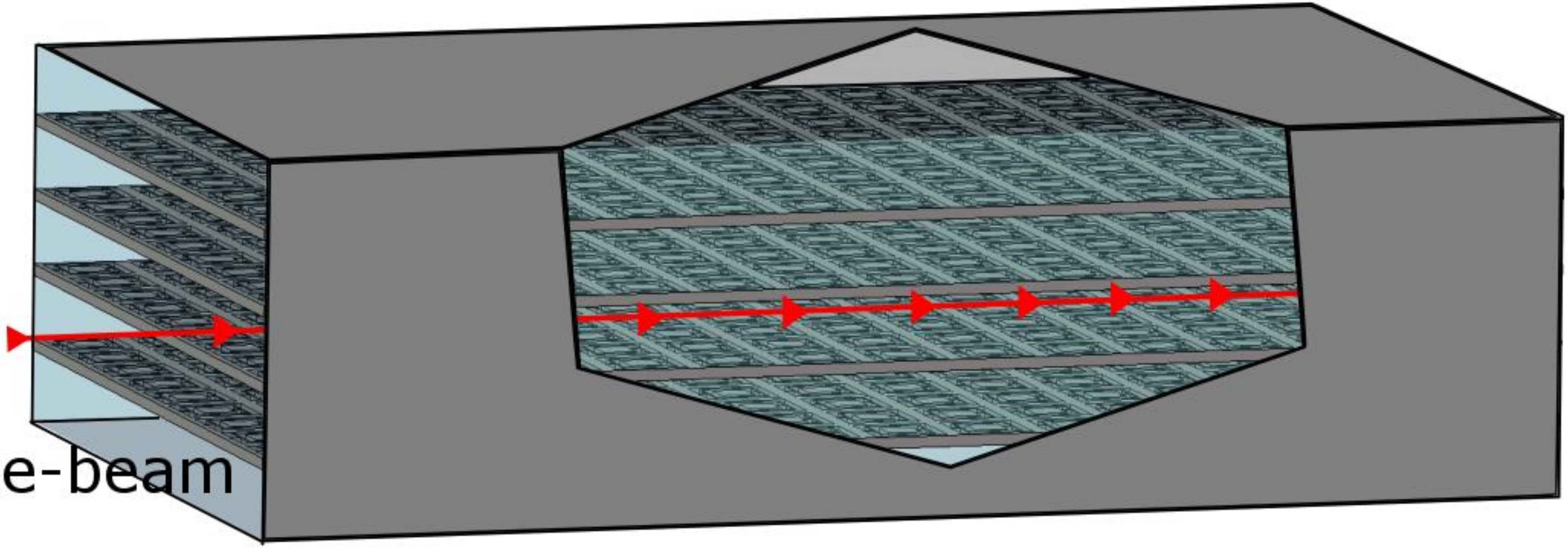
- Similar but slightly lower imaginary permittivity.
- Need high permittivity substrate to drive resonance.
- Much lower losses in the THz frequency range.

Material	Dielectric constant ε_∞	Plasma frequency ω_p (Rad/s)	Damping frequency γ (Rad/s)
Ag	5.0	1.4433×10^{16}	1.0×10^{14}
TiN	4.017	0.7×10^{16}	9.0×10^{14}
GZO	4.0	2.9×10^{15}	1.5×10^{14}
ZrN	1.117	1.2×10^{16}	3.5×10^{14}



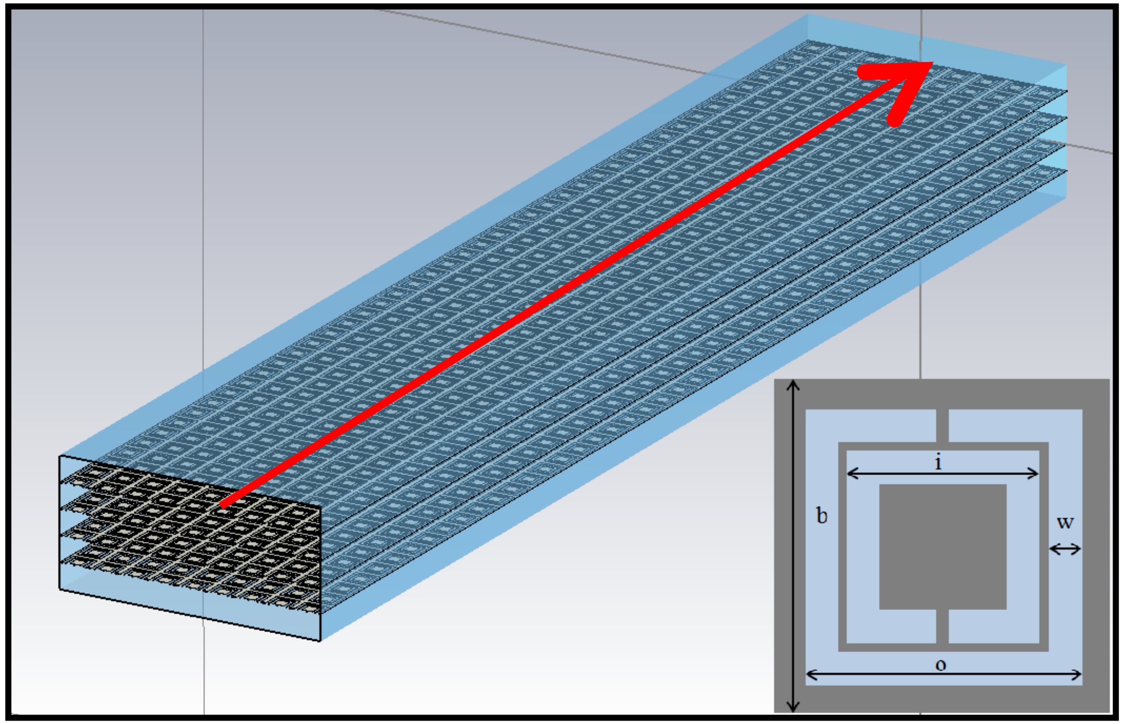
New plasmonic SRRs on high permittivity substrates mimic the response of metallic SRRs allowing for metamaterial applications at THz and optical frequencies.

Metamaterial Loaded waveguide



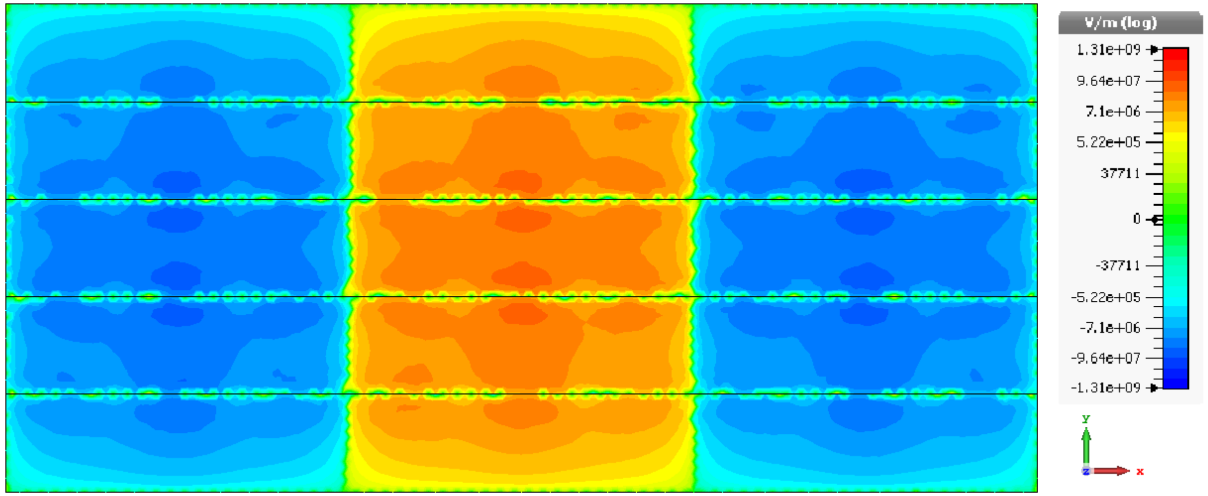
Complementary Split Ring Resonator (CSRR) Loaded waveguide design

CSRR loaded waveguide initial results

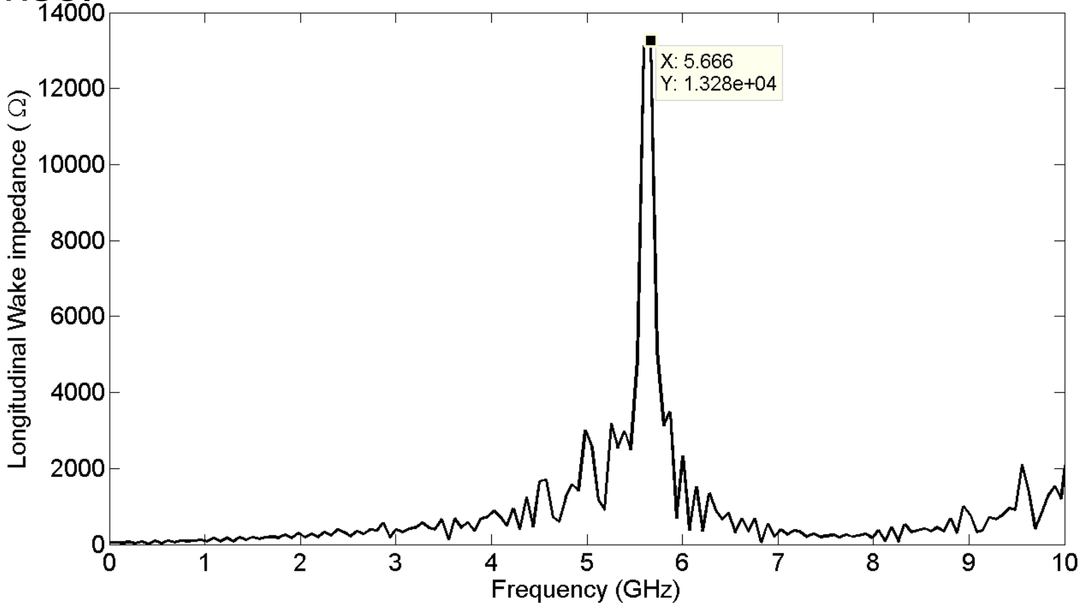


Four CSRR metasurface layers, 9 resonators across loaded into a metallic waveguide. Electron beam propagates between the central layers, in a space of 6 mm.

Mode	Frequency (GHz)	R/Q (Ω/m)	$R_{SH}(k\Omega/m)$
Hybrid	5.41	2.5	3.625
Hybrid	5.42	0.00	0.22
Hybrid	5.42	5	7.22
Hybrid	5.43	55	64.840
TM-Like	5.47	6600	10938
Hybrid	5.48	7.5	9.825



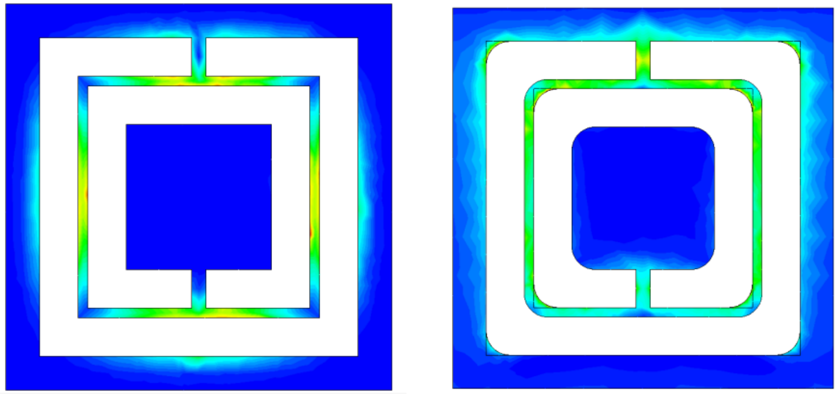
TM31 mode is the first transverse mode found in the structure, this mode has good R/Q, Shunt impedance and wakefield response.



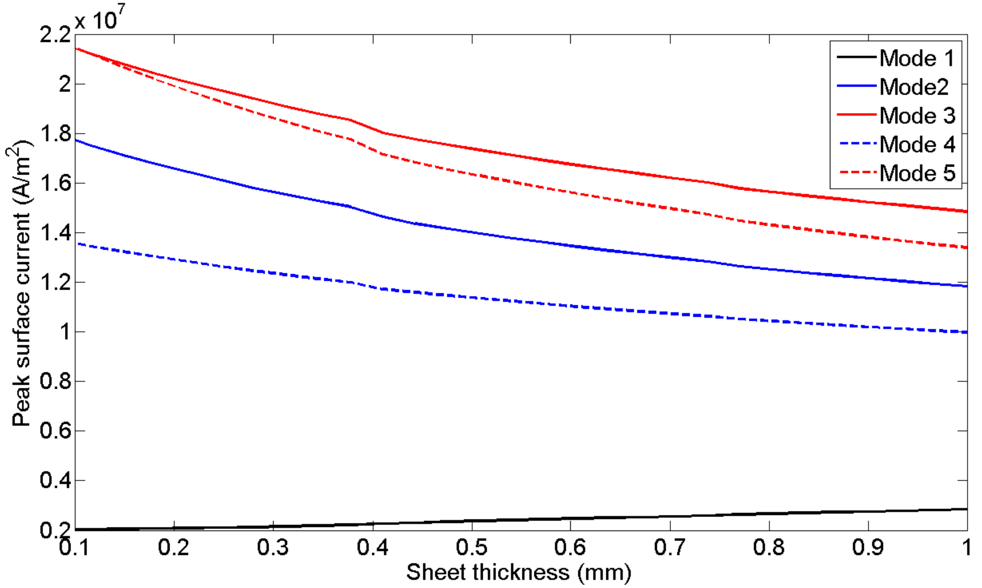
Design considerations

Aims

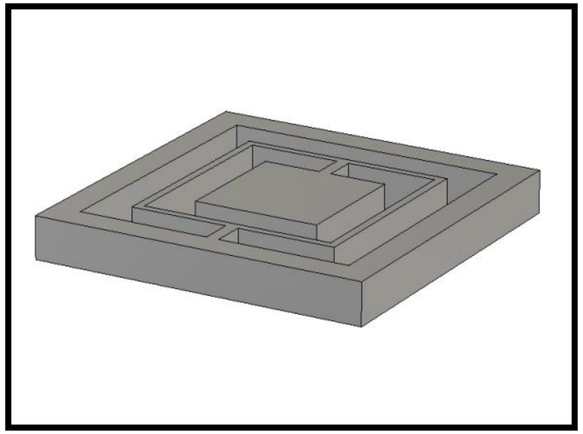
- **Reduce:** surface current and hybrid modes.
- **Increase :** fabrication suitability
- **Maintain:** field strength and beam coupling parameters.



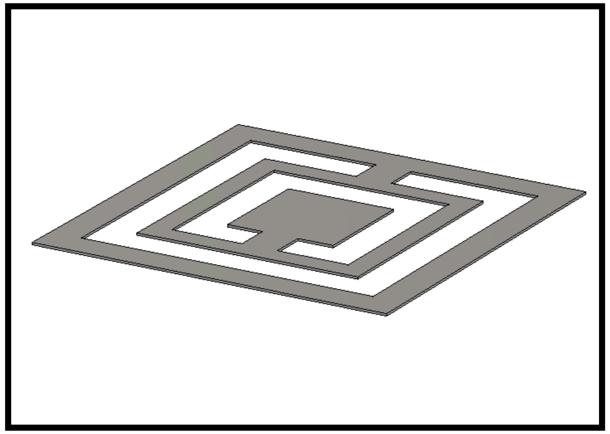
Surface current plots for a CSRR with and without curvature.



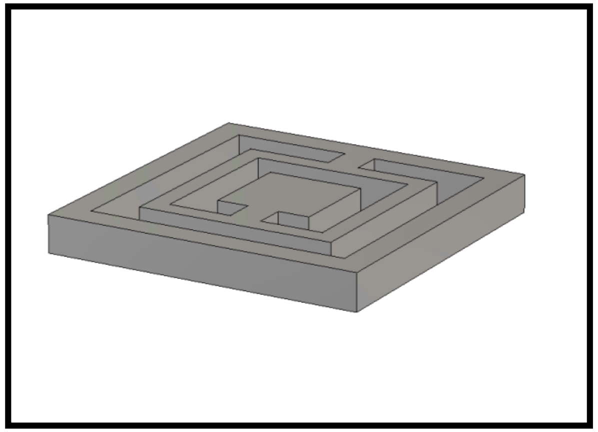
Plot showing reduction of peak surface current with increasing sheet thickness.



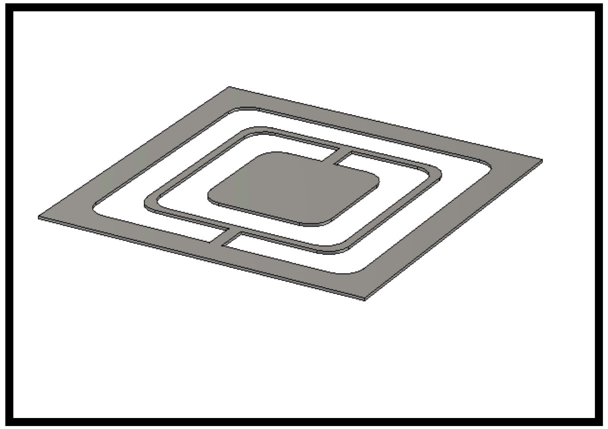
Waveguide A:
Increased sheet thickness t= 1mm



Waveguide B:
Increased ring separation i= 4mm

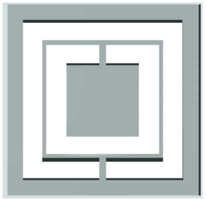


Waveguide C:
Increased thickness t=1 mm and ring separation i=4 mm



Waveguide D:
Additional radius of curvature of 0.5 mm

EM analysis of final design



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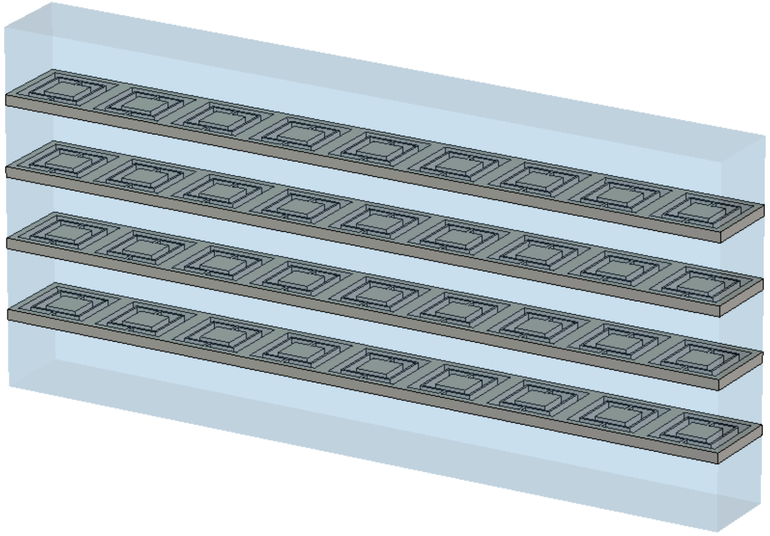
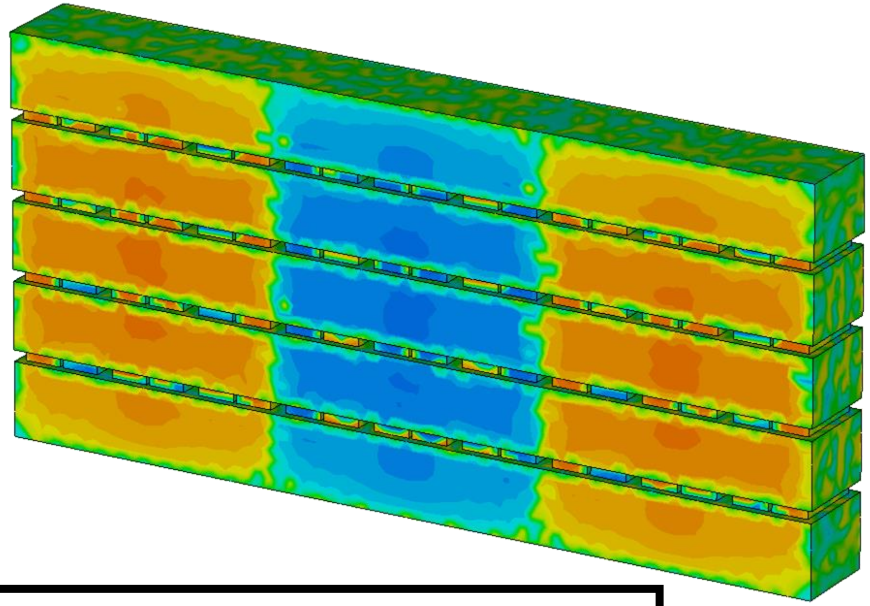


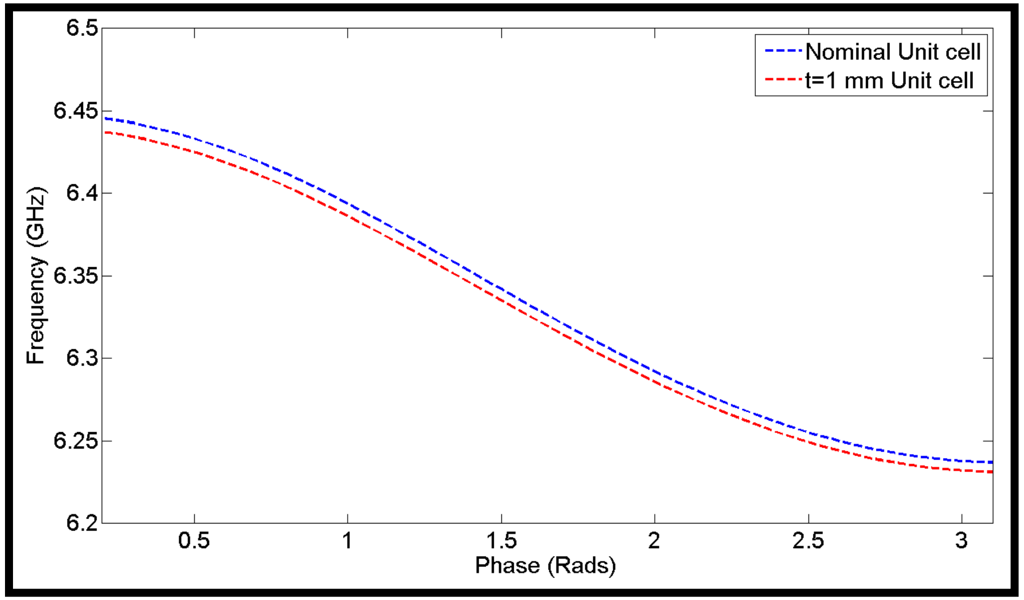
Field plot of E_z for the TM31-like mode at 5.86 GHz suitable for accelerator applications.



Final design uses thicker sheets of 1 mm and maintains initial CSRR design.

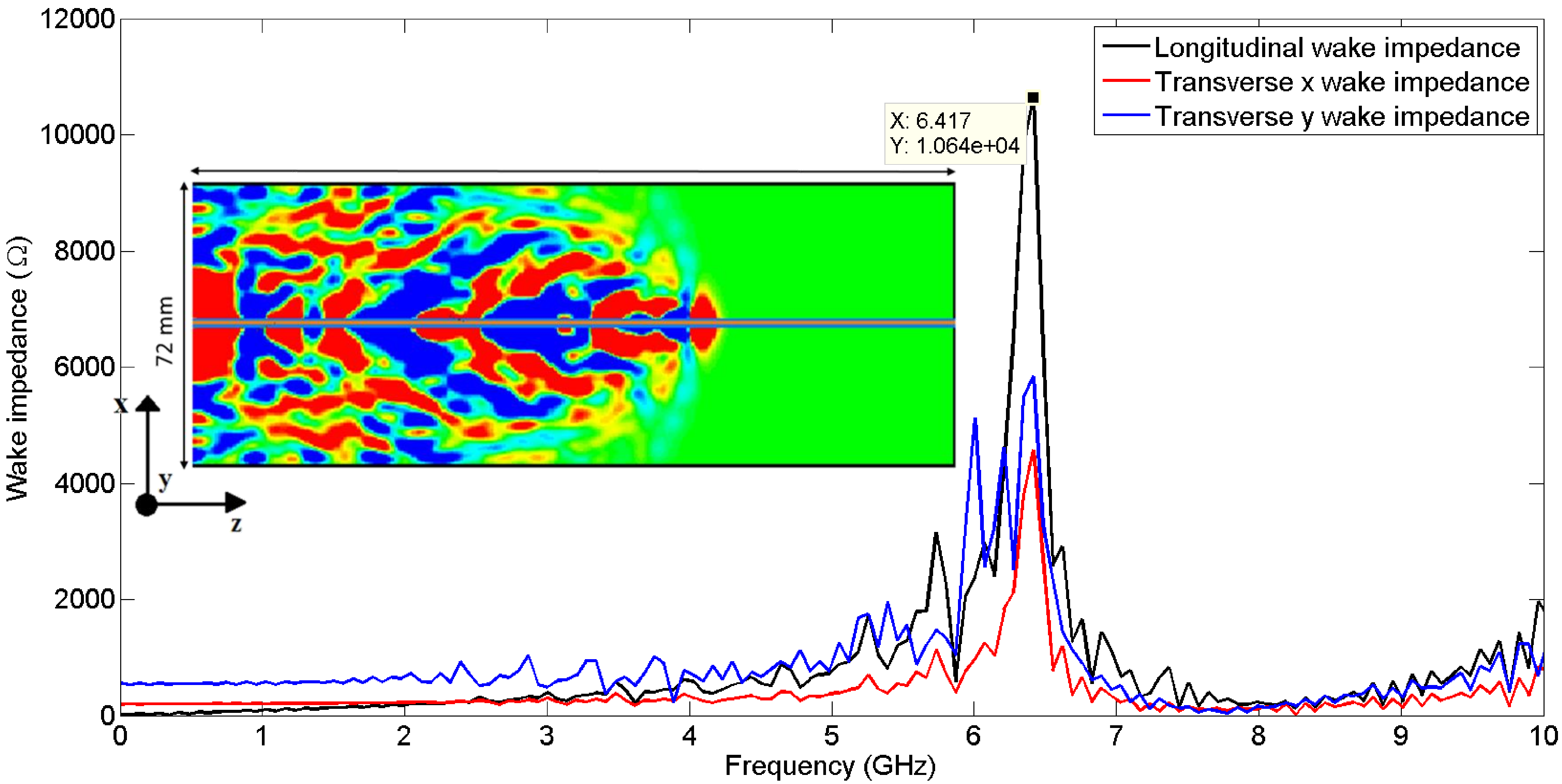
- **Fabrication suitability**: increased.
- **Coupling parameters**: increased
- **Surface current**: reduced
- **Hybrid modes**: reduced

Mode	Frequency (GHz)	R/Q (Ω/m)	R_{SH} (kΩ/m)
15	5.80	794.44	3062
16	**5.86**	**4500.00**	**22683**
17	5.94	0.00	0.00

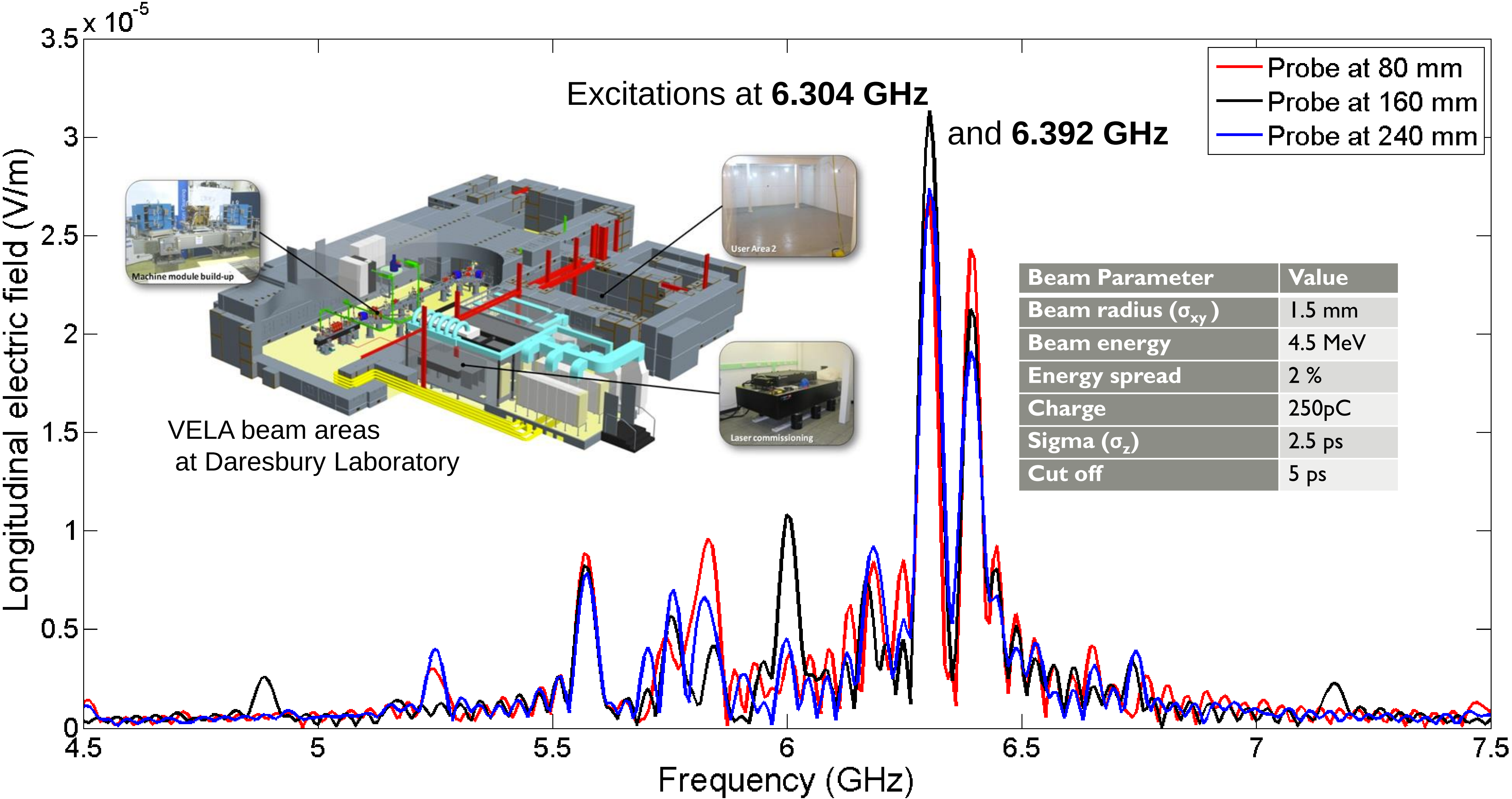


Comparison of dispersion gradients between the nominal Unit cell and the optimal unit cell.

Wakefield analysis of final design

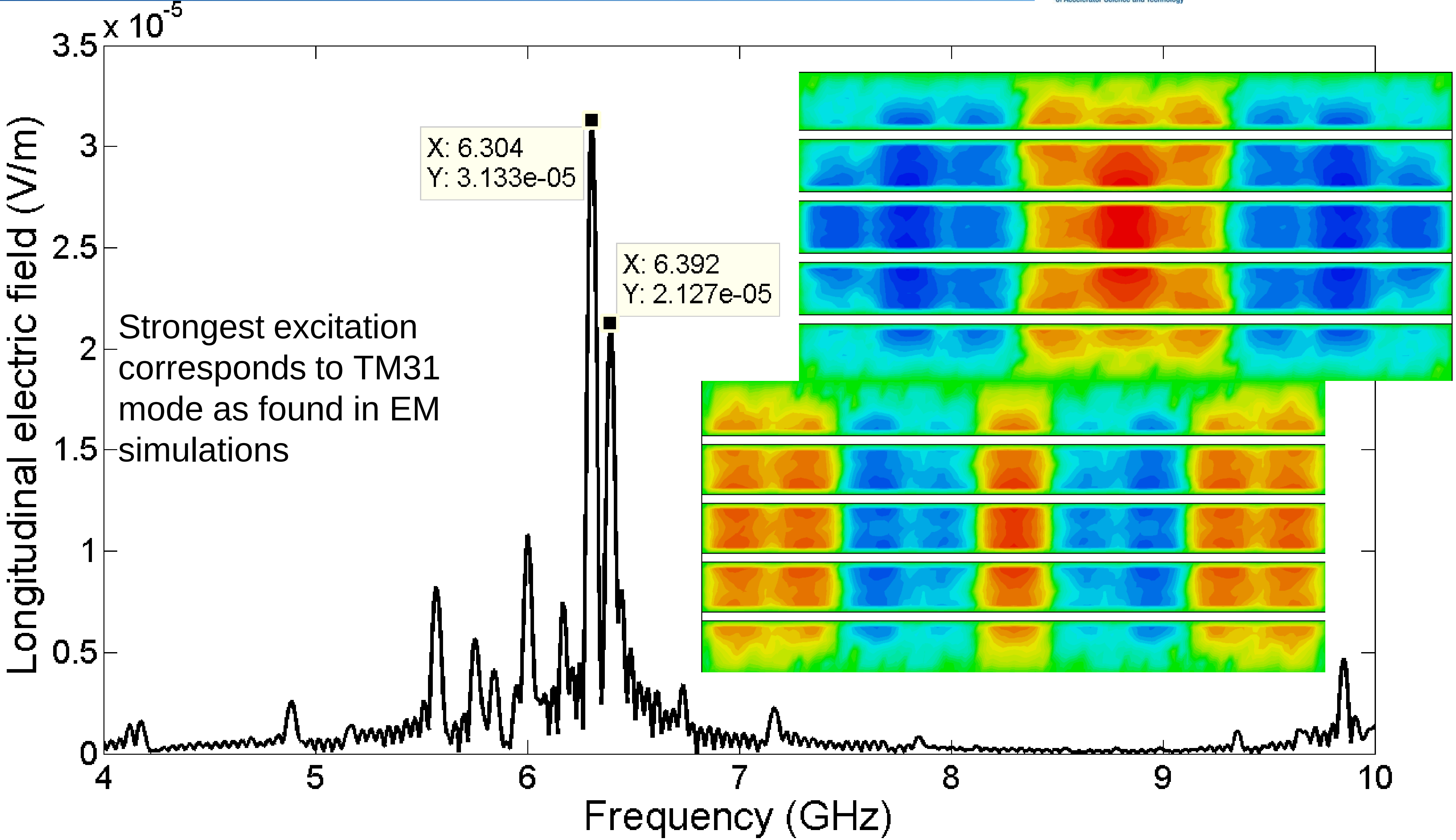


Particle in cell analysis: VELA



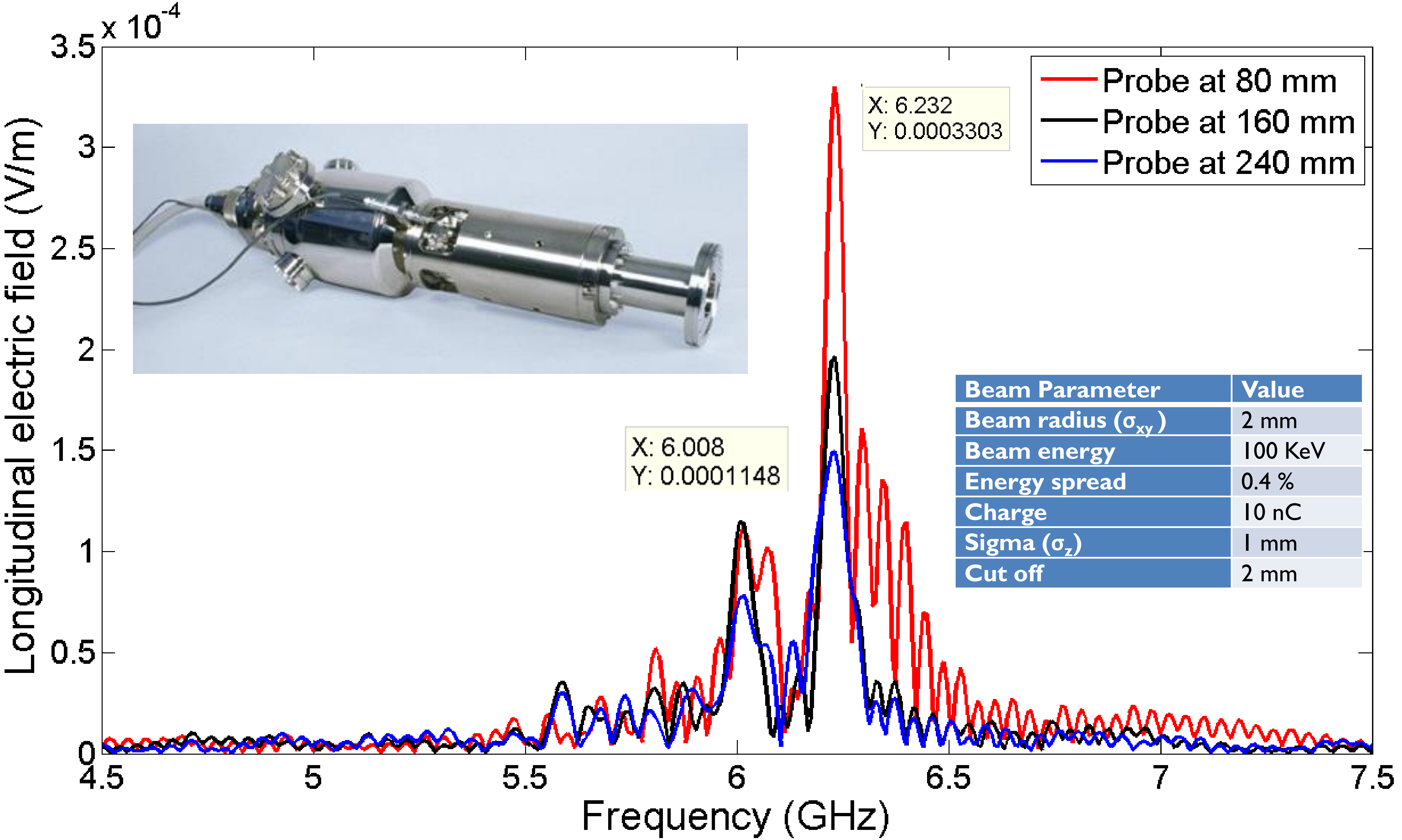
Beam Parameter	Value
Beam radius (σ_{xy})	1.5 mm
Beam energy	4.5 MeV
Energy spread	2 %
Charge	250pC
Sigma (σ_z)	2.5 ps
Cut off	5 ps

Particle in cell analysis: VELA



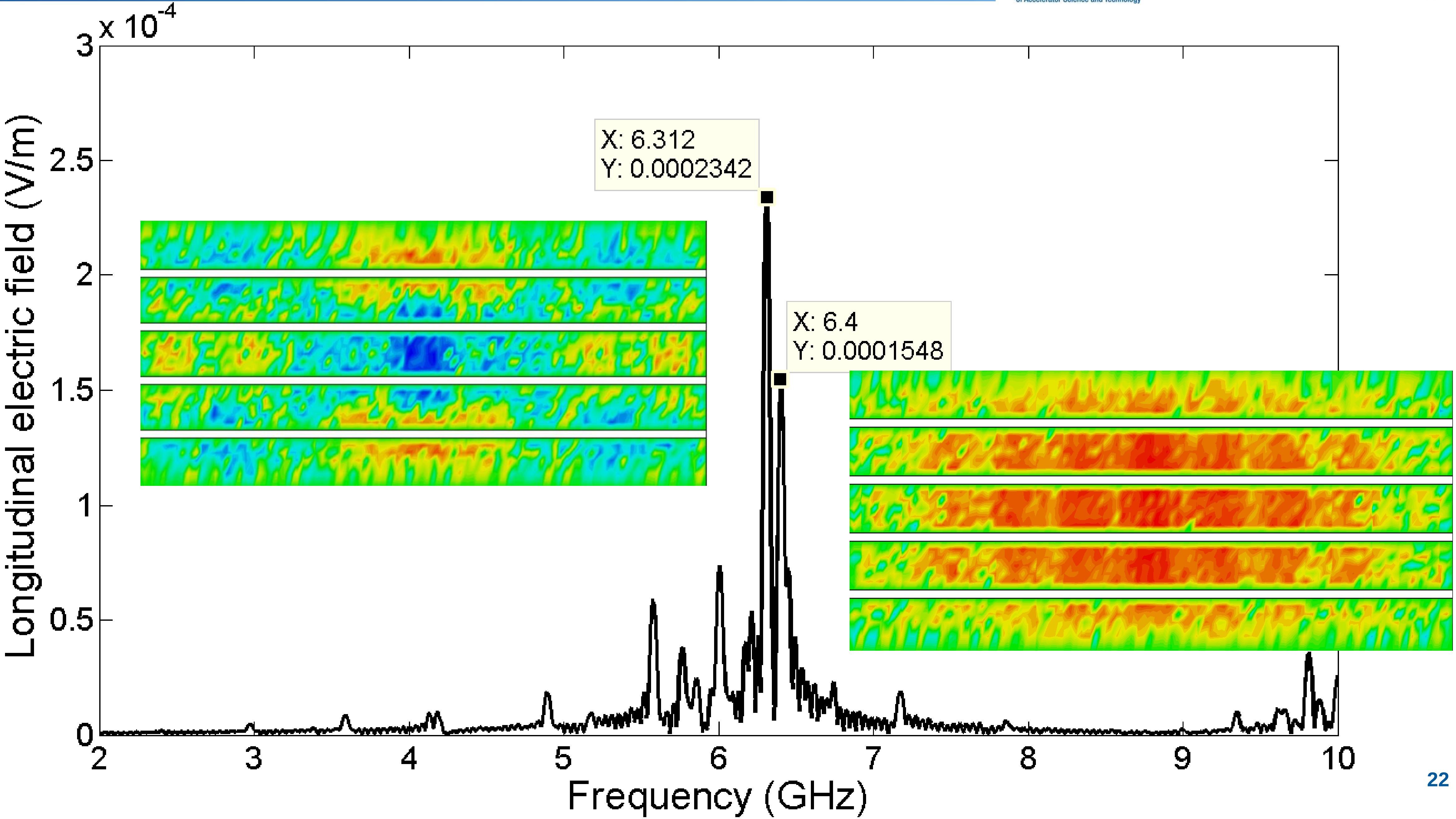
Strongest excitation corresponds to TM31 mode as found in EM simulations

Particle in cell analysis: Kimball



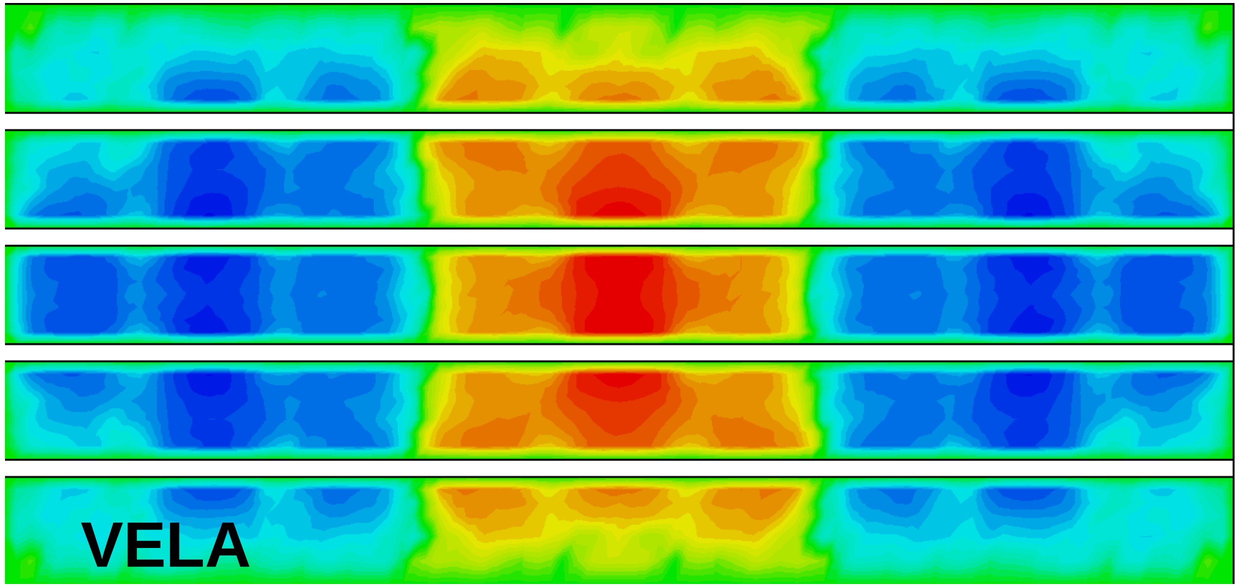
Beam Parameter	Value
Beam radius (σ_{xy})	2 mm
Beam energy	100 KeV
Energy spread	0.4 %
Charge	10 nC
Sigma (σ_z)	1 mm
Cut off	2 mm

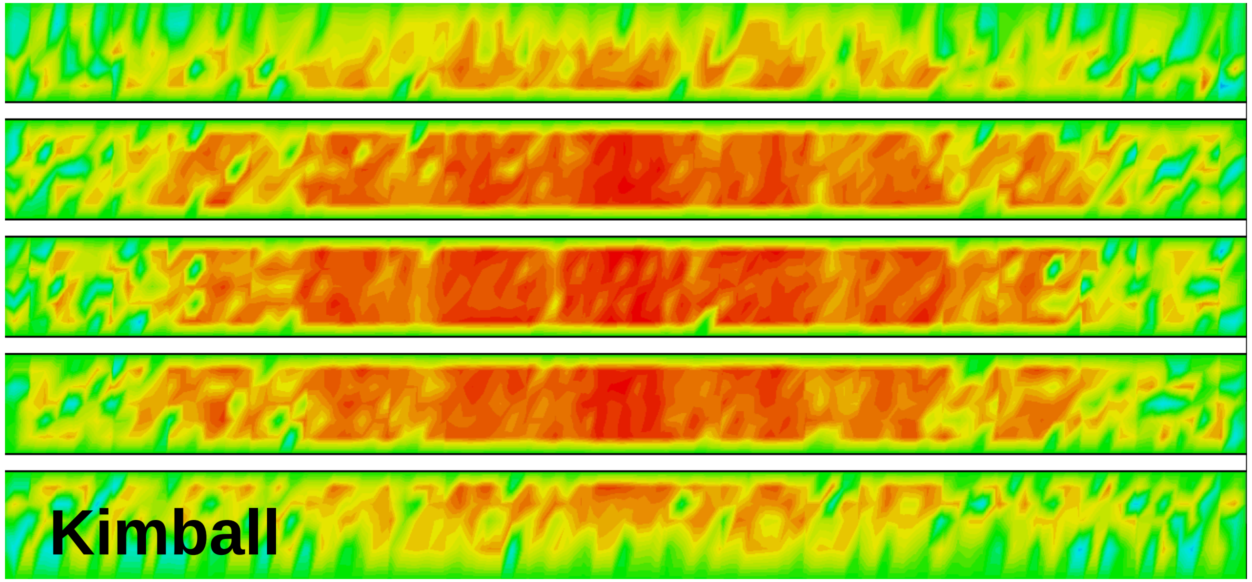
Particle in cell analysis: Kimball



Particle in cell comparison

			Primary excitation		Secondary excitation	
Beam	**Energy**	**Radius**	**Frequency**	**Strength**	**Frequency**	**Strength**
Kimball	100 KeV	2mm	6.008 GHz	114.8 µV/m	6.232 GHz	196.5 µV/m
VELA	4.5 MeV	1.5 mm	6.304 GHz	31.33 µV/m	6.392 GHz	21.27 µV/m





TM_{31} mode @ 6.304 GHz strength 31.33 µV/m

Pros: Well defined, corresponds to EM results

Cons: Complex coupling, weaker response

TM_{11} mode @ 6.232 GHz strength 196.5 µV/m

Pros: Strong excitation, simple coupling

Cons: Not supported by the structure

Summary

- Dispersion engineering allows for greater control of electromagnetic waves.
- Recent developments have increased the number of applications to accelerator science.
- Both wavelength and subwavelength scale dispersion engineering is possible for accelerator applications.
- CSRR loaded waveguide shown to be suitable for reverse Cherenkov applications.
- Design considerations create a robust structure without diminishing electromagnetic results.
- Clear beam coupling for the VELA beam, which will improve with CLARA upgrade.
- Fabrication challenges and high power damage still limit applications.

Future directions

- Movement away from negative index applications.
- Dispersion engineering coatings for accelerator applications

Thank you for listening
Any questions?

With thanks to Dr Rosa Letizia of Lancaster University who worked on this project with me at the Cockcroft institute.