Argonne NATIONAL LABORATORY

Metamaterial-Loaded Waveguides for Accelerator Applications

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Outline of the talk

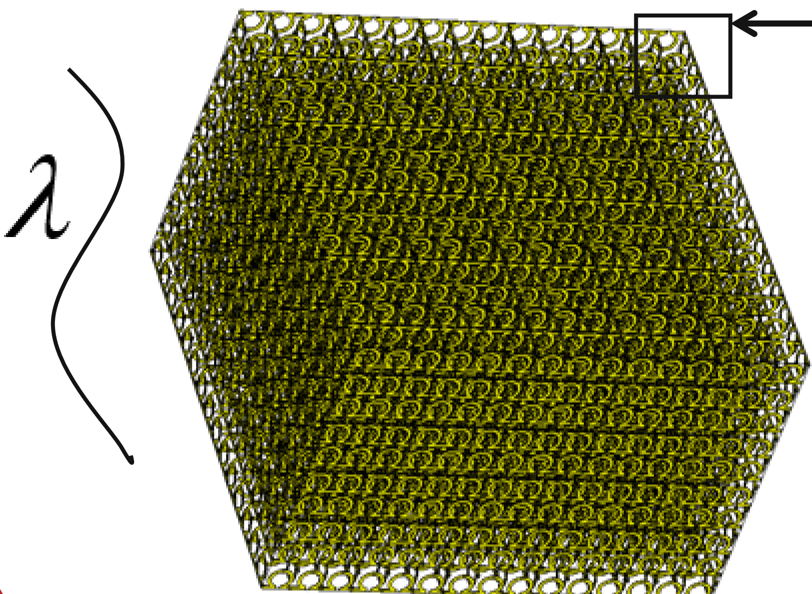
- Introduction to metamaterials
  - Artificial *ε and μ*
  - Properties of LHM
  - Simulations and Measurements
- Metamaterial-loaded waveguides
  - Dispersion analysis
  - Wakefield generation
  - Applications
- Conclusion, future directions

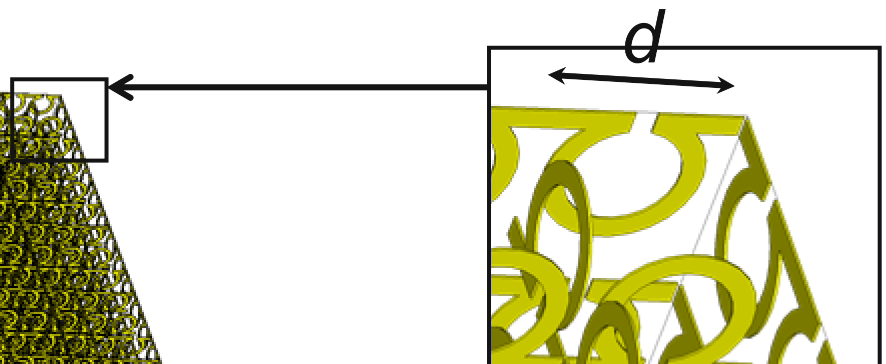
Introduction

- Metamaterials (MTM) are manmade materials with desired (electromagnetic) properties.
- For simplicity of design and manufacturing they are ***arrays of cells*** or basic elements

Effective media approximation

$$\lambda >> d \Rightarrow \exists\, \hat{\varepsilon}(\omega)\, \text{and}\, \hat{\mu}(\omega)$$



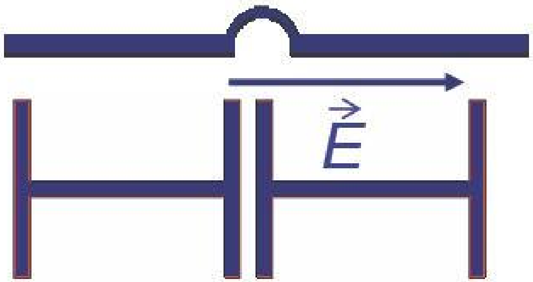


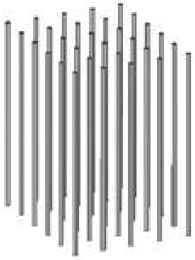
For *10GHz* (*3cm* wavelength) element size is ~*3mm*

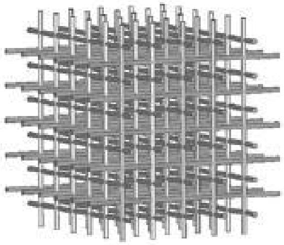
ε and μ can be negative!

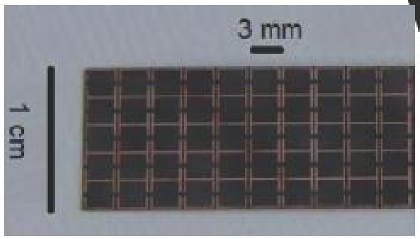
Artificial permittivity (ε)

- Different geometries for ε were studied (note anisotropy).



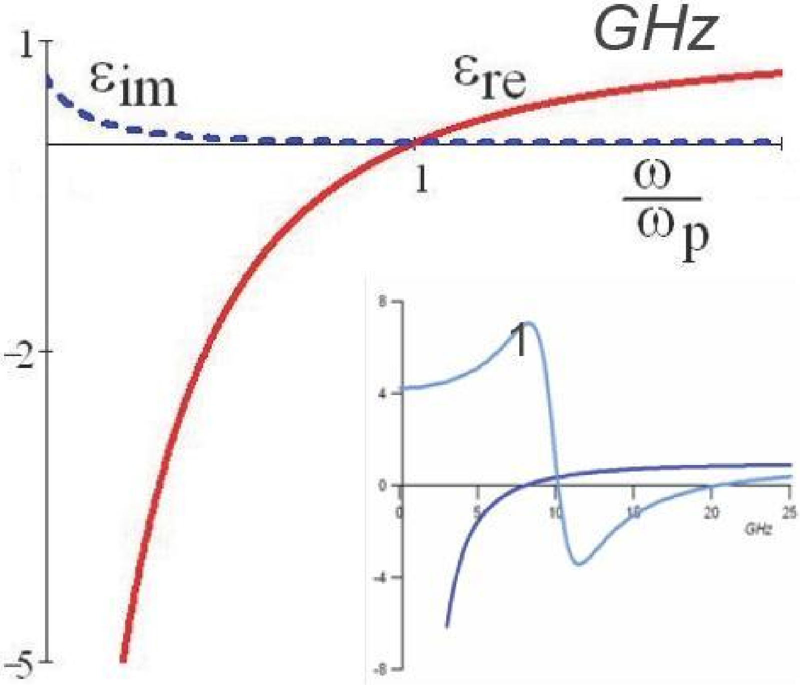




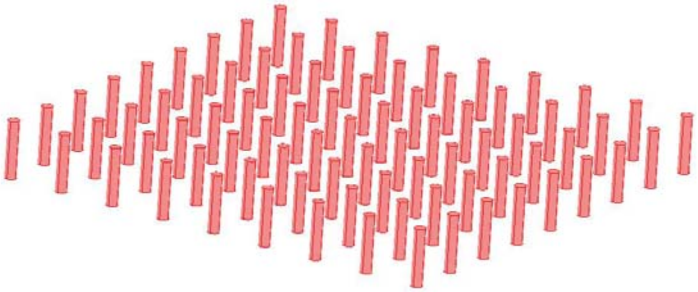


PCB etching

- For certain polarizations of fields they produce different responses:



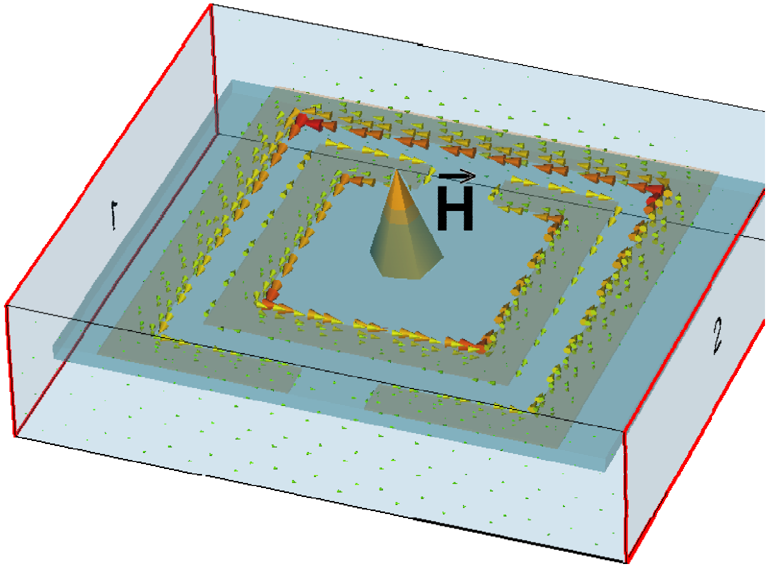
Plasma of electrons in metals

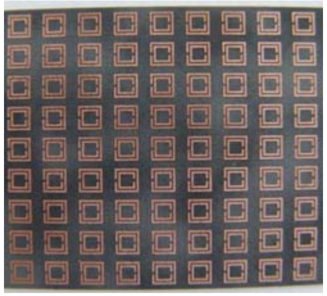


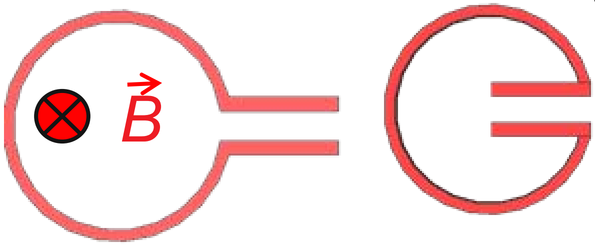
$$\omega_p^2 = \frac{ne^2}{\varepsilon_0 m_{eff}}$$

UV-optical for metals

Artificial permeability, Split Ring Resonator (SRR)

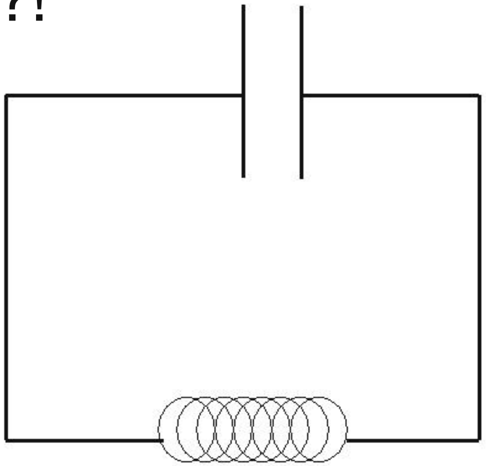


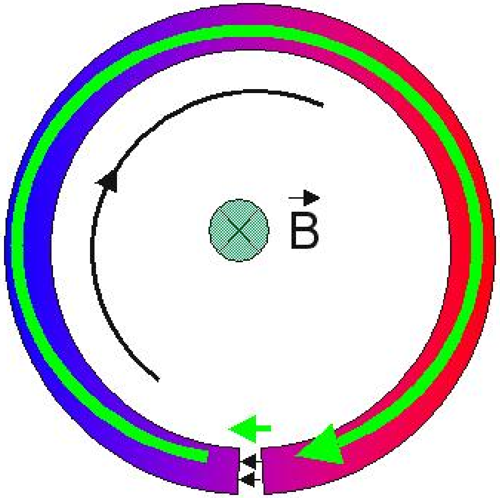




$$\mu_{eff} = 1 - \frac{\omega^2}{\omega^2 - \omega_0^2 + i\gamma\omega}$$

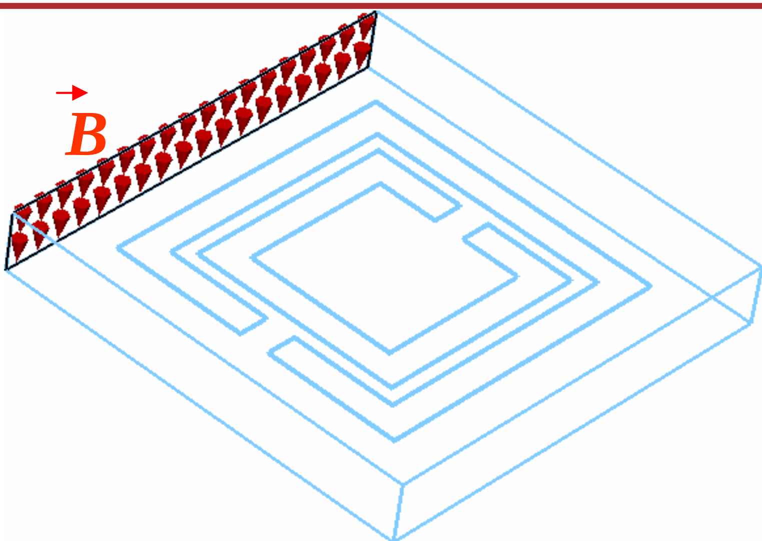
negative?!

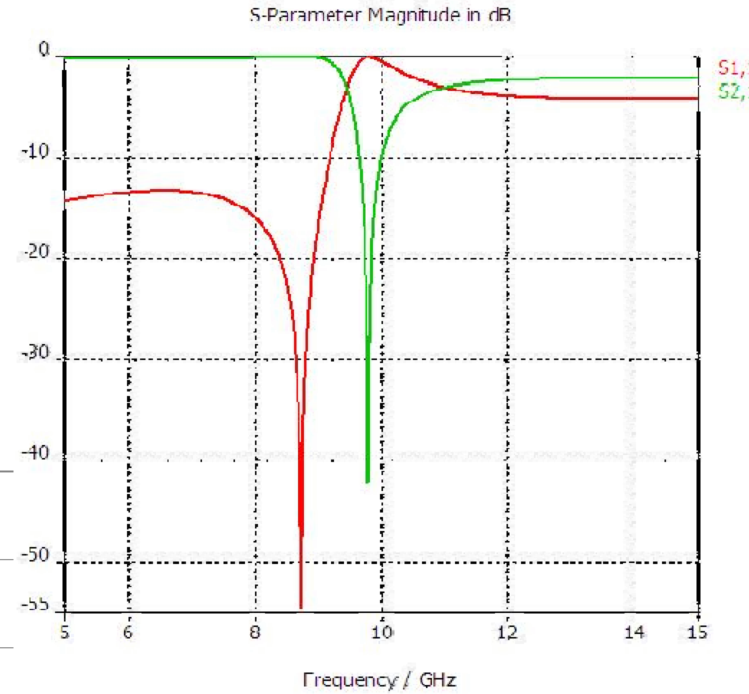


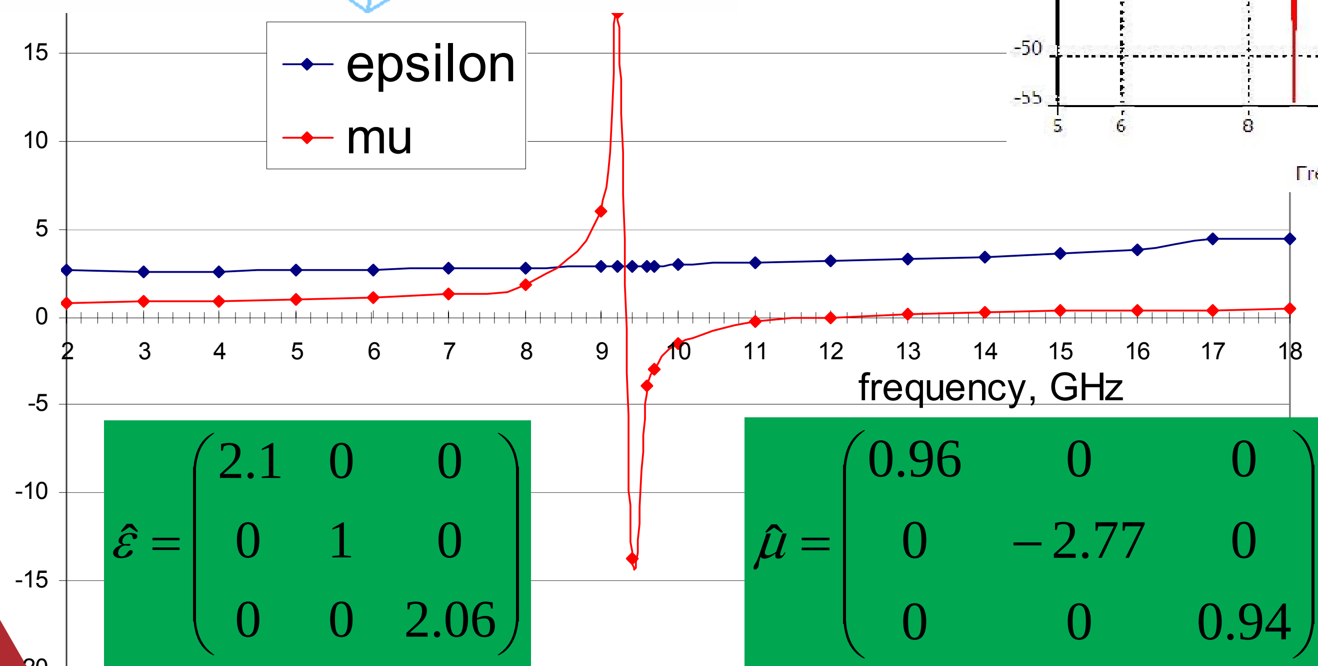


GHz design requires *mm*-scale elements to satisfy $\lambda >> d$ condition

Simulations







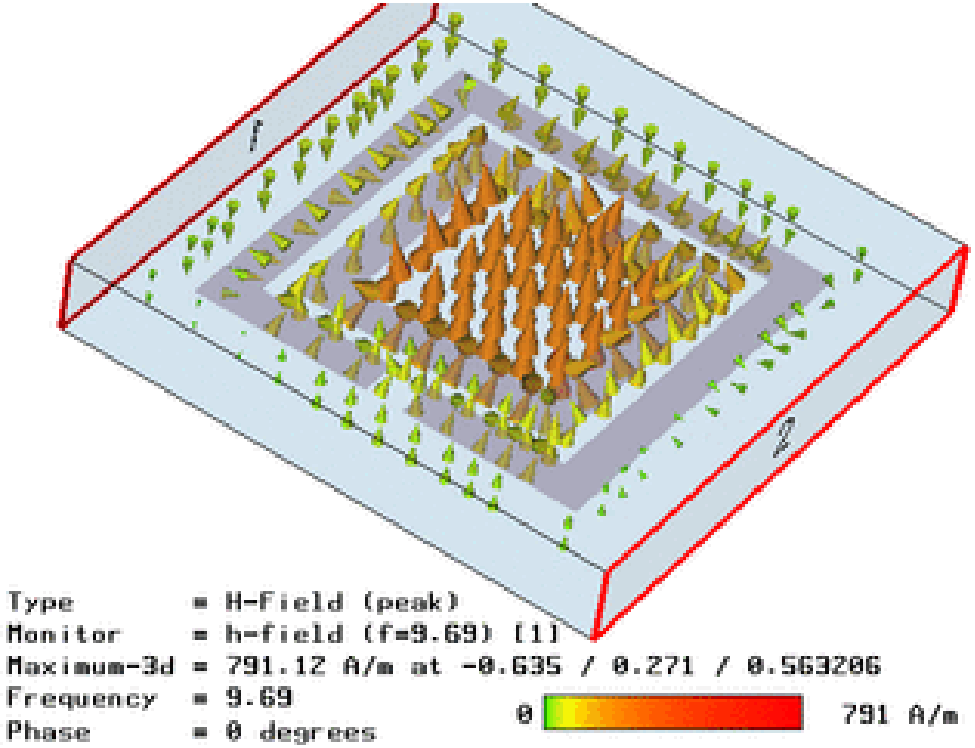
$$\hat{\varepsilon} = \begin{pmatrix} 2.1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2.06 \end{pmatrix}$$

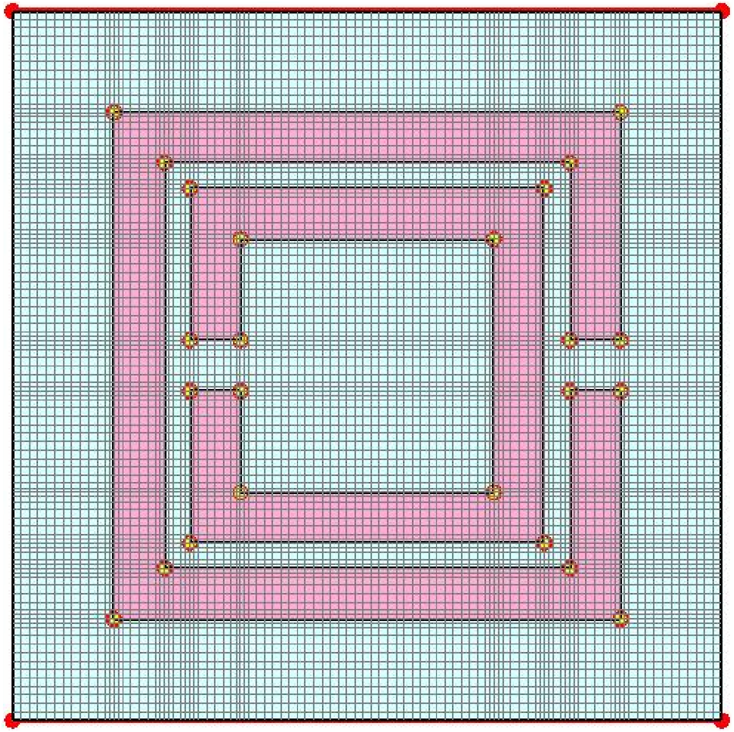
$$\hat{\mu} = \begin{pmatrix} 0.96 & 0 & 0 \\ 0 & -2.77 & 0 \\ 0 & 0 & 0.94 \end{pmatrix}$$

$$\Delta u = \frac{\varepsilon\mu}{c^2}\frac{\partial^2 u}{\partial t^2}$$

$$\mu_{eff} = 1 - \frac{\omega^2}{\omega^2 - \omega_0^2 + i\gamma\omega}$$

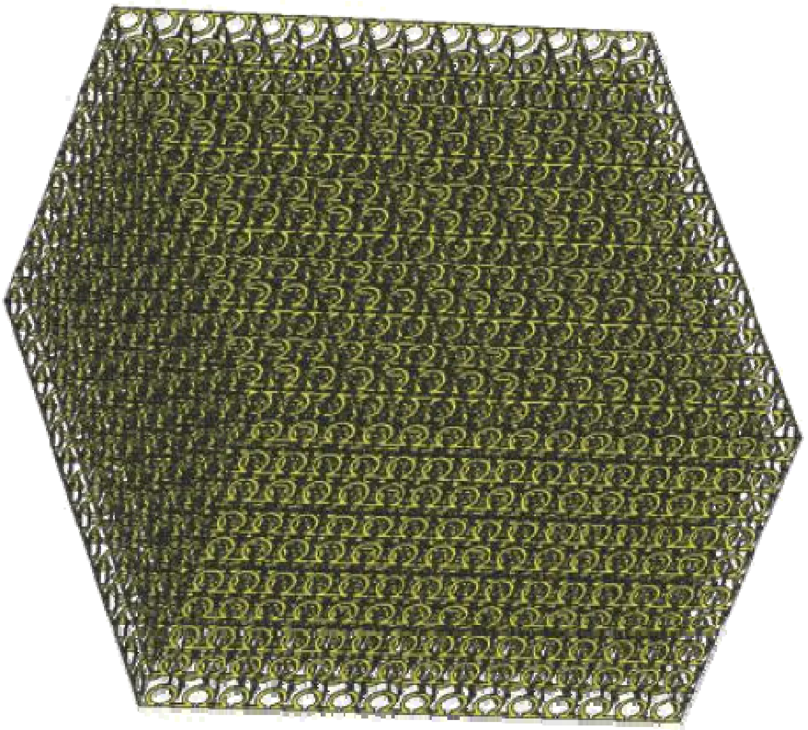
Simulations





$$\lambda >> d$$

Metamaterial vs. Dispersive, anisotropic media



LHM – left-handed media or metamaterial?

vs.

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix}$$

$$\varepsilon_1 = 1 - \frac{\omega_{pe}^2}{2i\gamma\omega + \omega^2} \qquad \varepsilon_{2,3} = 1$$

$$\hat{\mu} = \begin{pmatrix} \mu_1 & 0 & 0 \\ 0 & \mu_2 & 0 \\ 0 & 0 & \mu_3 \end{pmatrix}$$

$$\mu_2 = 1 + \frac{F\omega^2}{\omega_{m0}^2 - 2i\alpha_m\omega - \omega^2} \qquad \mu_{1,3} = 1$$

At the end of the day…

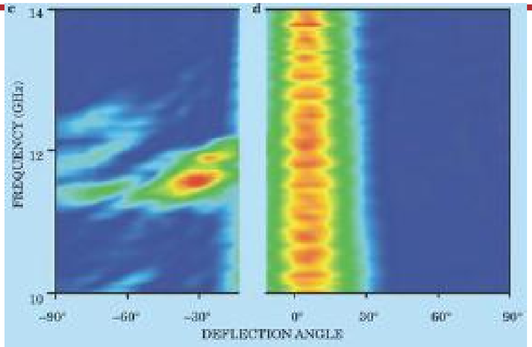
- We can design artificial materials with specific electromagnetic properties, at certain frequencies, needed for particular application

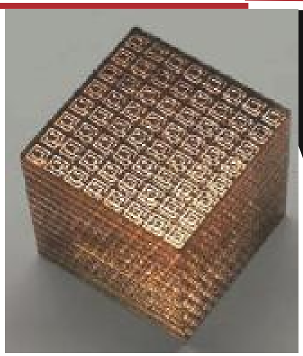
- We are also able to produce artificial materials with properties, that were not observed in natural materials, such as $\varepsilon<0$ and $\mu<0$ at some frequency ω
  - *This can lead to new types of devices*

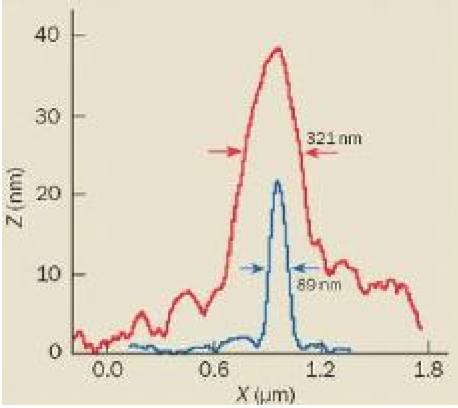
Media with ε<0 and μ<0 is called **Double-Negative (DNM)**or **Left-Handed (LHM)**

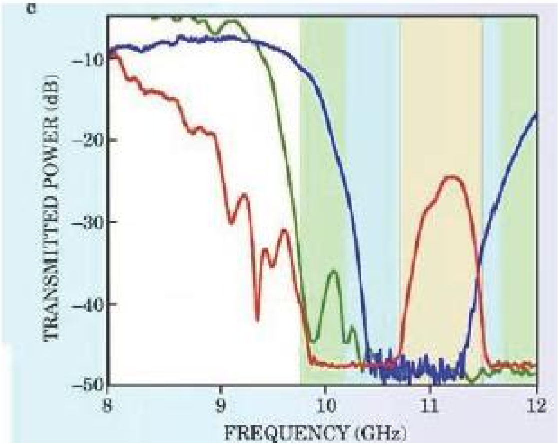
History of research

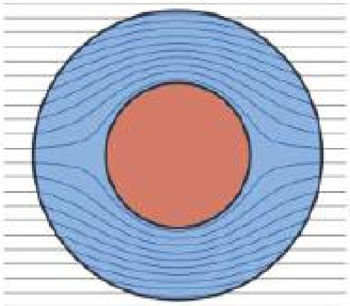
- 1967 properties of media with ε<0, μ<0
- 1996 wire array (Imperial college)
- 1999 split ring design (Imperial college)
- 2000 superlens proposal (Imperial college)
- 2000 experimental demonstration (srr+wire array, GHz) (UCSD)
- 2001 negative refraction (srr+wire array, GHz) (UCSD)
- 2004-2005 THz designs
- 2005 optical (nanopairs, Purdue)
- 2005 “near-sighted superlens” (silver film, UC Berkeley)
- 2006 cloaking device idea and proof of principal demonstration

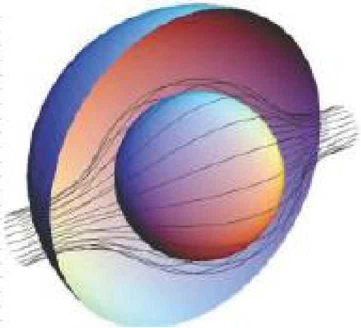








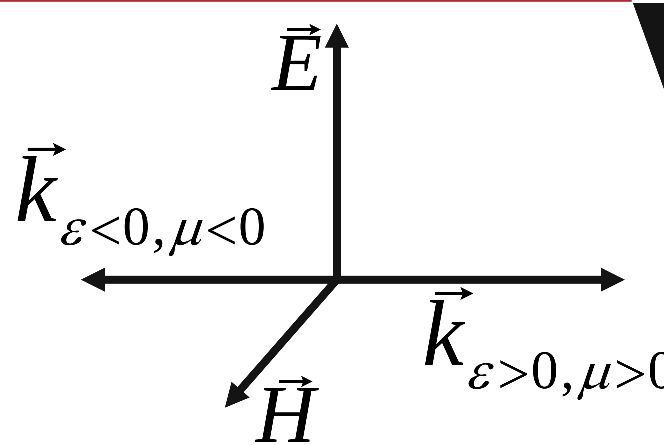




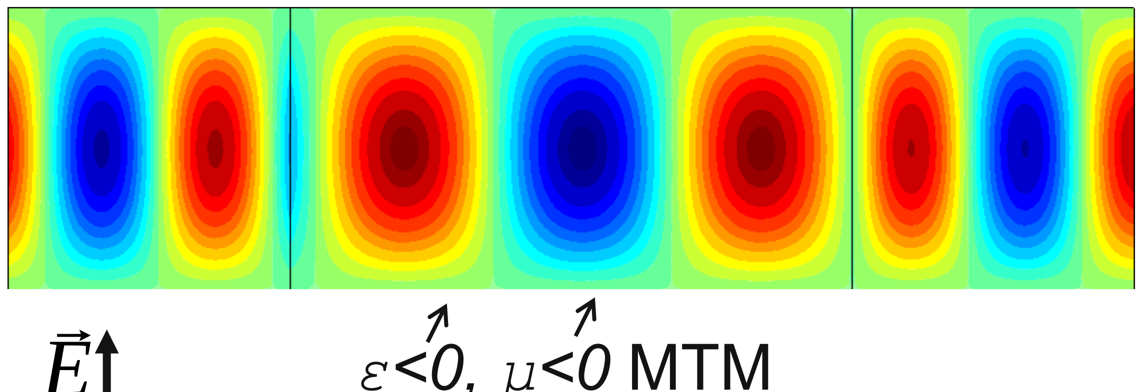
Left-Handed or Double Negative metamaterials (ε<0, μ<0)

$$\begin{cases} \left[\vec{k},\vec{H}\right] = -\dfrac{\omega}{c}\varepsilon\vec{E} \\ \left[\vec{k},\vec{E}\right] = \dfrac{\omega}{c}\mu\vec{H} \end{cases}$$

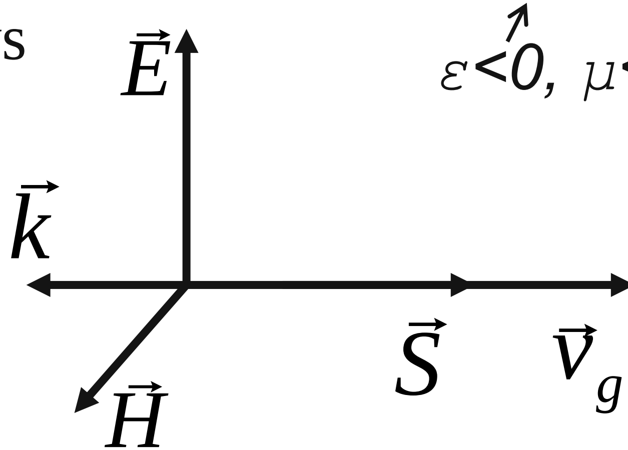
form left-handed vector system instead of usual right-handed.



$$\vec{S} \overset{def}{=} \frac{c}{4\pi}\left[\vec{E},\vec{H}\right]$$

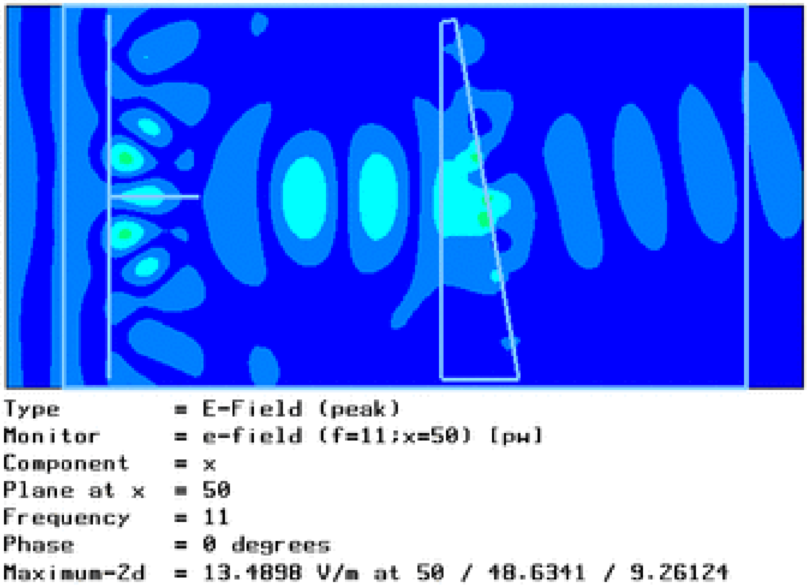


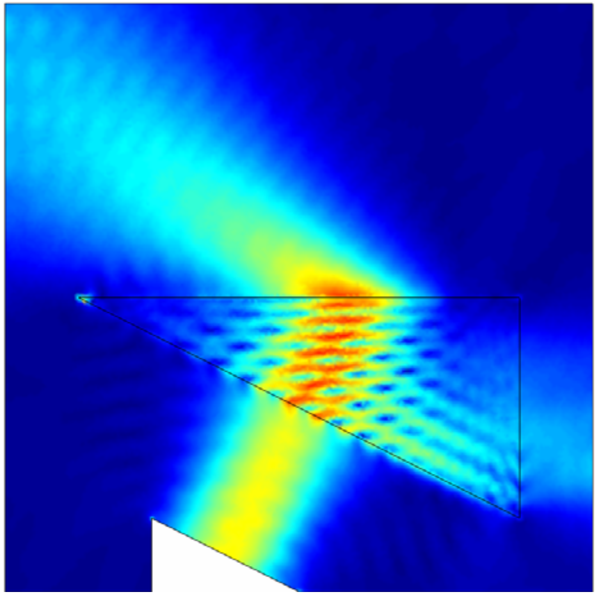
Poynting vector always forms a right-handed system with the field vectors

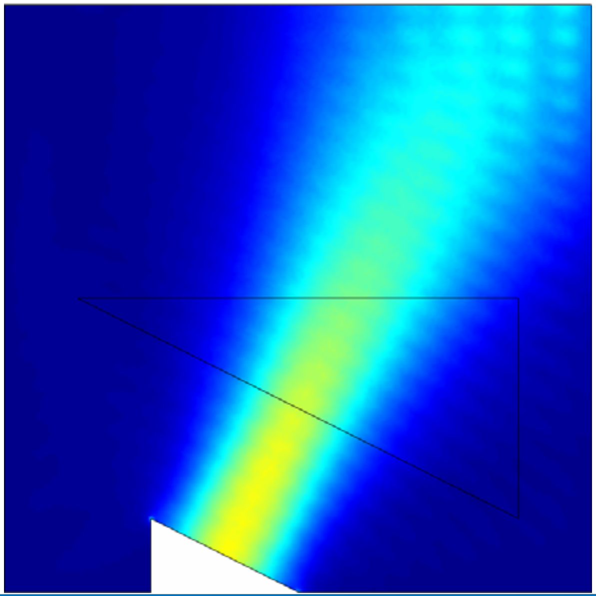


Energy propagates counterdirected to the phase front.

Negative refraction





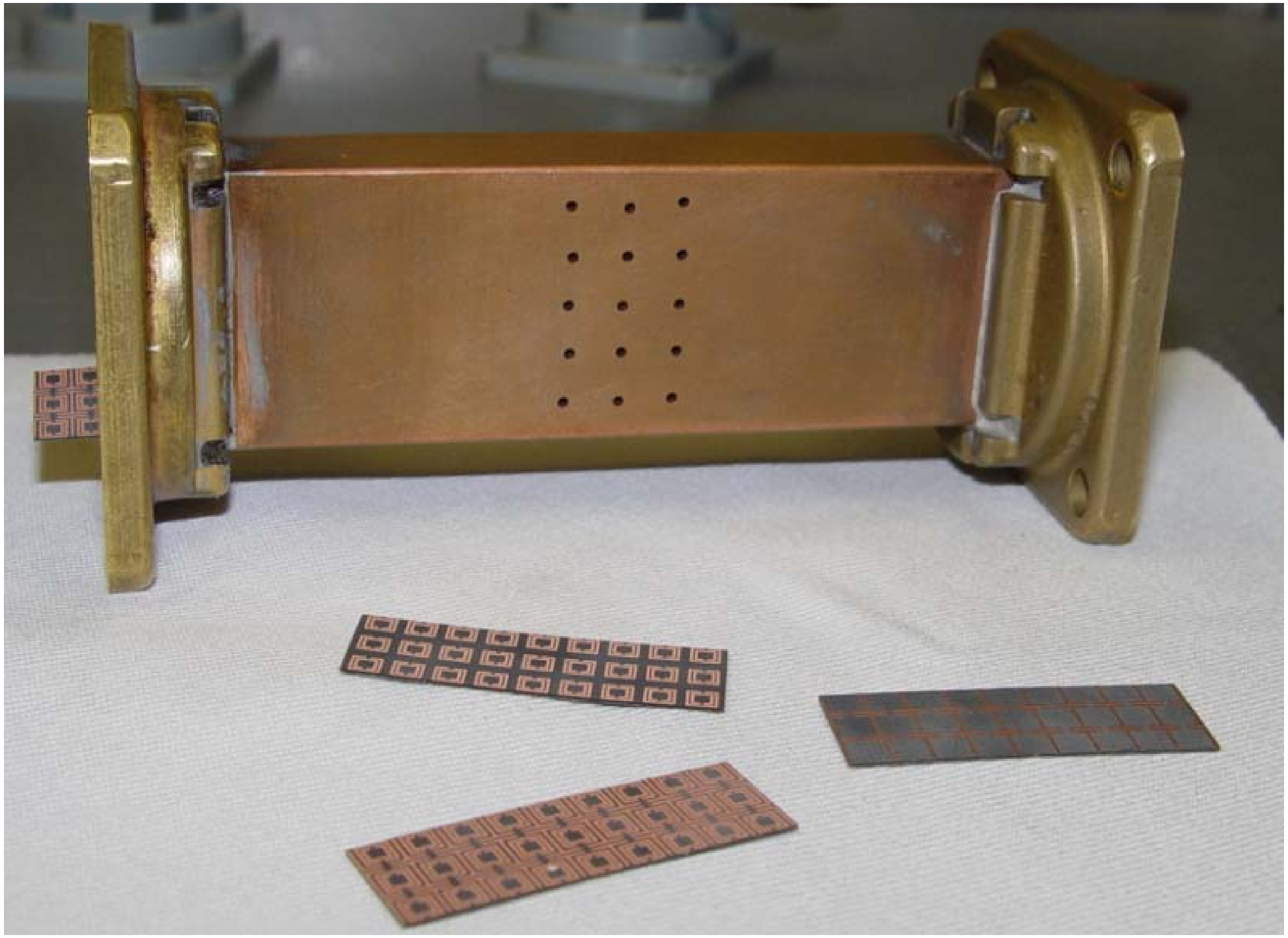


$$n = -\sqrt{\left|\varepsilon_{xr}\mu_{yr}\right|}\left[1 - \frac{i}{2}\left(\frac{\varepsilon_{xi}}{\left|\varepsilon_{xr}\right|} + \frac{\mu_{yi}}{\left|\mu_{yr}\right|}\right)\right]$$

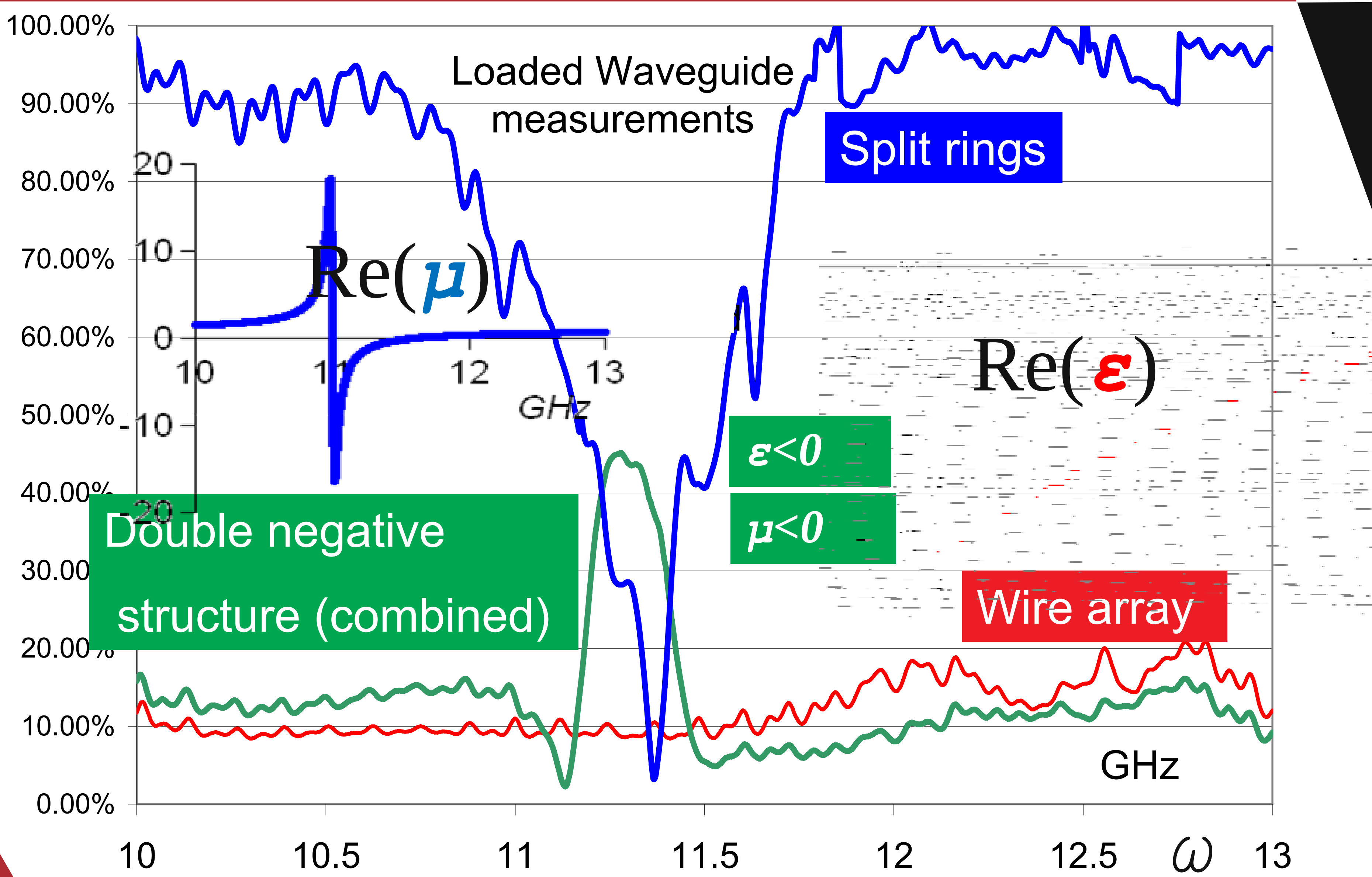
We repeated the original experiment

TE_{10} mode in MTM-loaded waveguide (experiment)

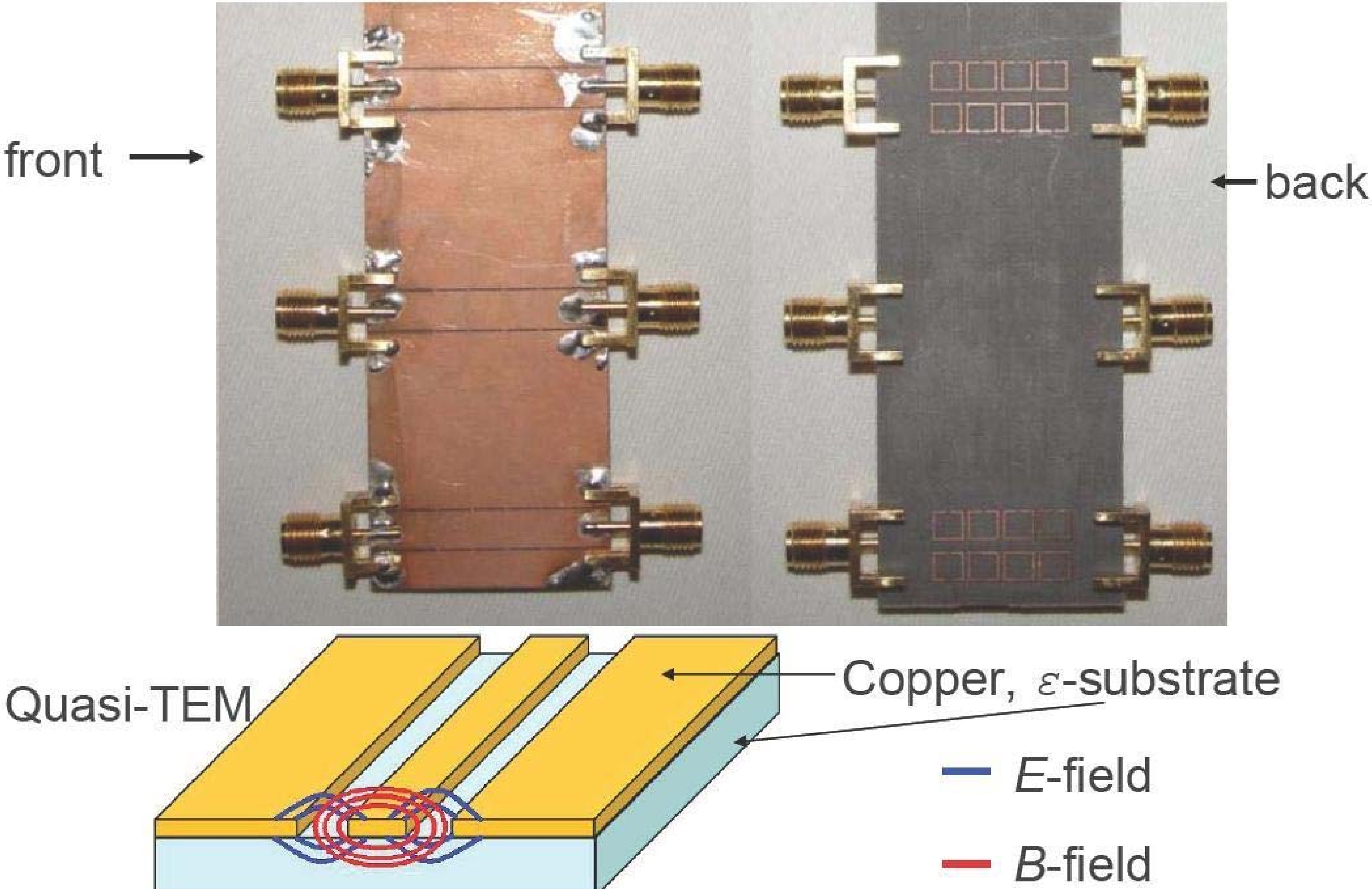
We study the effects of metamaterial insertions on transmission through the waveguide. Note Anisotropy. Dispersion engineering



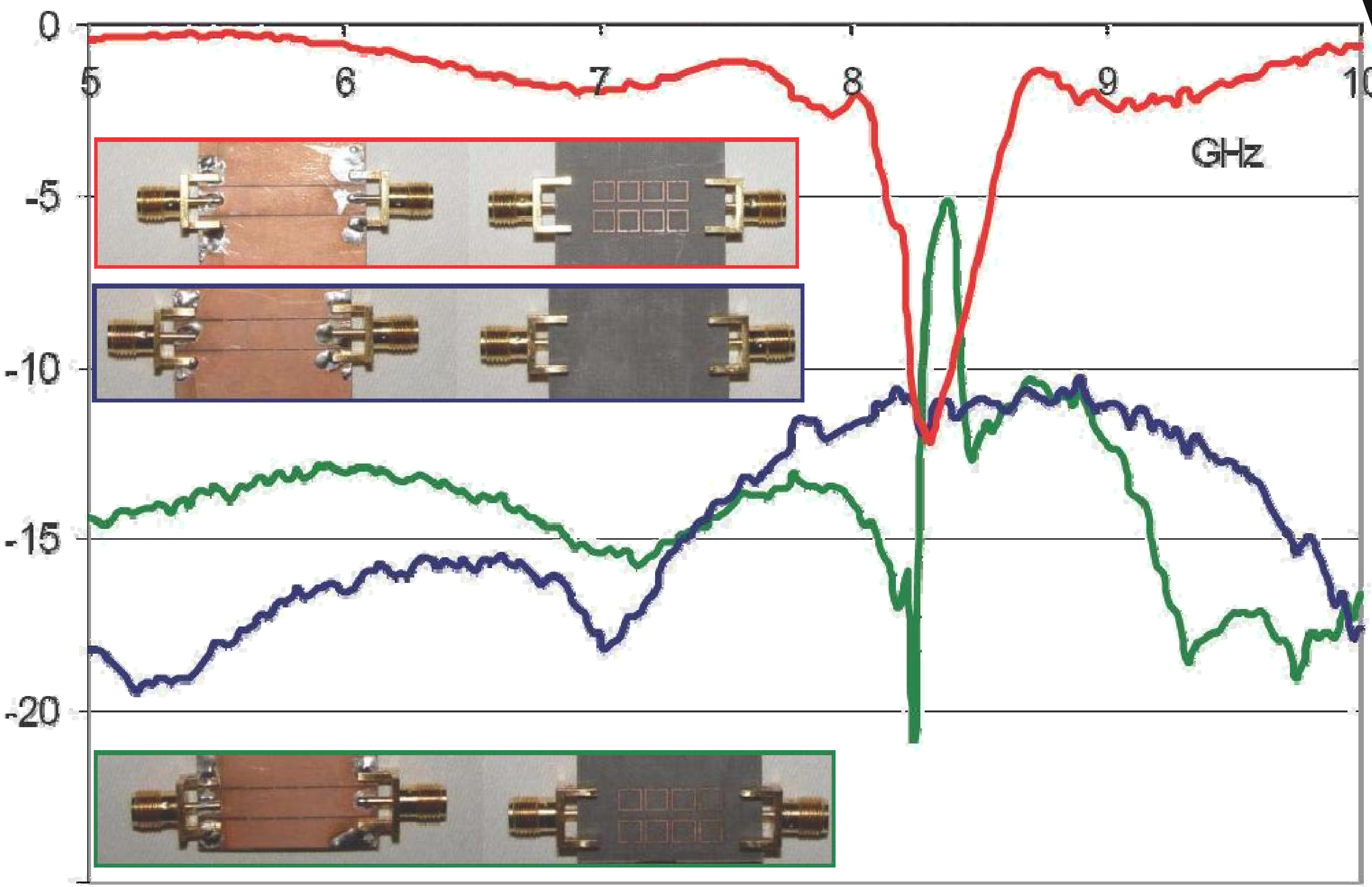
TE_{10} mode in MTM-loaded waveguide (experiment)



Metamaterials and Coplanar waveguides

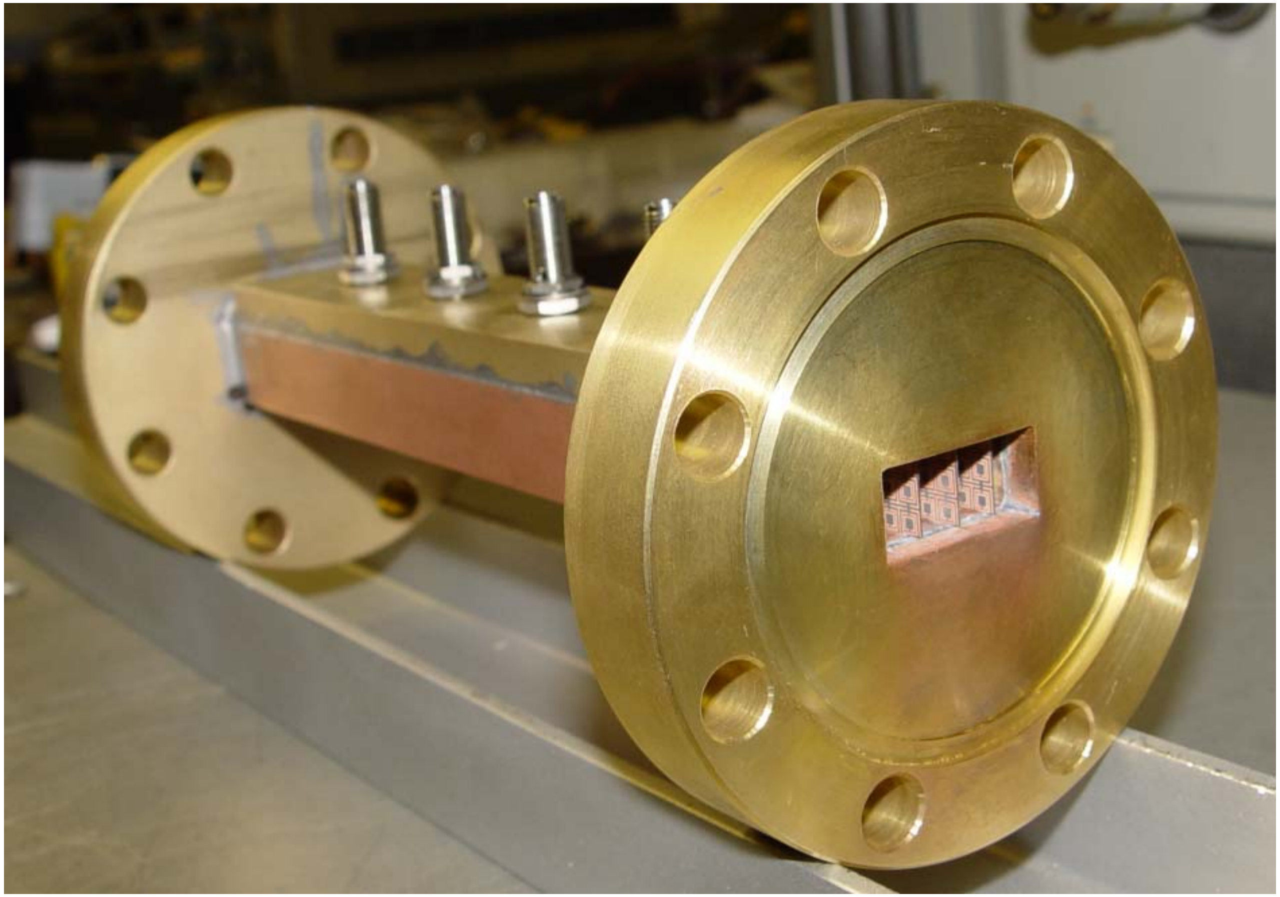


Results. Compact band pass filter. Transmission.



Accelerator applications:

- Particle – metamaterial interaction => Cherenkov synchronism



Argonne Wakefield Accelerator Facility

- RF Single klystron: 1.3 GHz, 24 MW, 8μs
- Photoinjector: 1½ cell, currently running with Mg photocathode
- Charge per bunch: 1 to 100 nC
- Bunch length: 14 ps FWHM
- Maximum energy(after high current LINAC): 14 MeV
- Length: ~7 meters

  – Brief history:

The AWA Facility successfully demonstrated

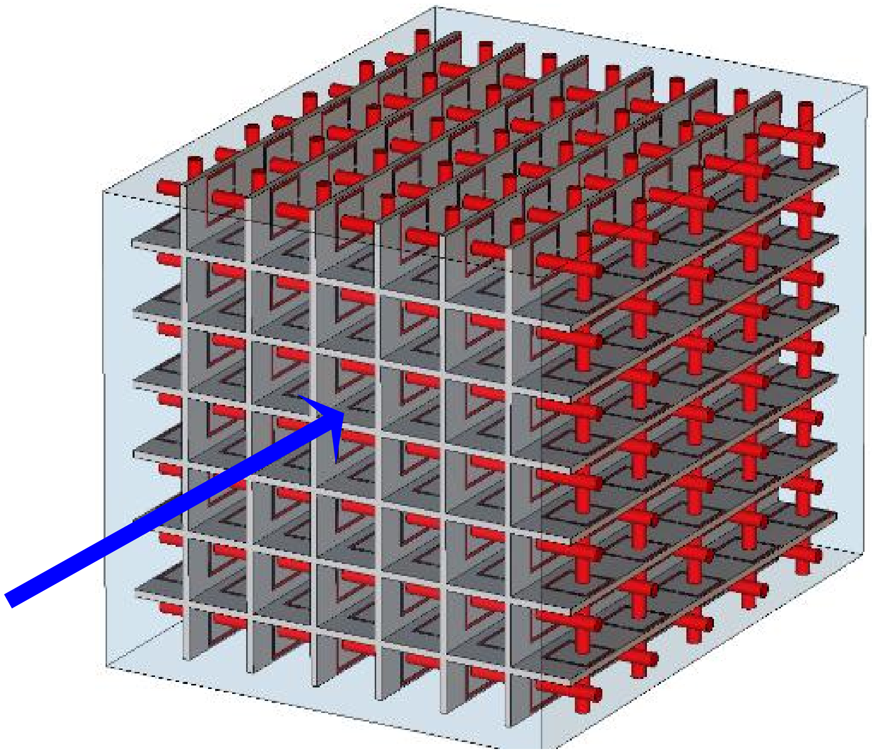
- *collinear wakefield acceleration*
- *two-beam-acceleration in dielectric loaded structures*
- *the upgraded drive gun has led to increasingly higher gradients, recently reaching **100 MV/m**.*

http://www.hep.anl.gov/awa/

TM Modes in MTM Loaded Waveguide (z-oriented)

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix}$$

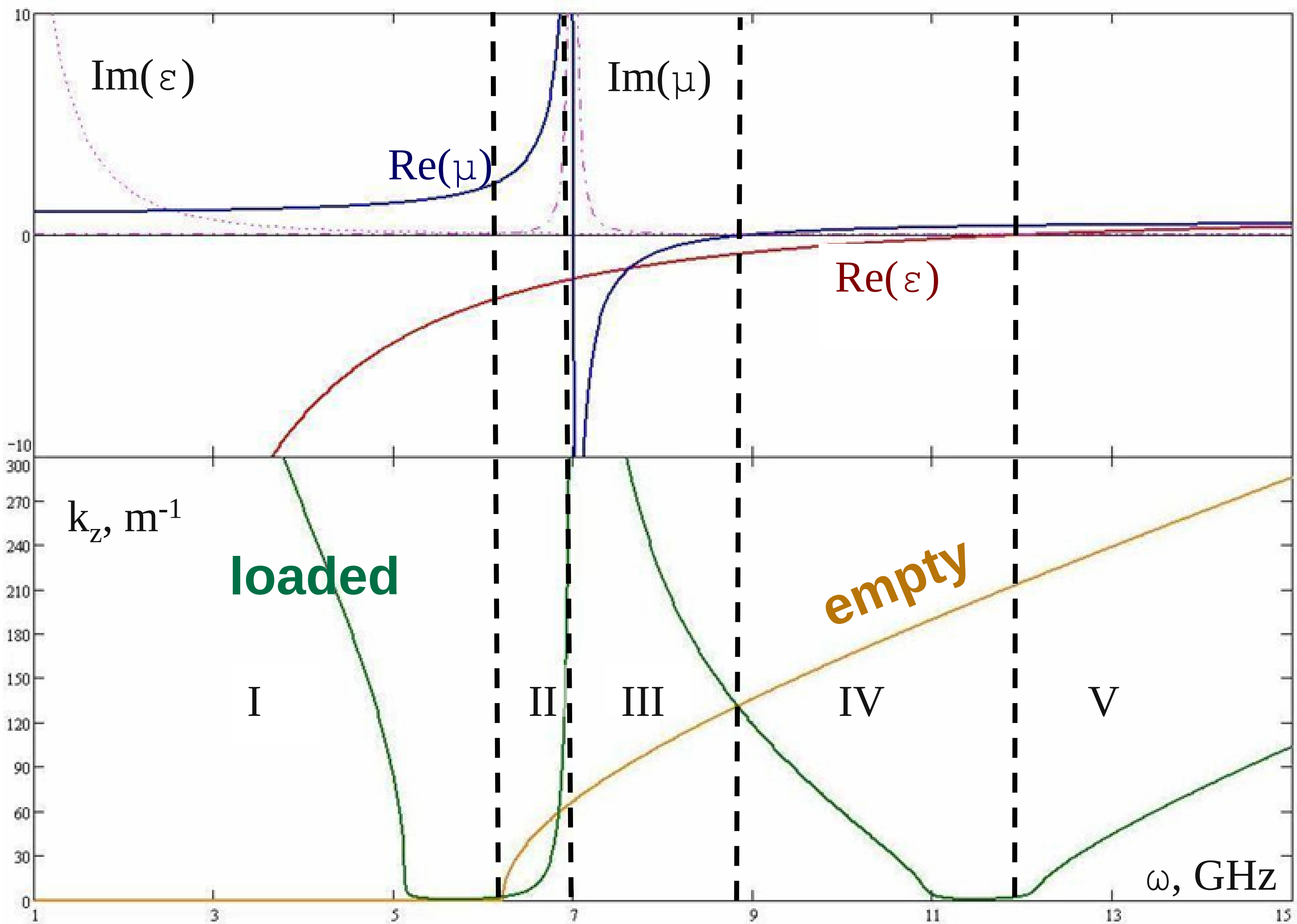
$$\hat{\mu} = \begin{pmatrix} \mu_\perp & 0 & 0 \\ 0 & \mu_\perp & 0 \\ 0 & 0 & \mu_\parallel \end{pmatrix}$$



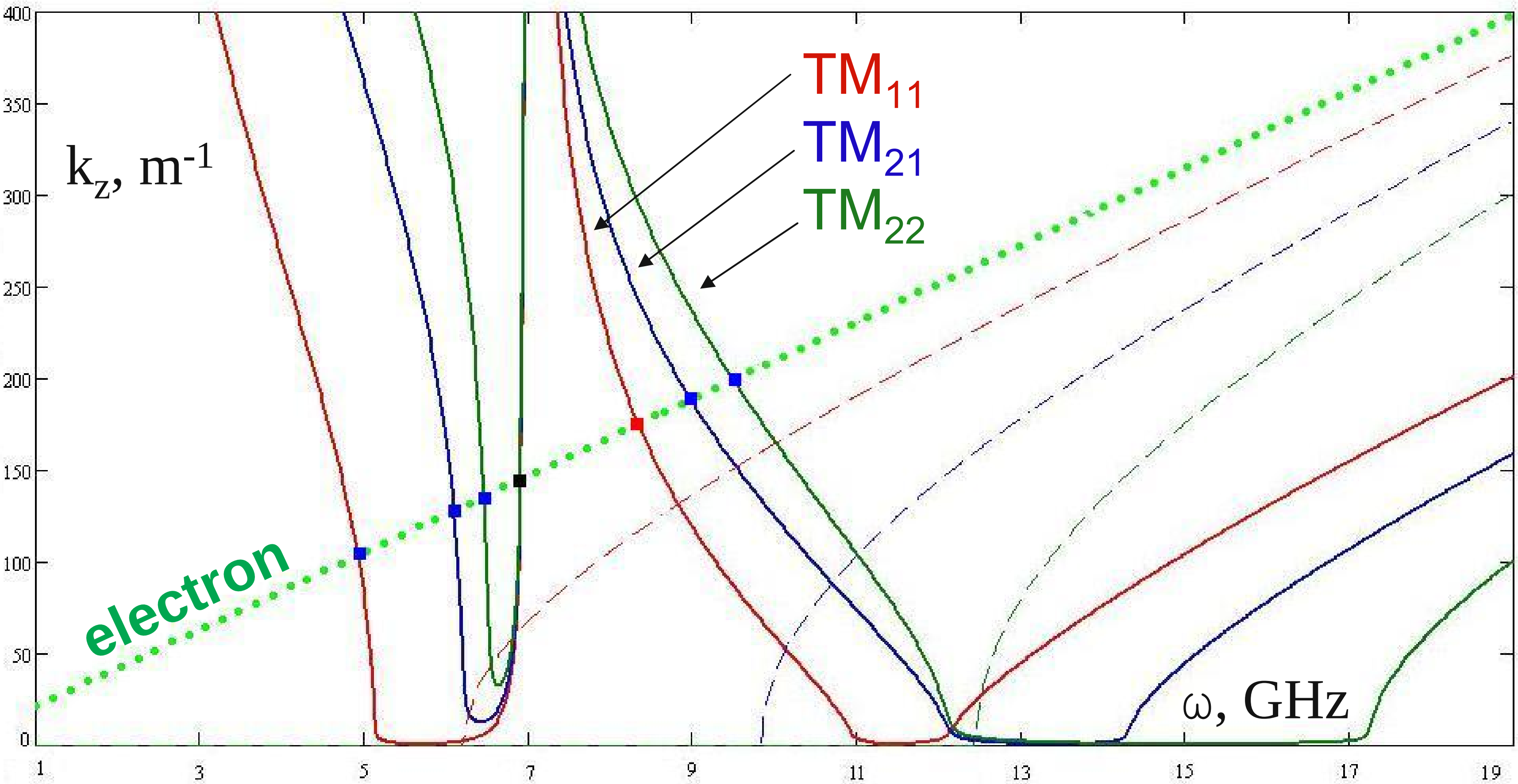
Dispersion for TM modes in rectangular waveguide:

$$k_z = k_0 \sqrt{\varepsilon_\perp \mu_\perp \left(1 - \frac{\chi_x^2 + \chi_y^2}{\varepsilon_\parallel \mu_\perp k_0^2} \right)}$$

Dispersion of TM modes in MTM-loaded waveguide

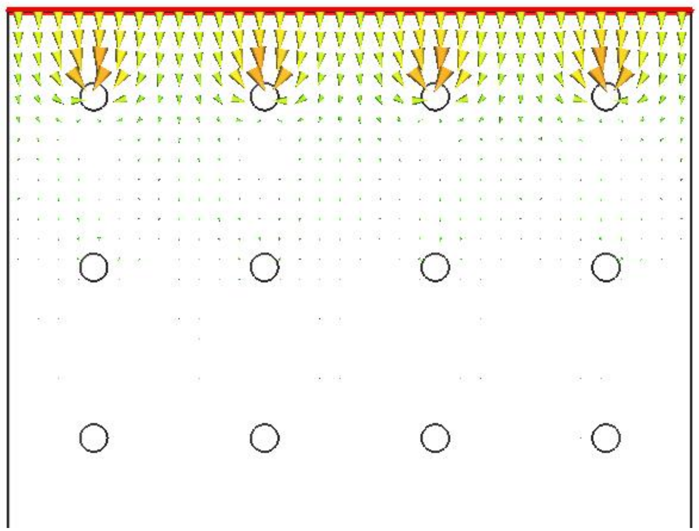


Mode excitation analysis



- Provides frequency of generation for each mode
- Does not provide energy exchange (beam dependent)

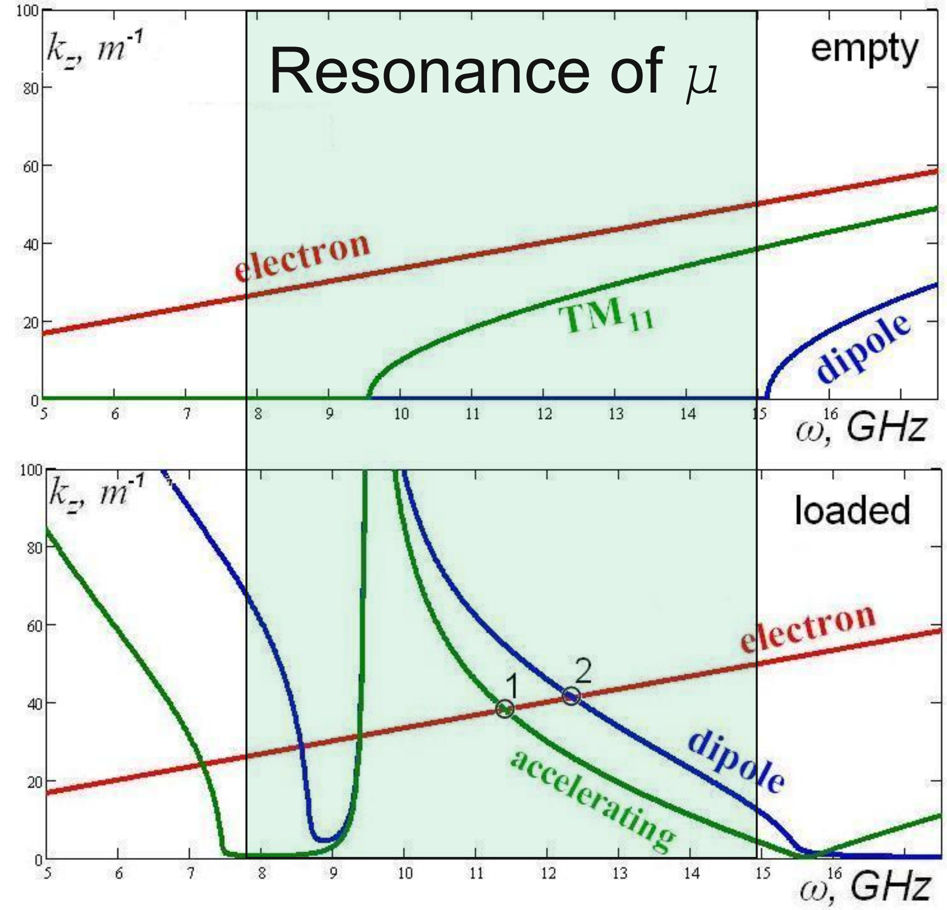
Application: accelerator with dipole mode suppression



Non-magnetic regime does not exist for wire array!

This is an idea:

We do not discuss losses, mode coupling, breakdown, charging etc..

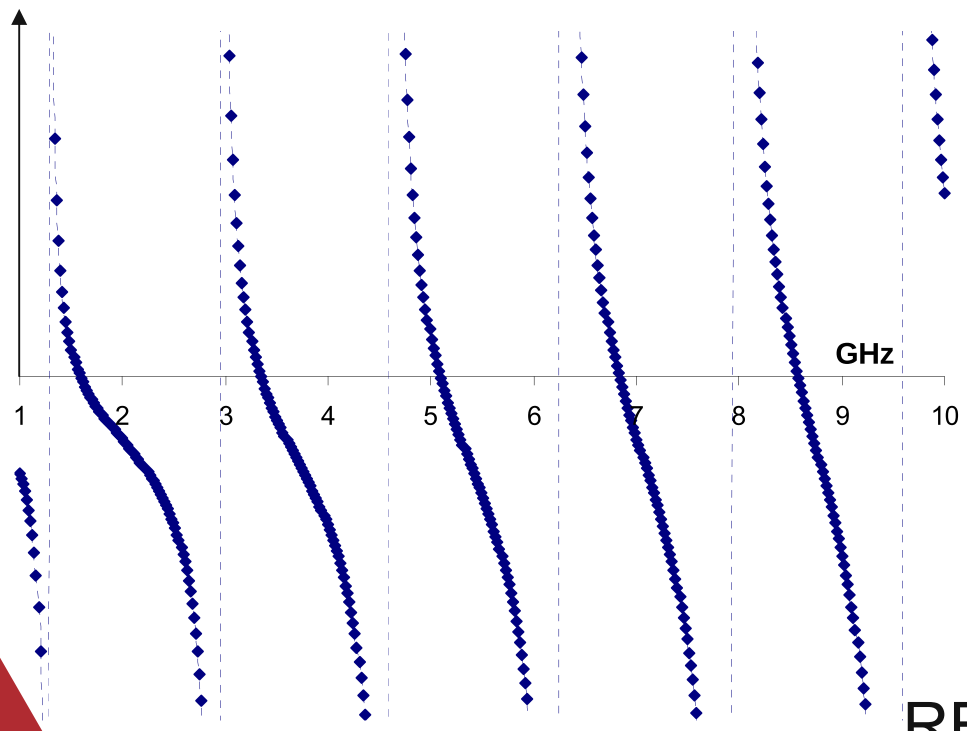


High order modes synchronize in non-magnetic region

Wakefield calculation in metamaterial-loaded waveguides

- Long waveguide of any cross section
- Uniformly (⊥) loaded with anisotropic and dispersive media
- "Pancake" beam (δ(z-vt)) passing along waveguide axis
- Fourier transform in time and z → 2D simulation with parameter *ω*

$E_{z,\omega}(x, y, \omega)$



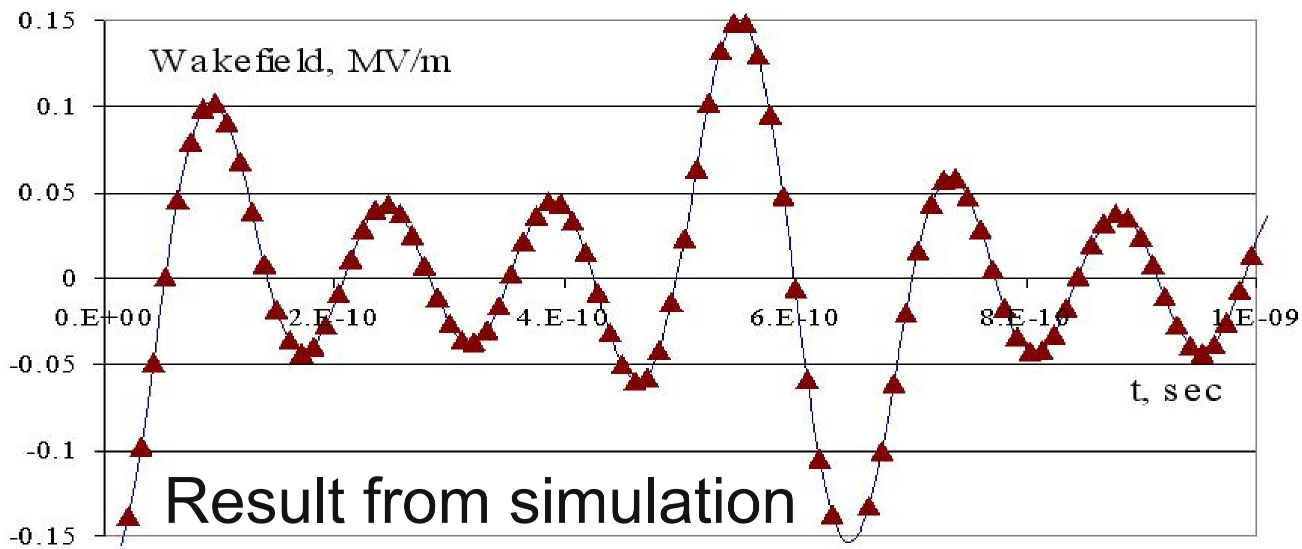
Divergences corresponds to poles of inverse Fourier trasform

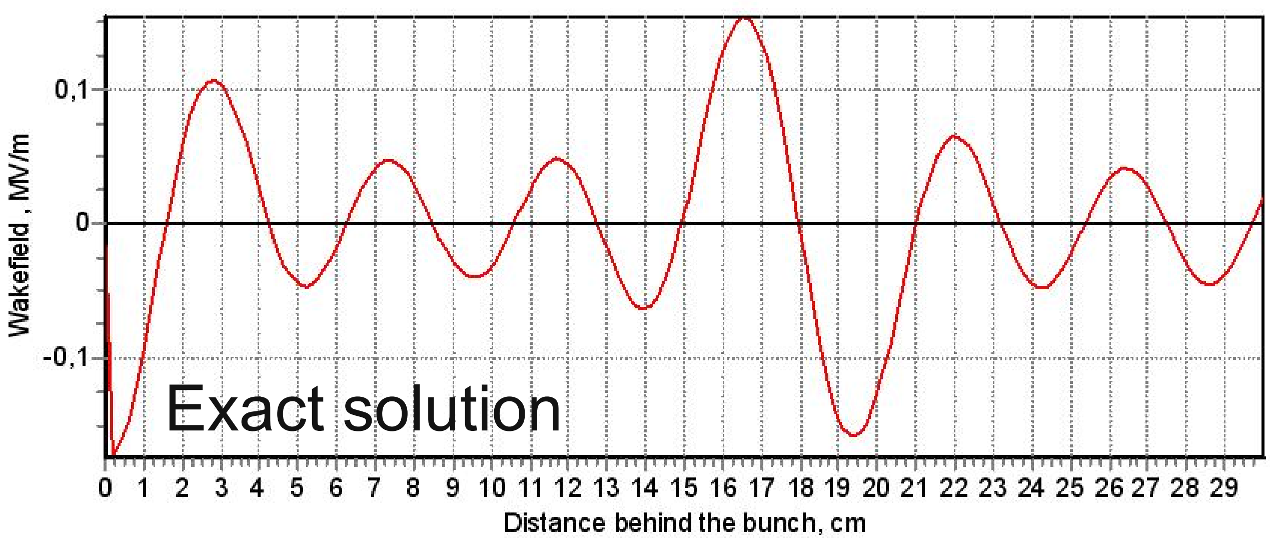
Postprocessing:

1. FFT for simple cases
2. Direct spectrum calculation through residue method

RES(f, z=z0)=Lim(f(z)(z-z0), z→z0)

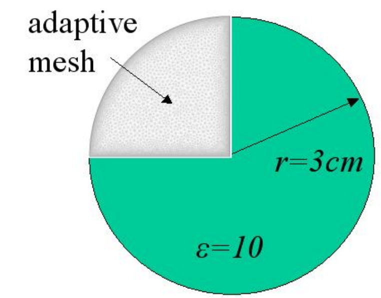
Wakefield: comparison with Dielectric-loaded Accelerator





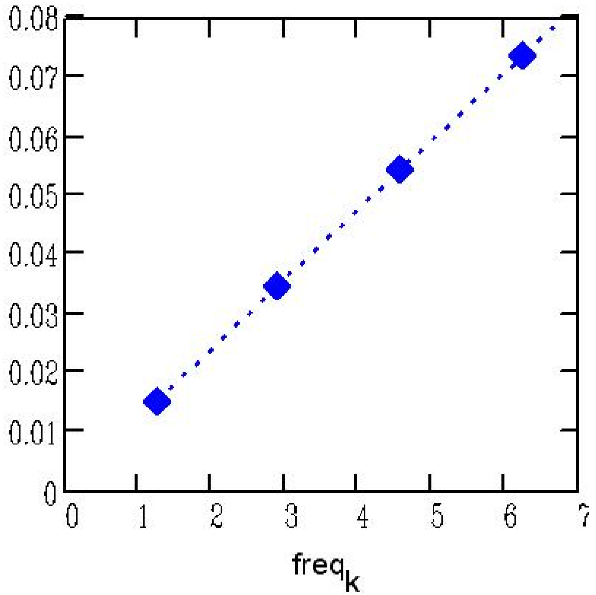
Cylinder waveguide, *R=3cm, ε=10, 1nC beam, 5MeV energy*

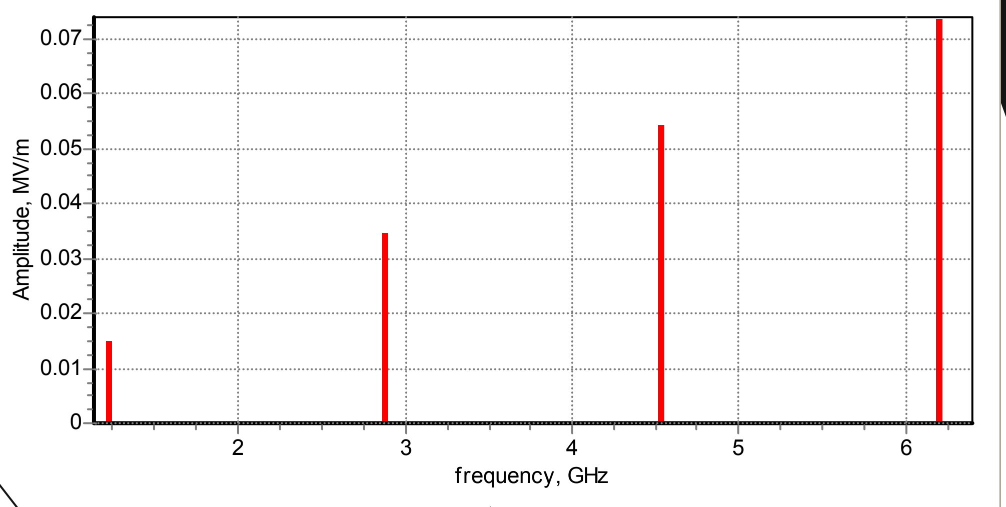
E_z field behind the bunch, MV/m



DLA script by
A. Kanareykin et al.

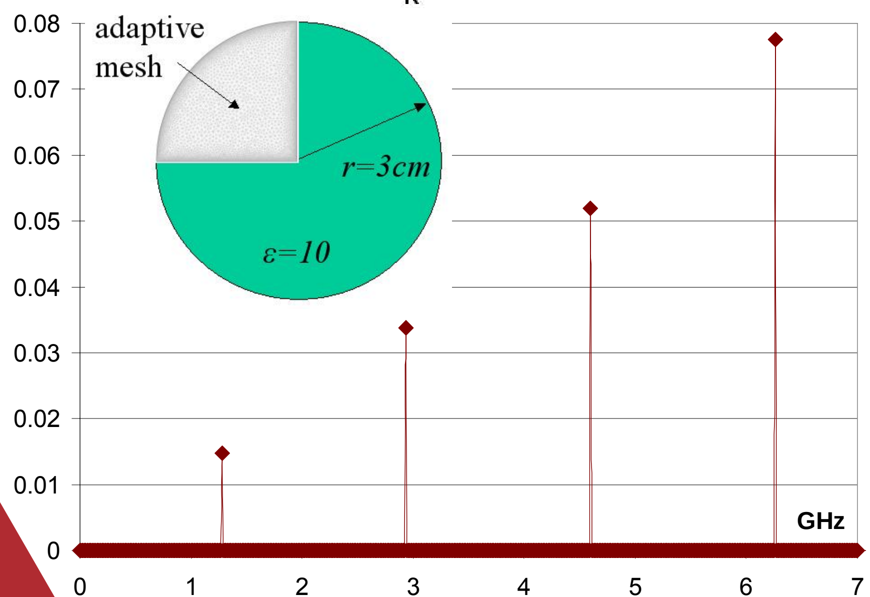
Excitation spectrum: comparison continued..





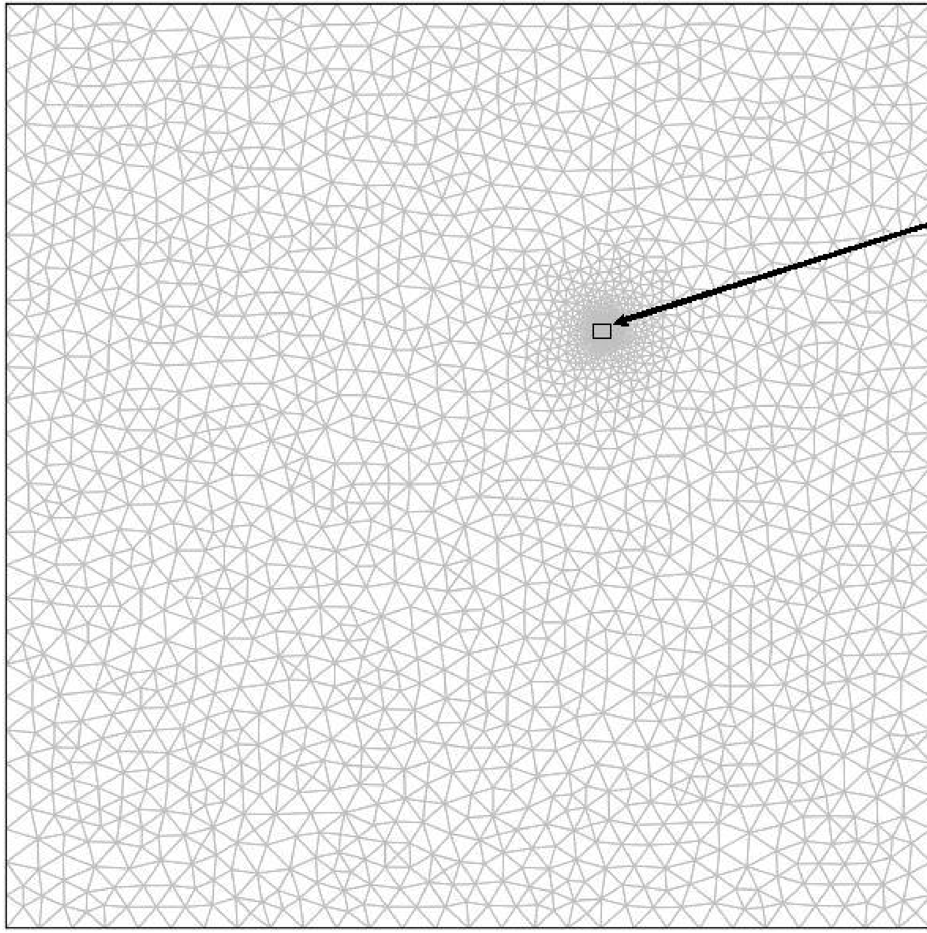
A. Kanareykin (Euclid)

J. Power, W. Gai (AWA)

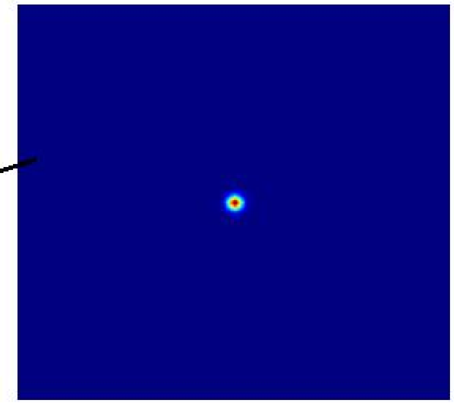


Results from simulation

Waveguide loaded with anisotropic and dispersive media



34.036mm



20 micron

FEM simulation.

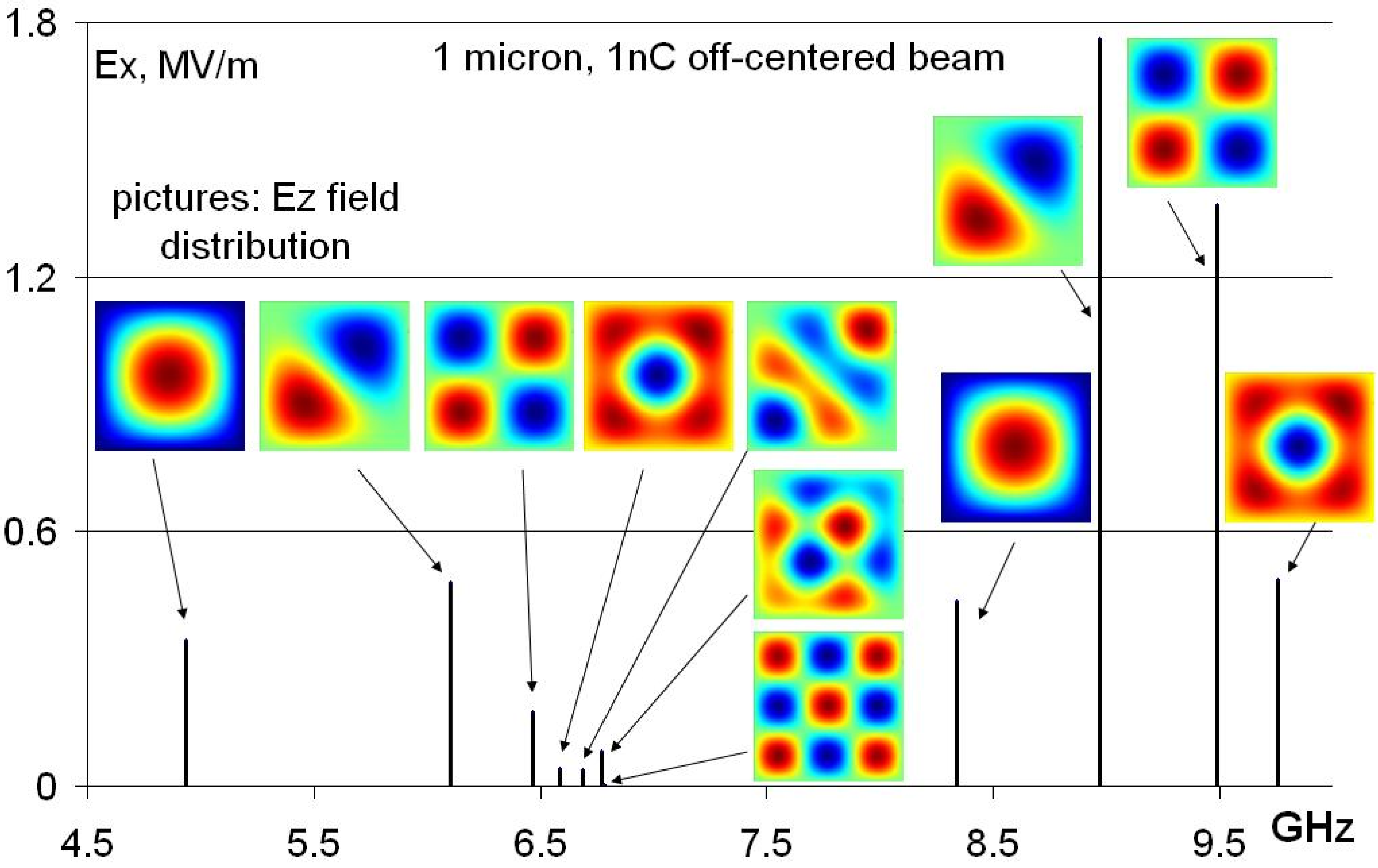
Irregular mesh allows to resolve point-like sources!

$$\varepsilon_{\perp} = 1 + \frac{\omega_{pe}^2}{\omega_{re}^2 - 2i\omega_{de}\omega - \omega^2} \qquad \mu_{\parallel} = 1$$

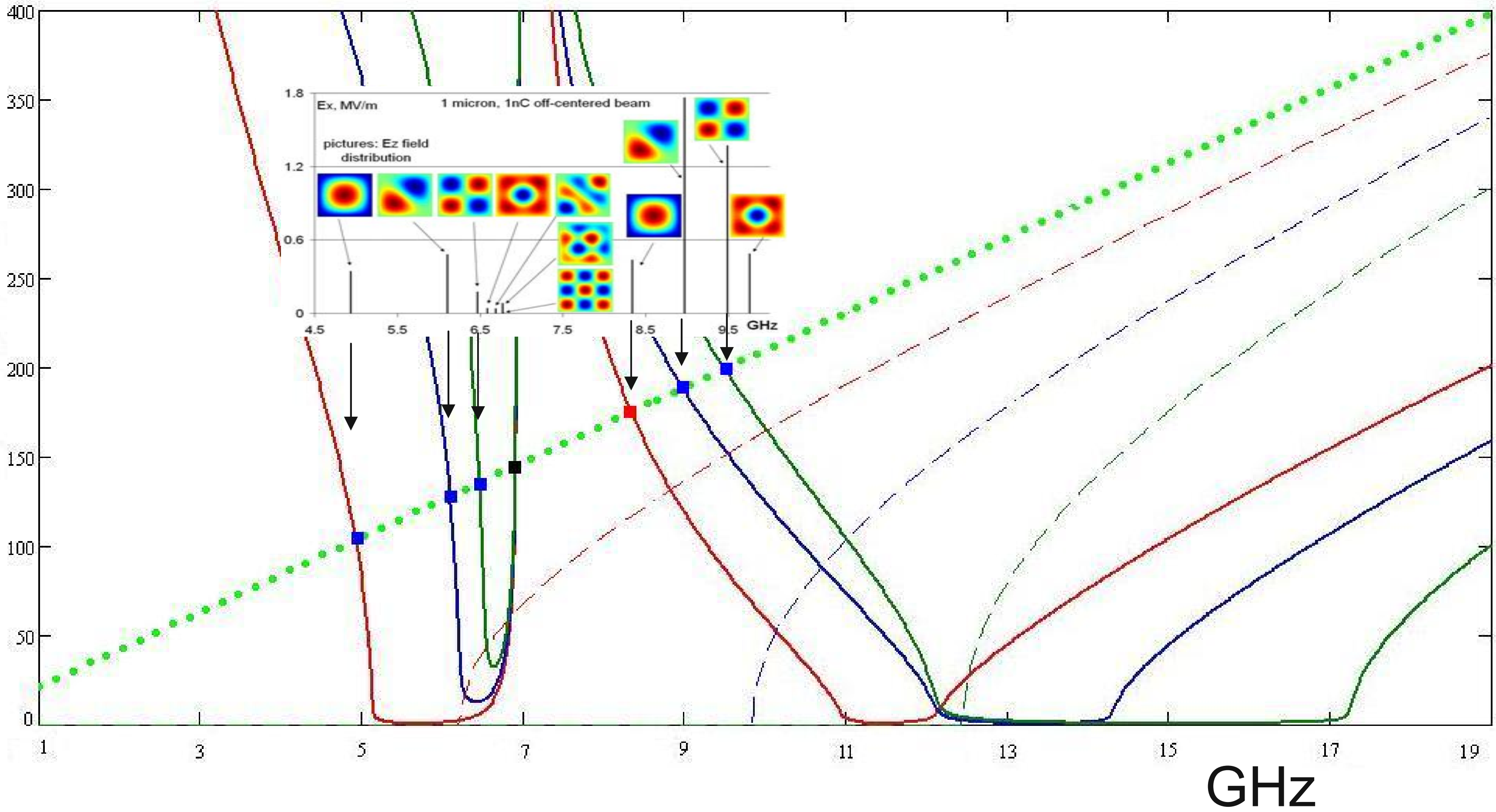
$$\mu_{\perp} = 1 + \frac{F\,\omega^2}{\omega_{rm}^2 - 2i\omega_{dm}\omega - \omega^2} \qquad \varepsilon_{\parallel} = 1$$

$$-\varepsilon_{\perp}\Delta_{\perp}E_0 + \left(\varepsilon_{\parallel}\left(\frac{\omega}{v}\right)^2 - k_0^2\varepsilon_{\parallel}\varepsilon_{\perp}\mu_{\perp}\right)E_0 = i\cdot 4\pi\cdot\omega\cdot q\cdot T(x,y)\cdot\left(\frac{\varepsilon_{\perp}\mu_{\perp}}{c^2} - \frac{1}{v^2}\right)$$

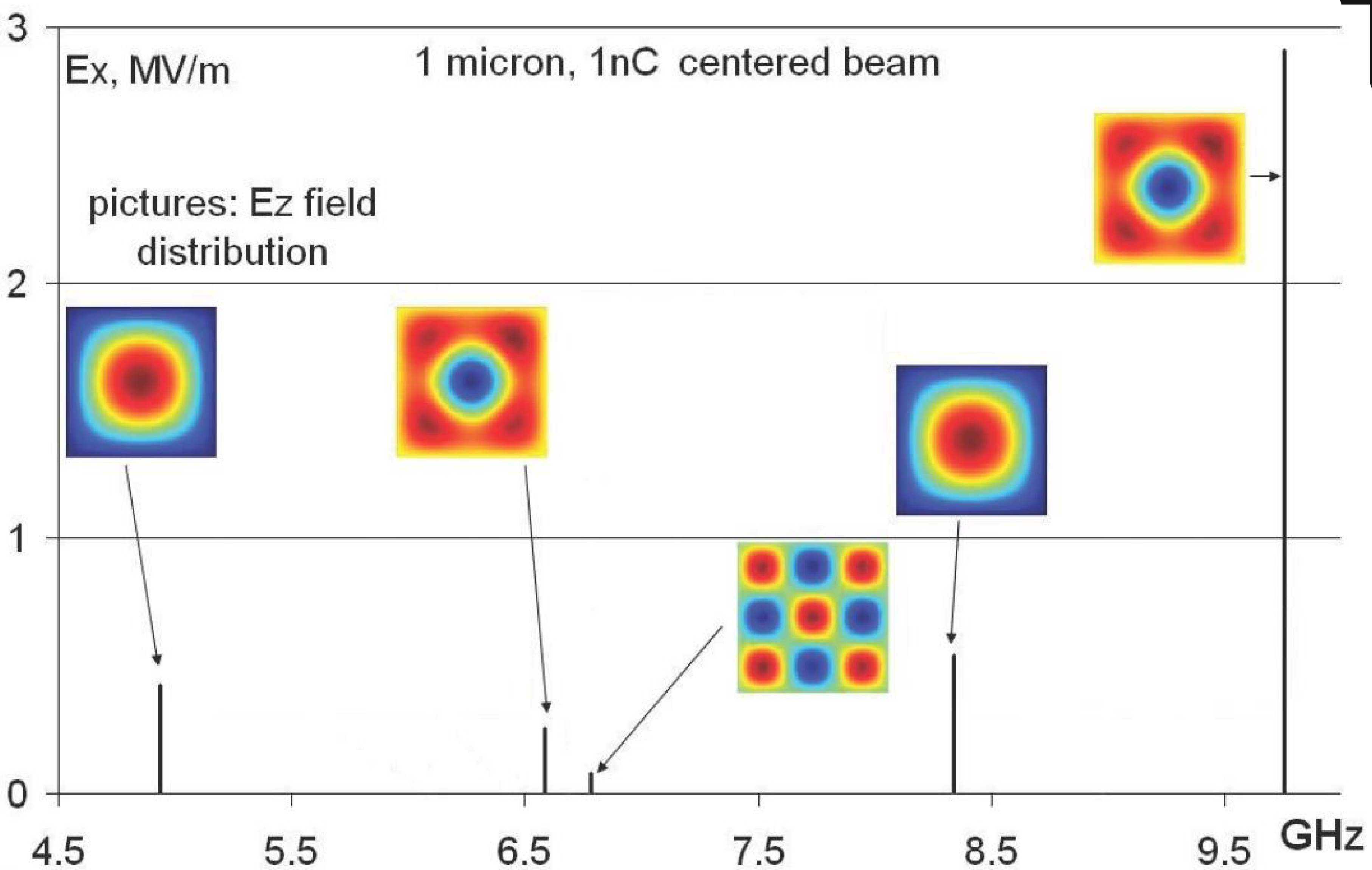
Simulation results: Excited spectrum, off-centered beam



Comparison with dispersion analysis

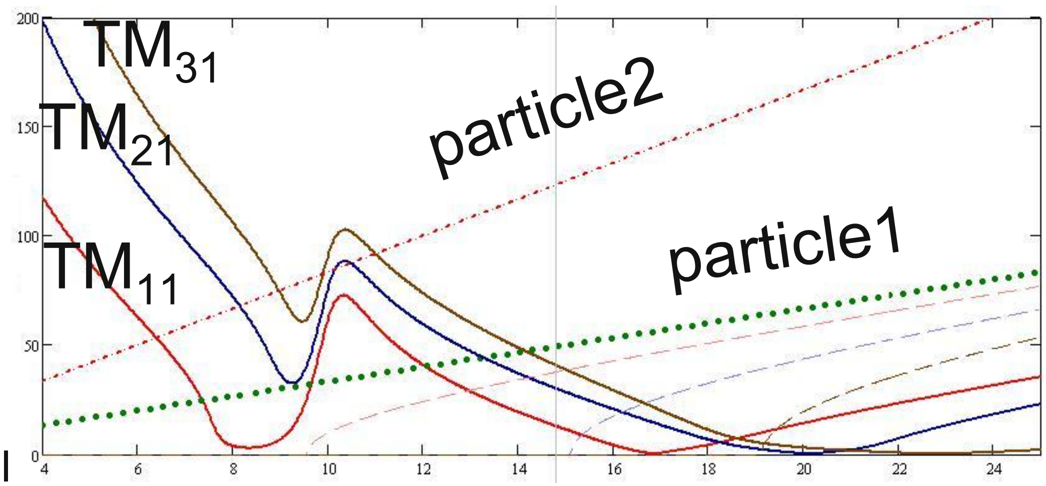


Simulation results: Excited spectrum, centered beam



Detection applications

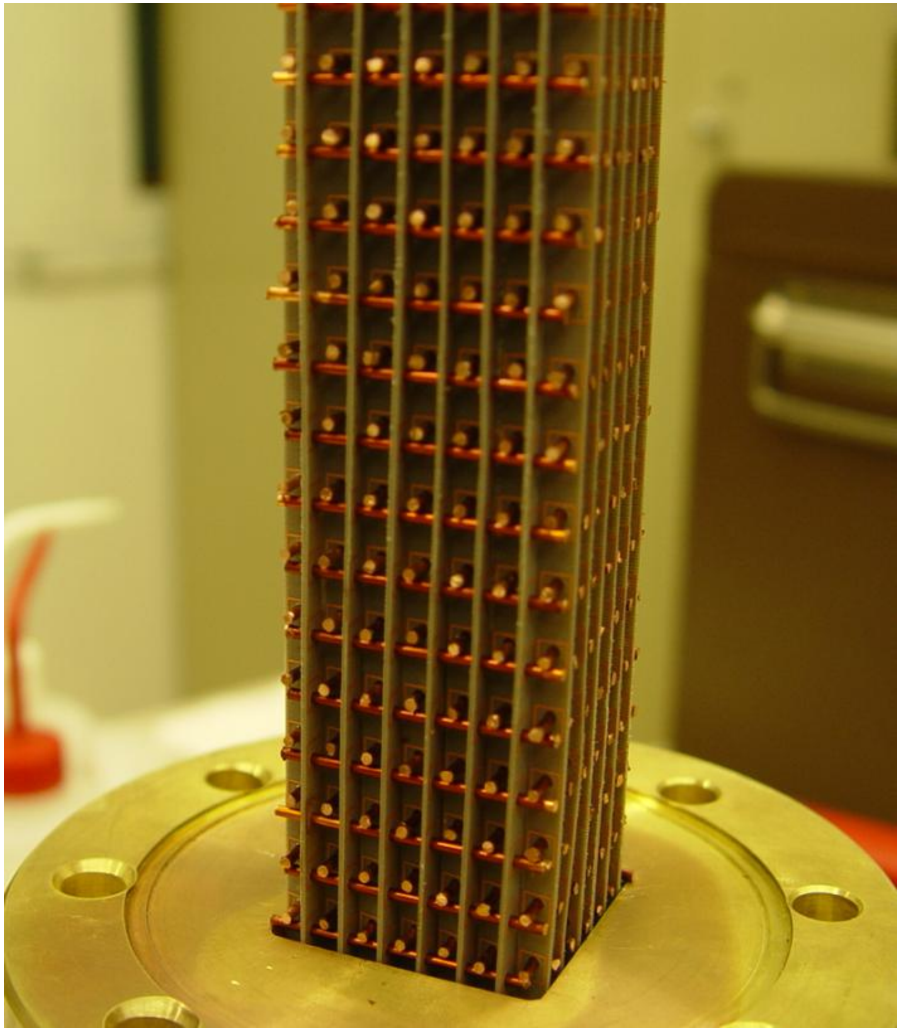
- Backward modes
- Several excitation regimes
- Multithreshold excitation (non-magnetic – left-handed regime)
- Strong dependence on longitudinal distribution (future studies)
- Stronger signals at resonance
- High angle values for CR cone in bul configuration
- Backward radiation in bulk (was not yet observed)

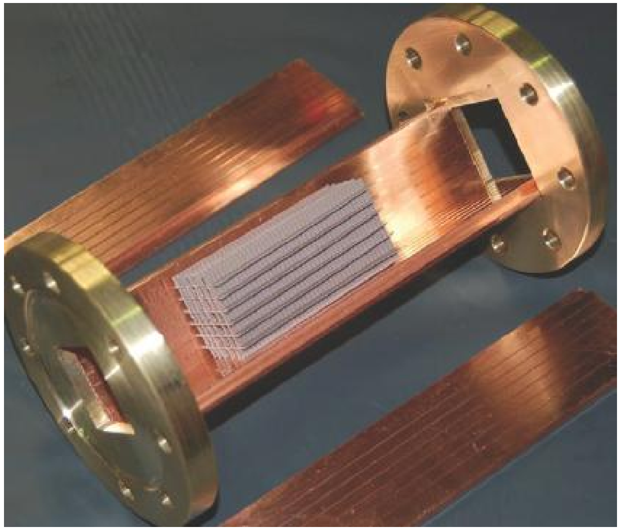


Conclusion, Future plans

- We studied metamaterials: theory, simulation, experiment
- Learned how to design and manufacture them
- Loaded waveguide studies
  - Dispersion
  - Wakefield generation: ***developed robust, universal simulation***
- Plan to perform a wakefield experiment at AWA.
  - goal is to detect backward mode
- Future studies include:
  - Longitudinal beam distribution for wakefield generation
  - Non-magnetic regime studies
  - Large scale simulation development for metamaterials. VORPAL

The experiment is on the way…





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