Mechanical tuning in Metamaterial-inspired resonators

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The ALPHA Collaboration

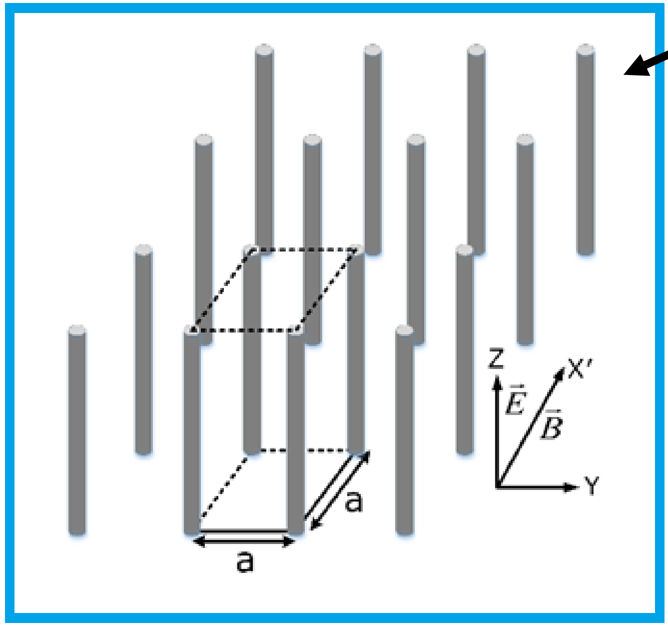
The ALPHA Collaboration meeting at Yale University, September 25-26, 2023

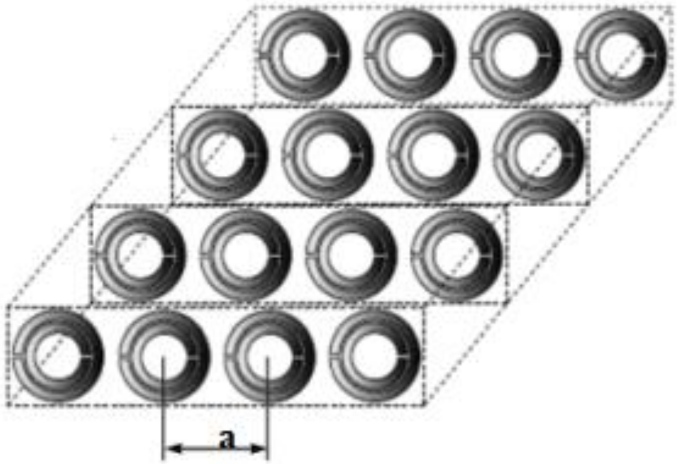
ALPHA White paper: Phys. Rev. D 107, 055013 (2023)

Metamaterial

Wire metamaterial

Controlling ε and μ





Negative ε

Negative μ

Negative ε and μ

$$\varepsilon(\omega) = \varepsilon_0 \left[1 - \frac{{\omega_p}^2}{\omega(\omega + i\gamma)}\right]$$

$$\mu_{eff}(\omega) = 1 + \frac{F\omega^2}{{\omega_0}^2 - \omega^2 - i\Gamma\omega}$$

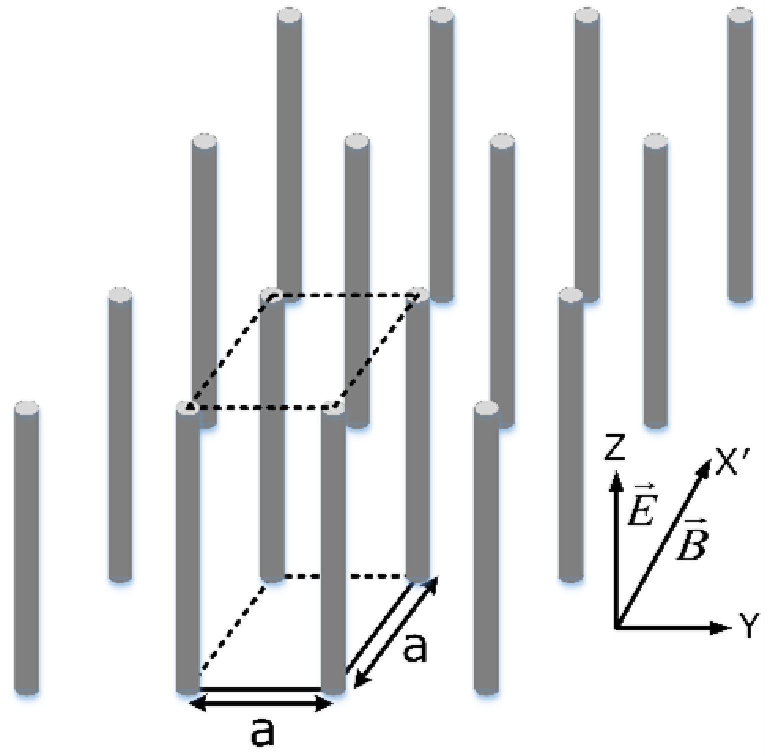
Tech. Phys. 58, 1-24 (2013)

Wire Metamaterial: Controlling frequencies

Plasma frequency depends entirely on lattice geometry

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

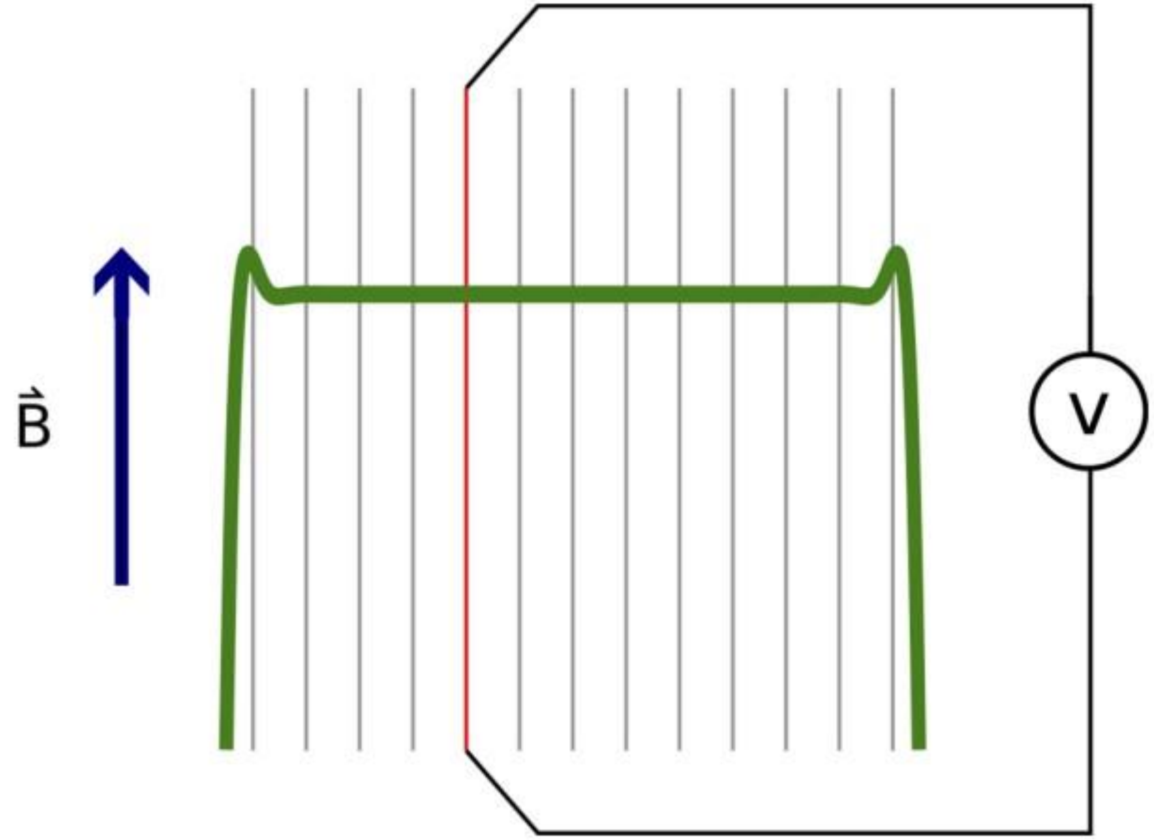
$$m_{eff} = \frac{\mu_0 \pi r^2 e^2 n}{2\pi} \ln(\frac{a}{r})$$



Pendry et al.(1996) PhysRevLett.76.4773

Motivation behind designs: Plasma Haloscope

- Array of wires as effective medium
- Axion detection with tunable cryogenic plasma
- Axion mass matched to plasma frequency
- Metamaterial based detector
- Can in theory scan through a range of axion masses



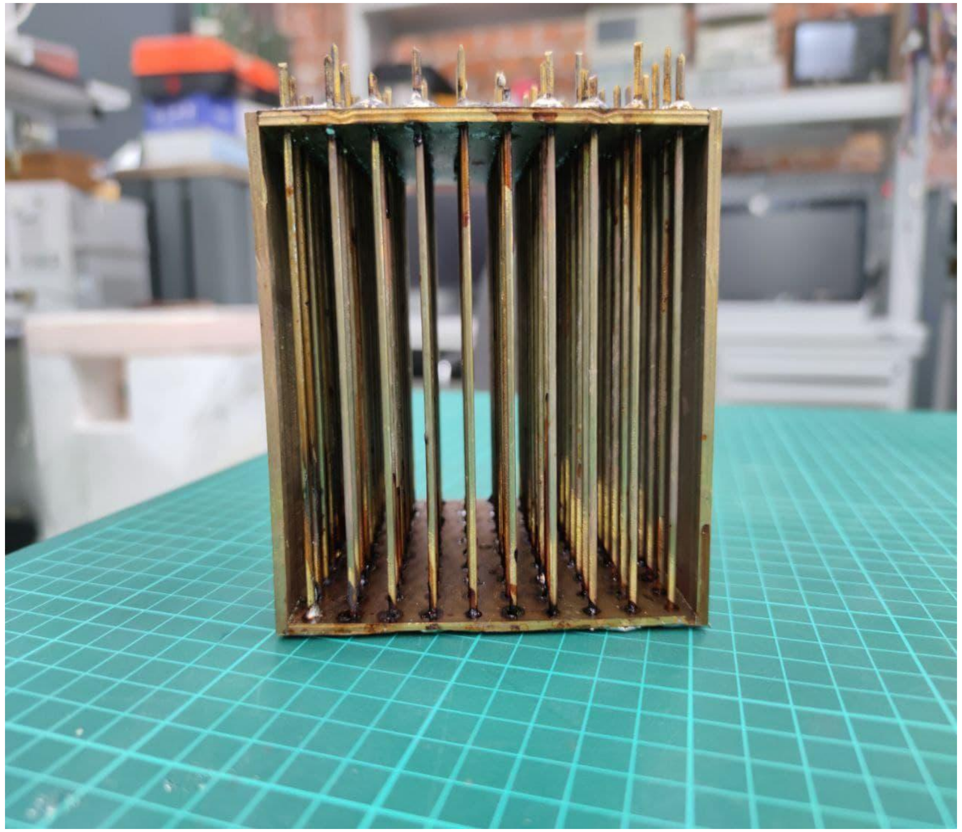
Lawson et al. (2019), PRL

Motivation behind designs: WM filled resonator

$$\frac{\omega_p^2}{c^2} = \frac{2\pi/a^2}{ln\left(\frac{a}{2\pi r}\right) + F(1)}$$

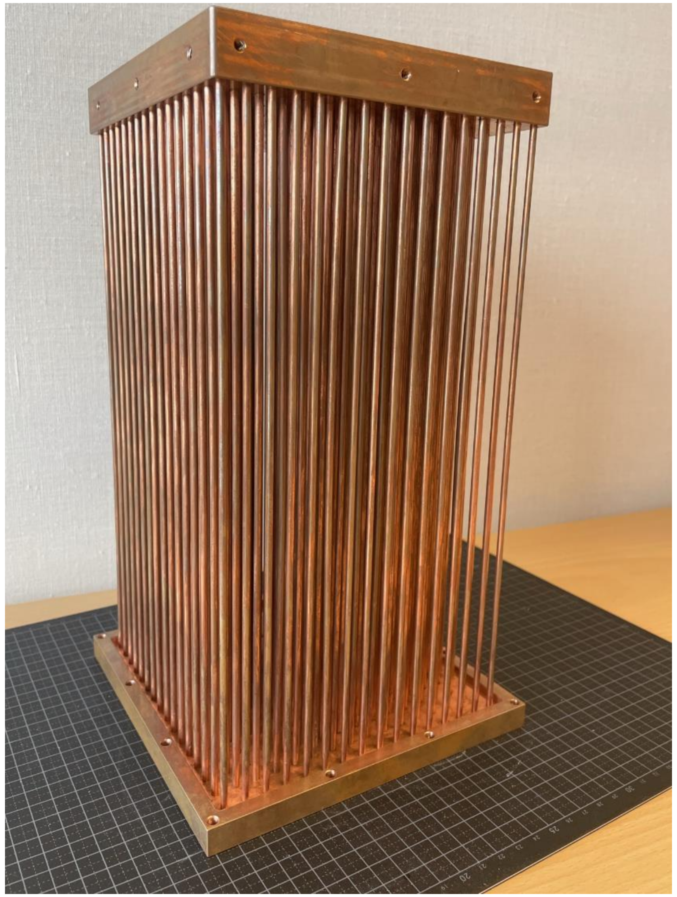
$$Q \simeq \frac{2\mu_0 r}{\mu\delta}\left(ln\left(\frac{a}{2\pi r}\right) + F(1)\right)$$

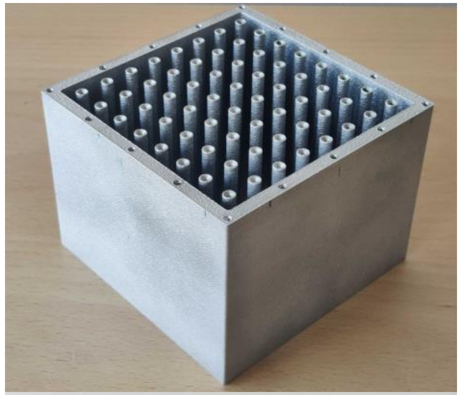
Wire radius = 1 mm, wire period = 10 mm, 10x10 array

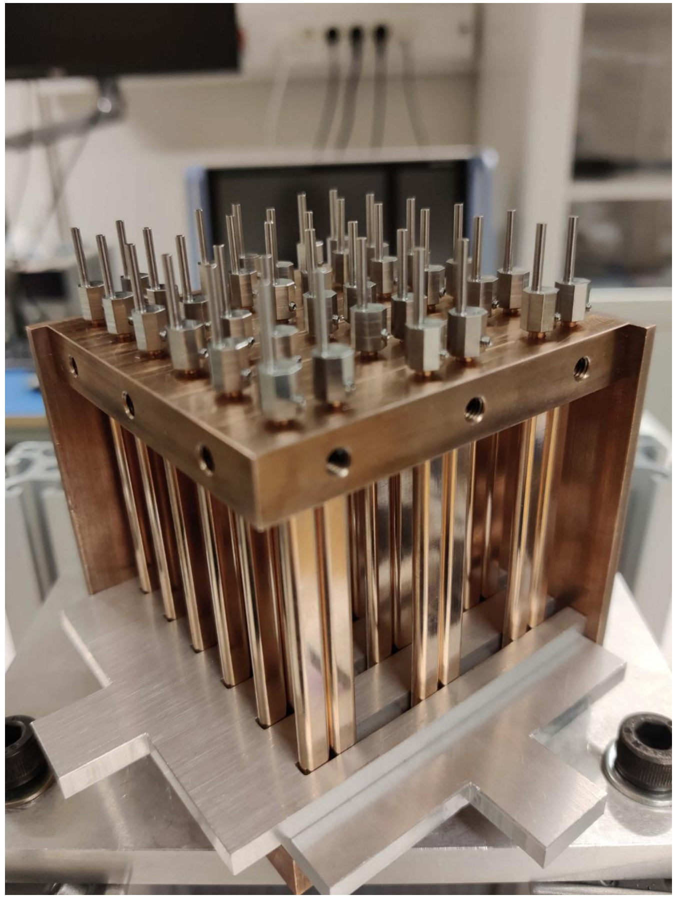


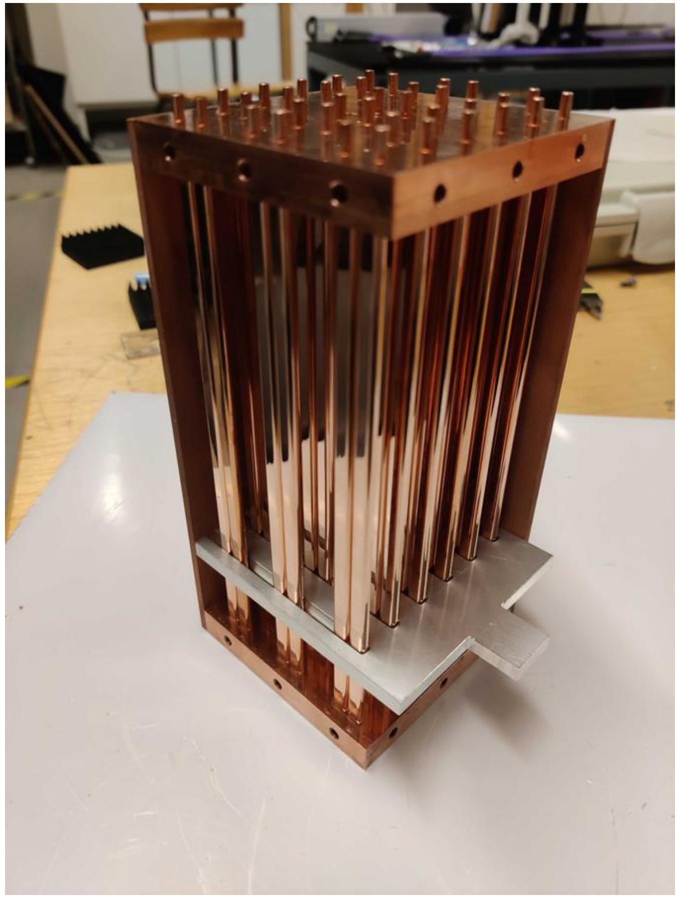
Rustam et al. (2022), PRB

Metamaterial-inspired Resonator prototypes









Optimizing designs

1. 3D mechanical model

2. Run CST/COMSOL simulations

3. Get the design manufactured

4. Assemble resonator in lab

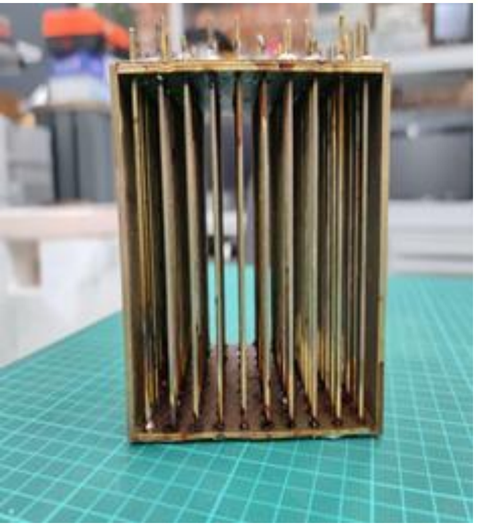
5. VNA measurements

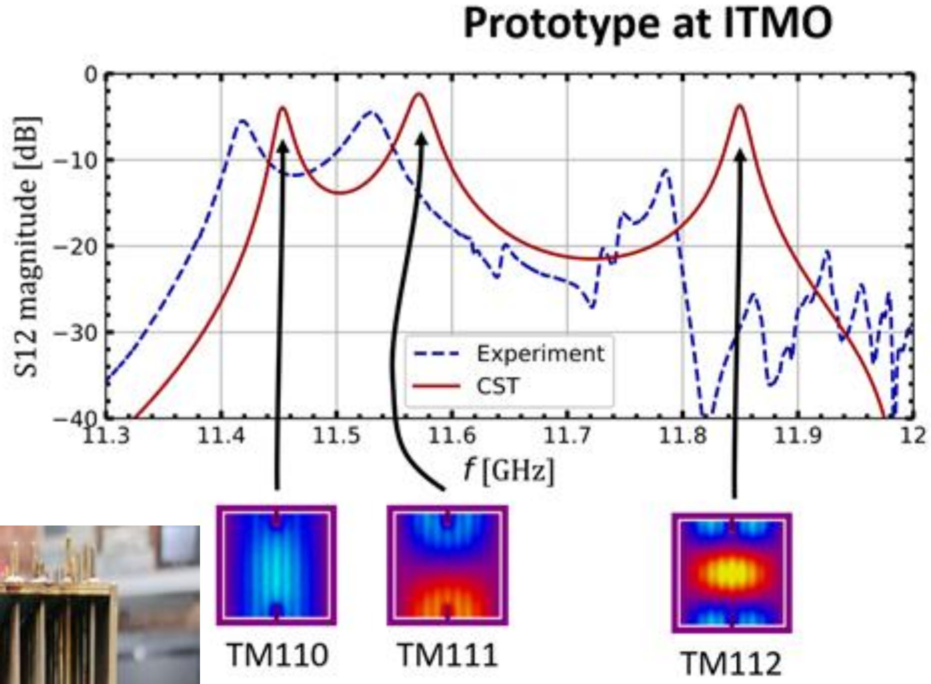
Critical steps

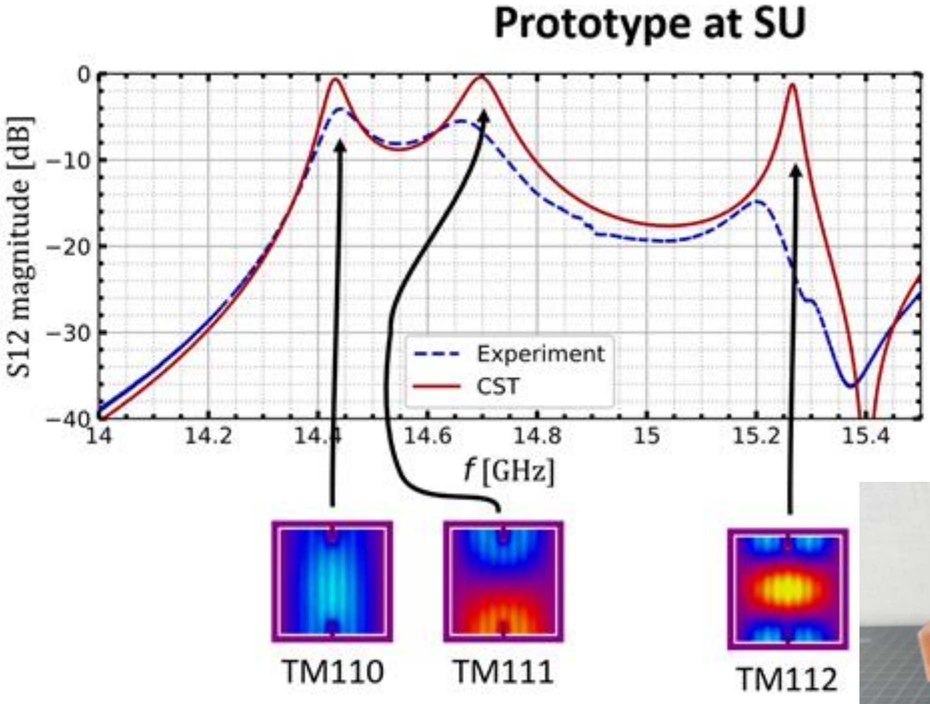
Optimization parameters:

- Losses
- Coupling strength
- Quality factor
- Tuning range

Static prototypes







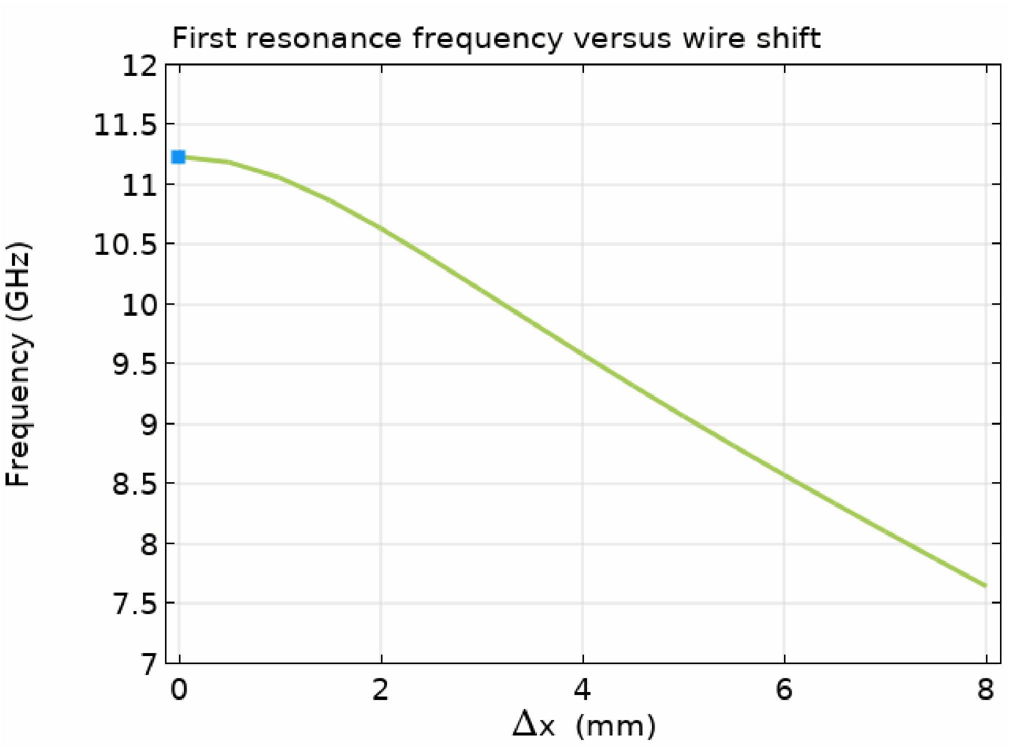
Rod radius = 1 mm,
Periodicity = 10 mm,
10x10 array

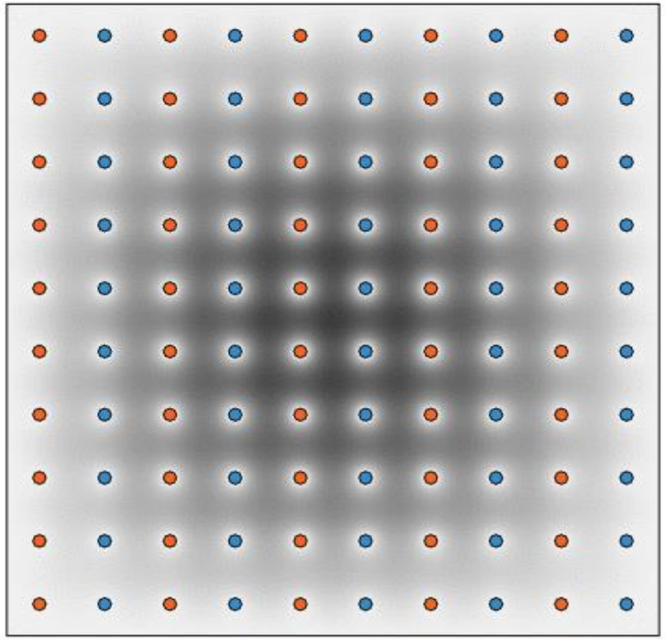
Rod radius = 1.5 mm,
Periodicity = 10 mm,
6x6 array

Rustam et al. (2022), PRB

Tunable prototype: First tuning mechanism

Rustam Balafendiev

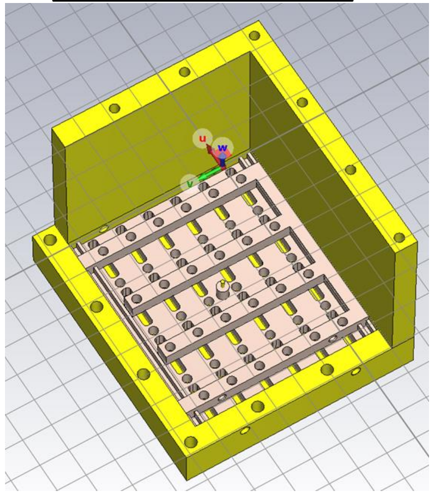




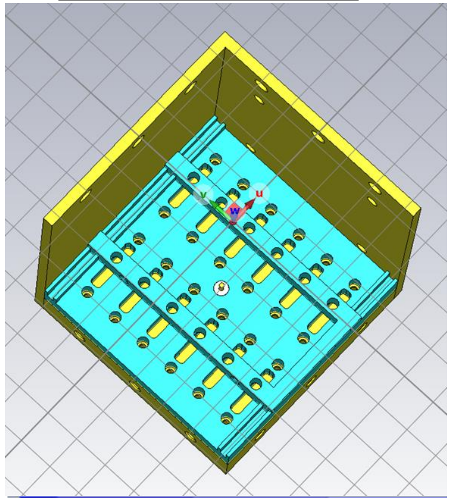
R&D at Stockholm University, guided by theory and simulations from the ITMO/St. Petersburg group (**R. Balafendiev, P. Belov**, M. Gorlach, et al.)

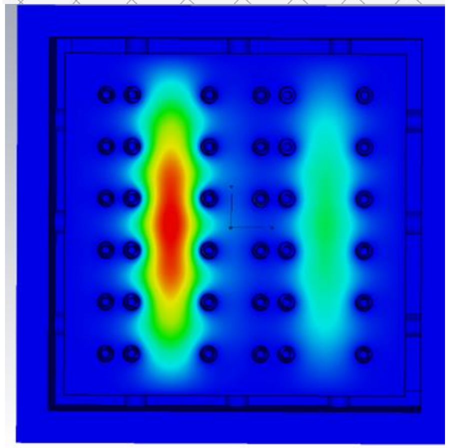
Translational design: Optimization

7X6 design

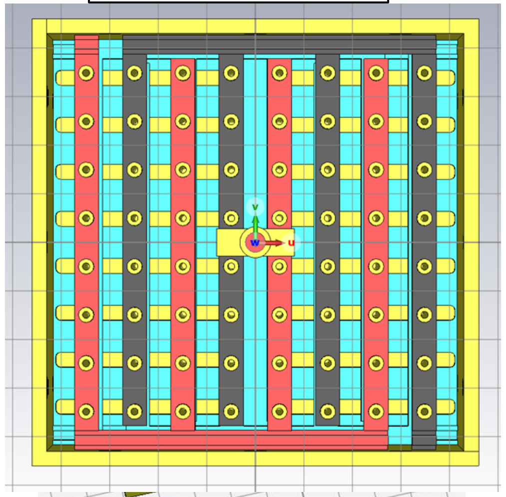


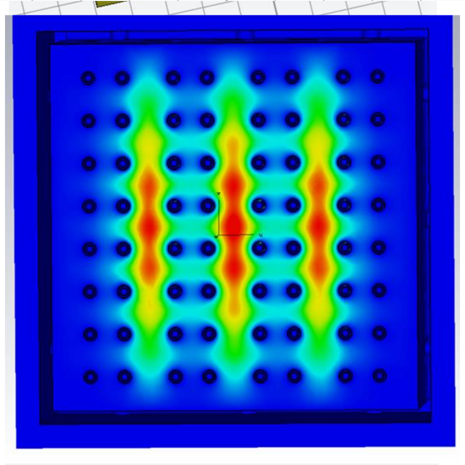
6X6 design





8X8 designs





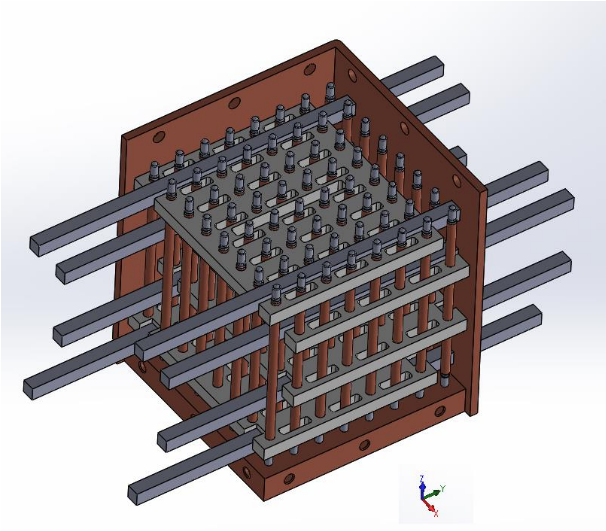
- Metal discontinuities causes mode mixing
- Symmetry of design is critical for uniform field distribution

Static design vs tunable:

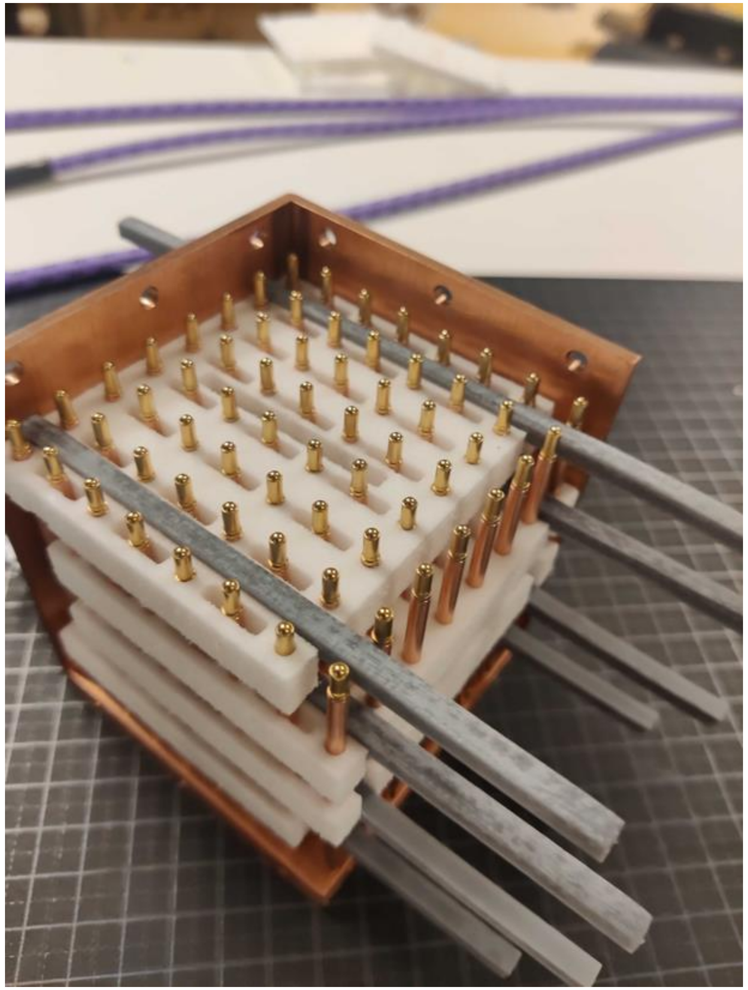
Quality factor: ~4500 for static

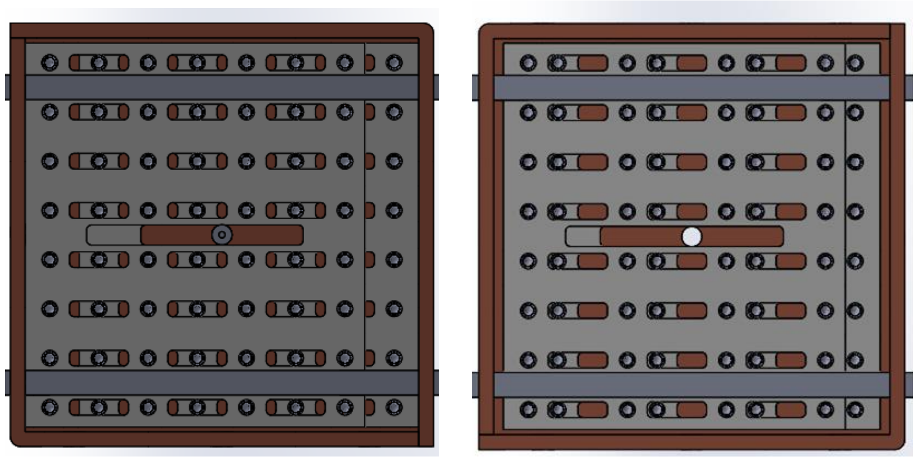
~1500 to 2500 for tunable designs

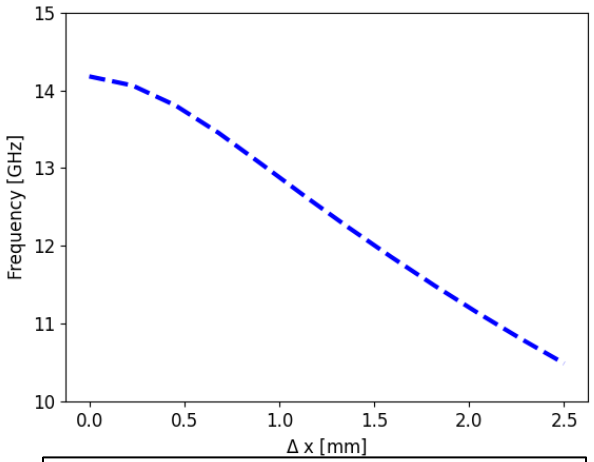
Translational prototype



- Lateral translation of rods
- Material of translational combs critical
- Still modifying to improve connectivity and avoid mode mixing

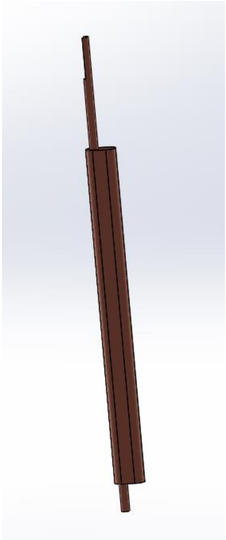




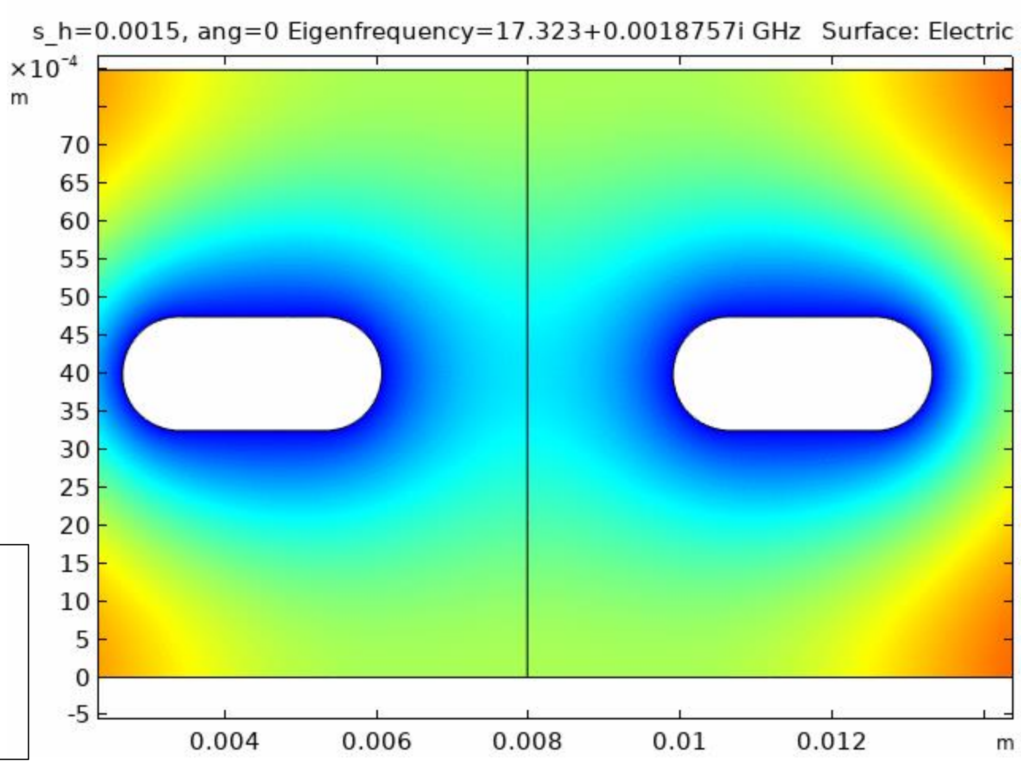


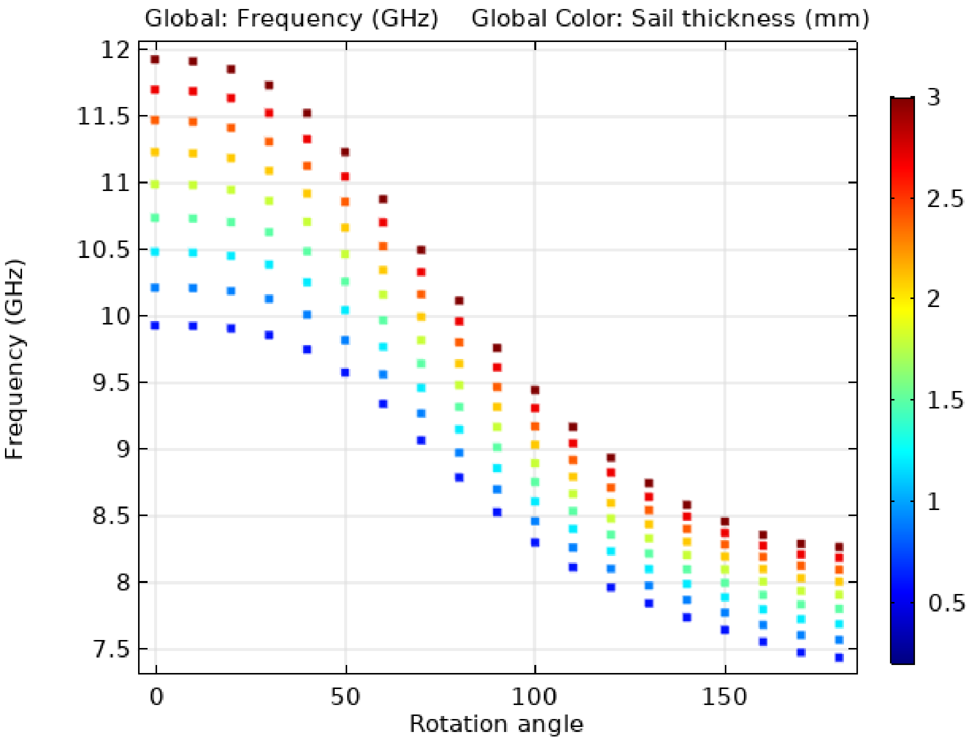
Frequency of lowest resonant mode

Rotational prototype: Design optimization



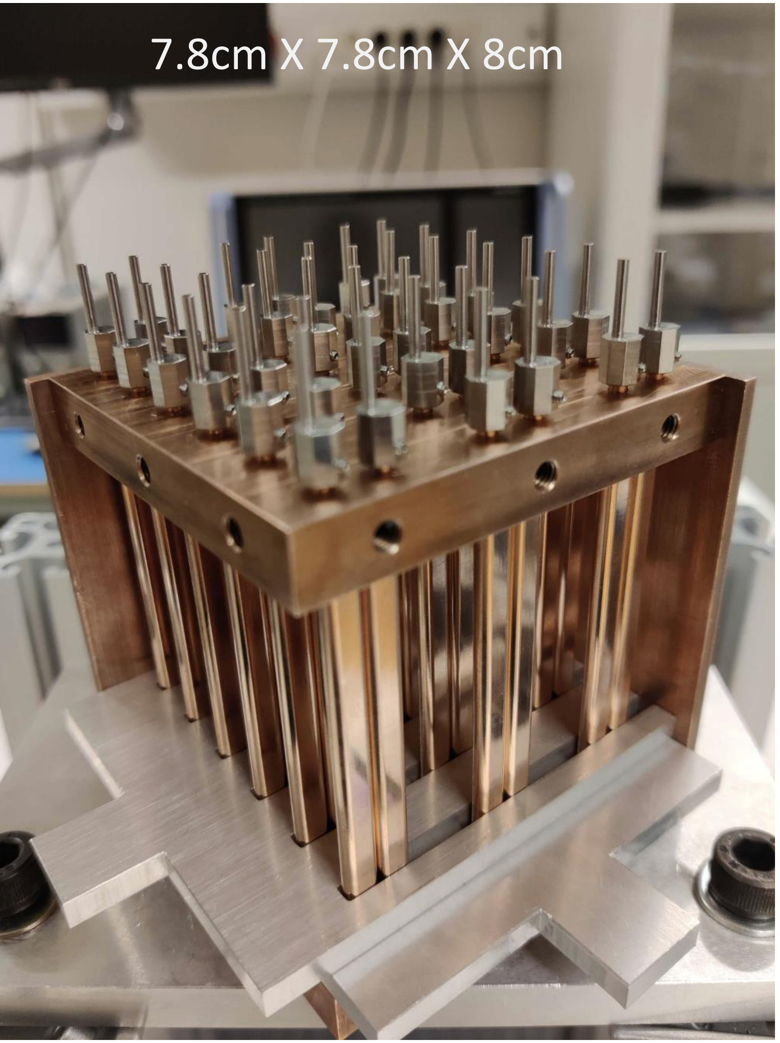
Tuning achieved by rotation of sail-type periodic element





Credit: Rustam Balafendiev

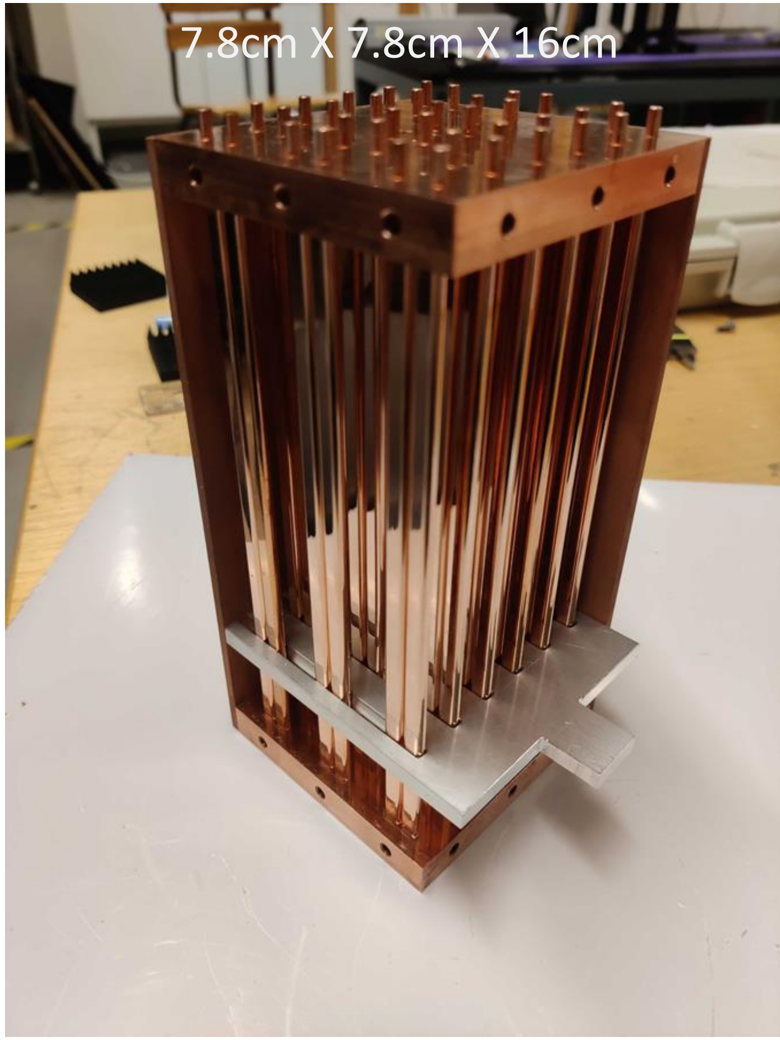
Rotational prototype



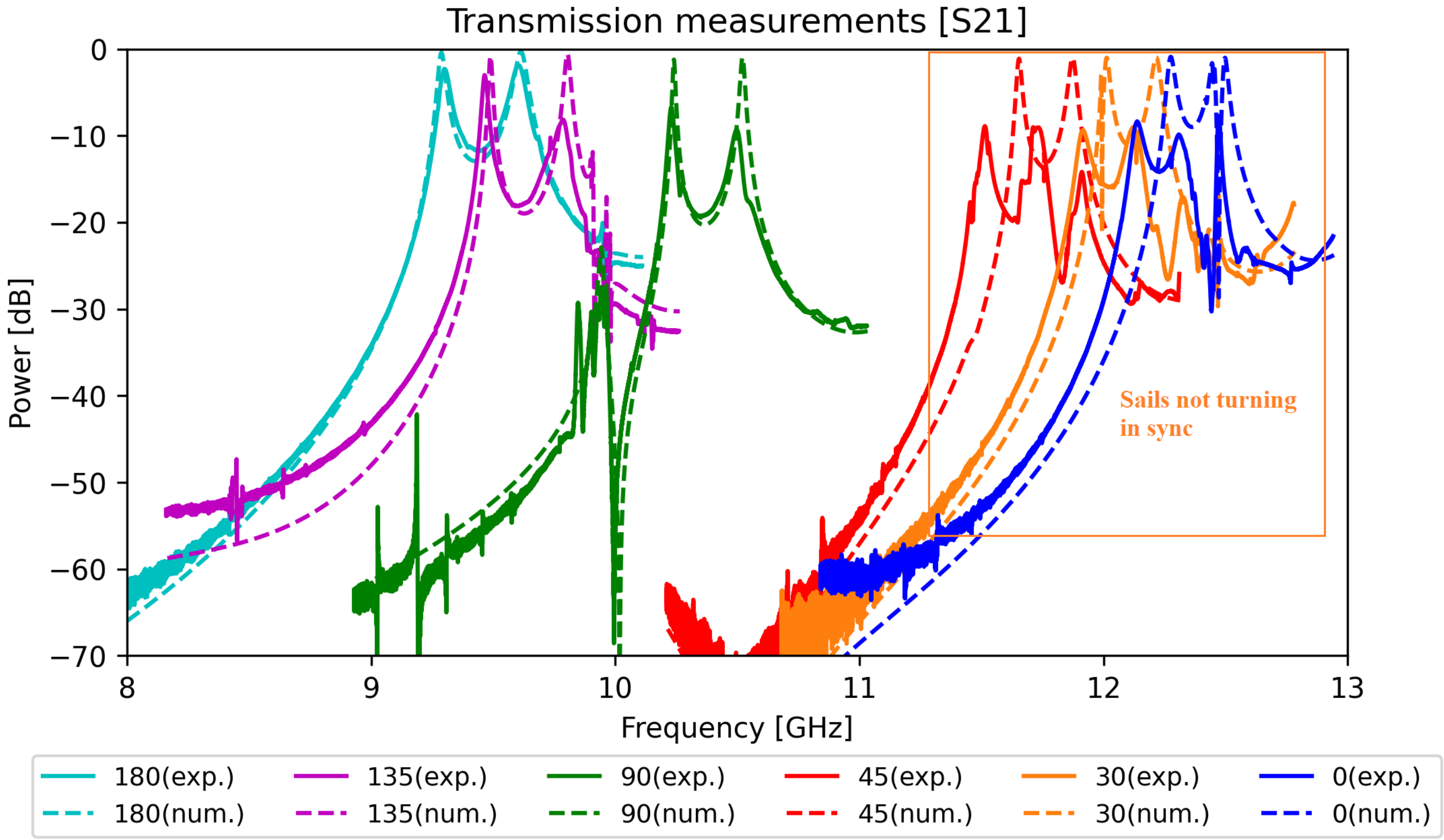
- Sail-based, metamaterial-inspired resonator
- Copper conductors on a rectangular lattice
- **Resonator dimensions:**

Smaller: 7.8cm X 7.8cm X 8cm

Larger: 7.8cm X 7.8cm X 16cm



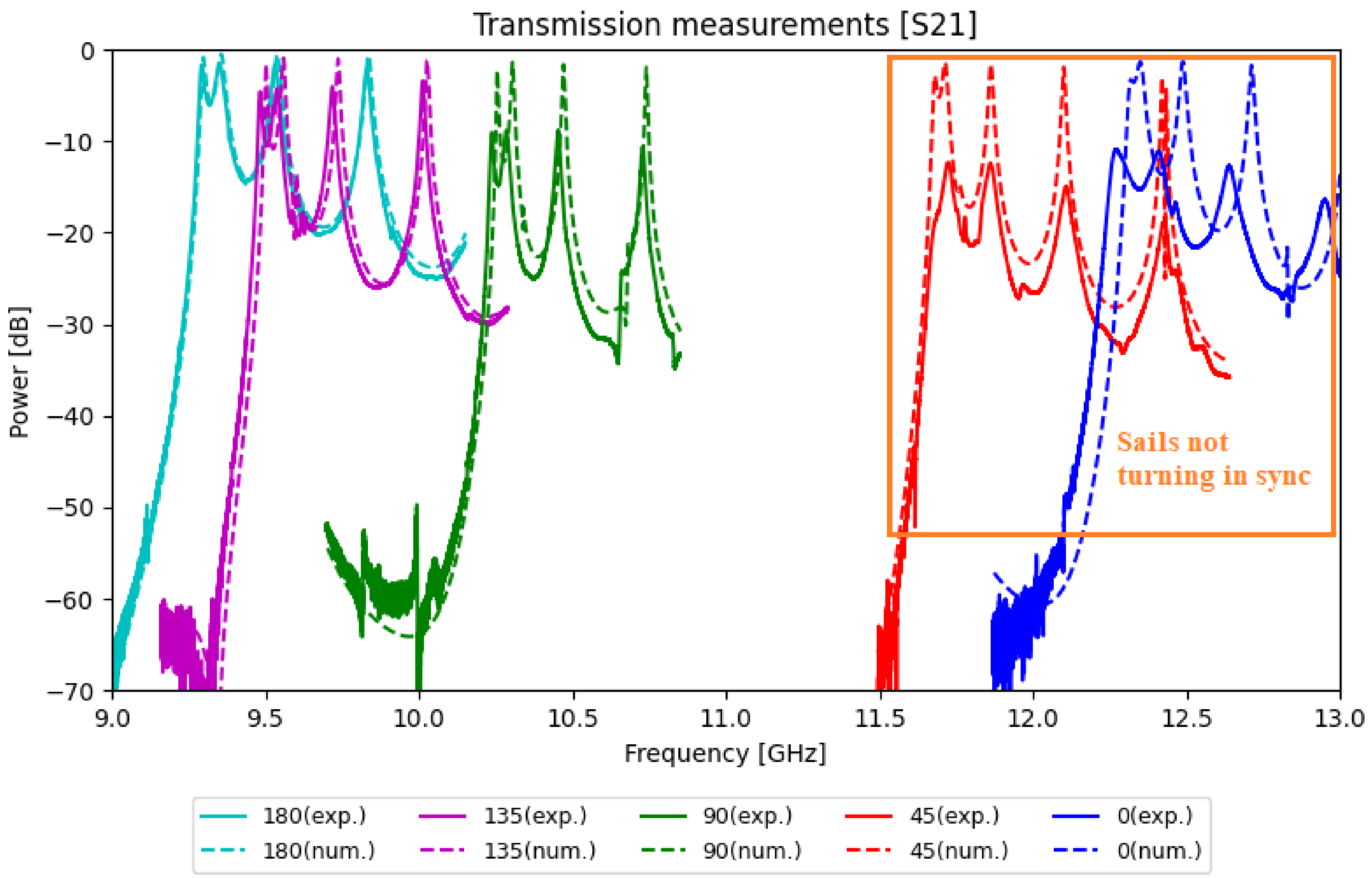
Transmission spectrum: Small prototype



7.8cm X 7.8cm X 8cm

Comparing experiment with simulations

Transmission spectrum: Large prototype

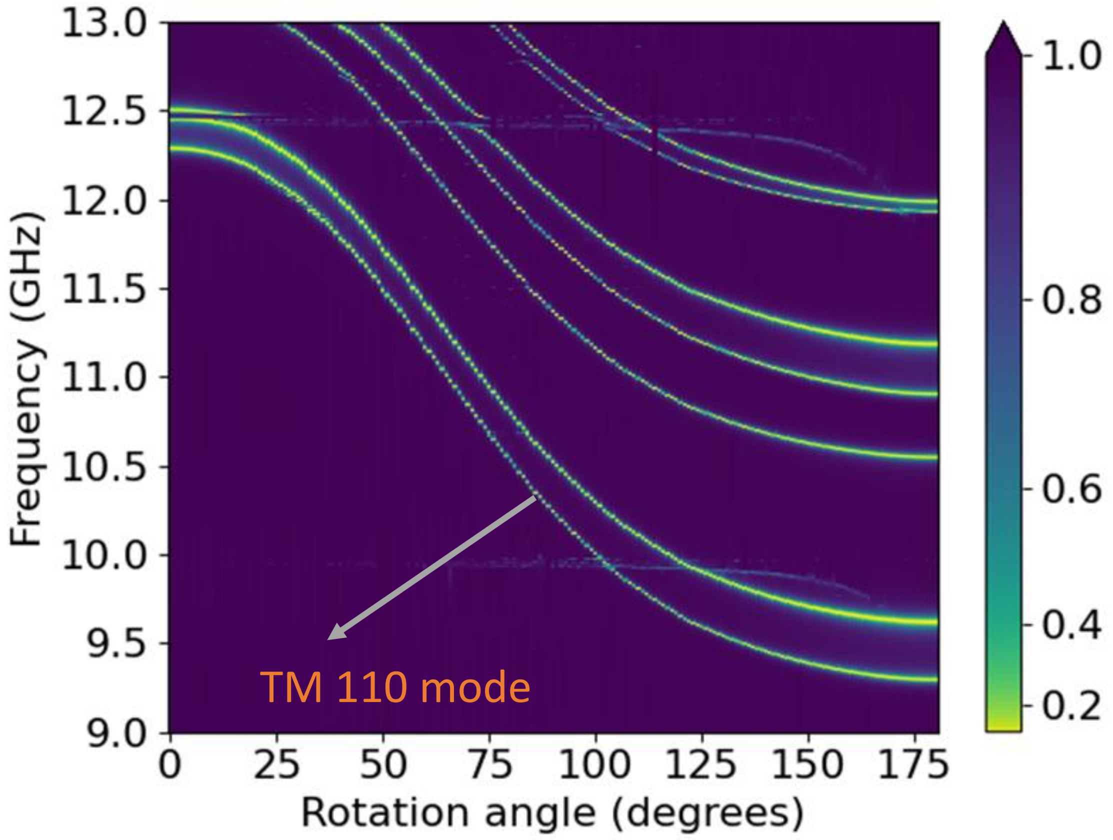


7.8cm X 7.8cm X 16cm

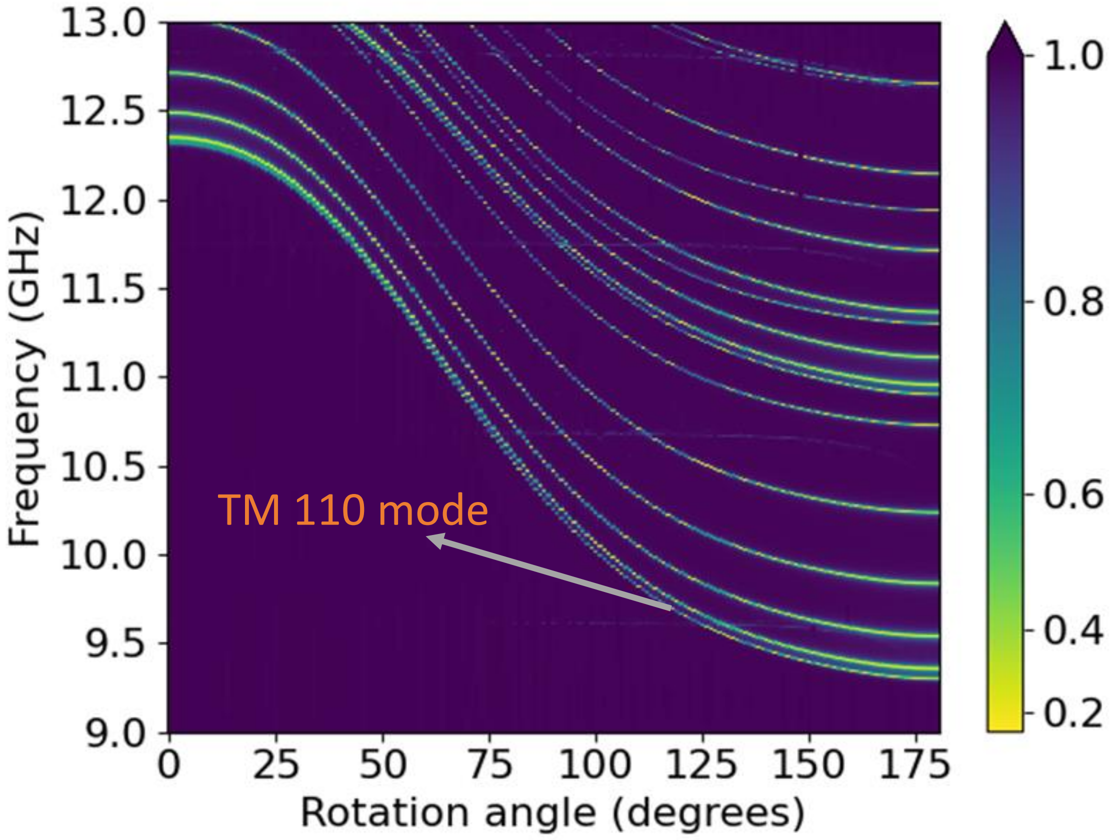
Comparing experiment with simulations

Mode map (3D CST sims)

7.8cm X 7.8cm X 8cm



7.8cm X 7.8cm X 16cm



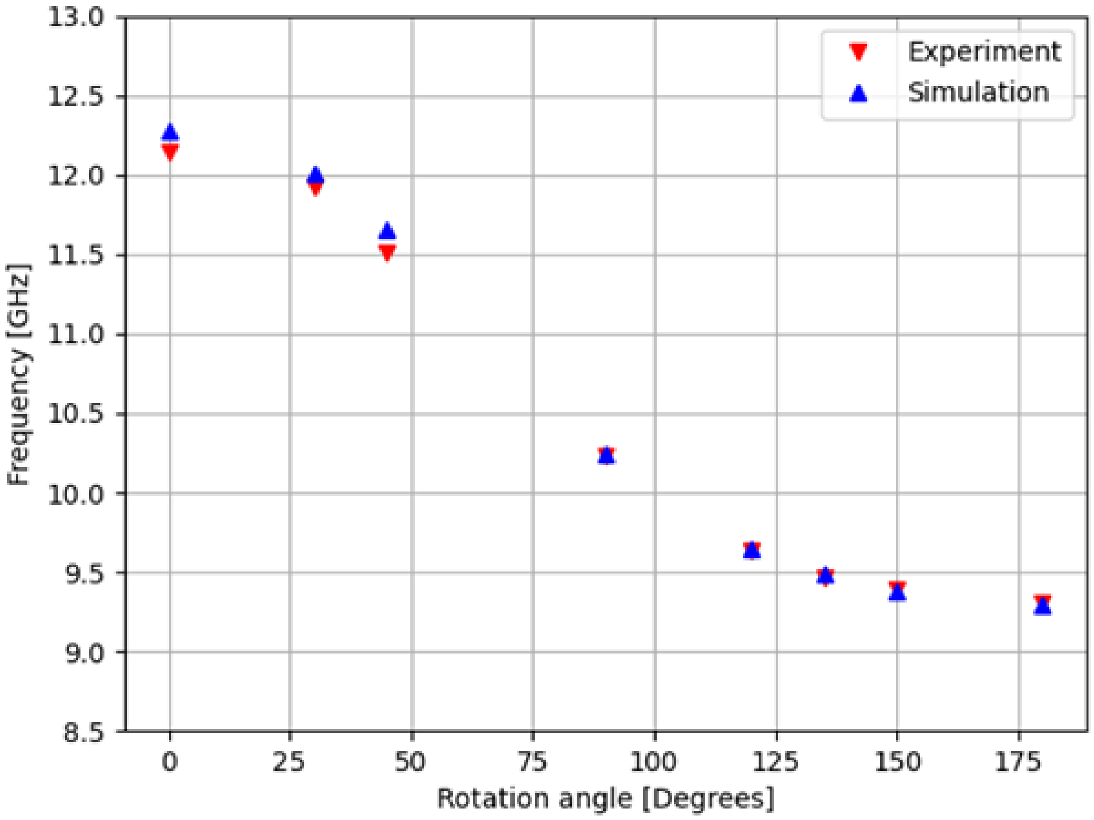
TEM modes:

•Small prototype: 10 GHz, 12.5 GHz

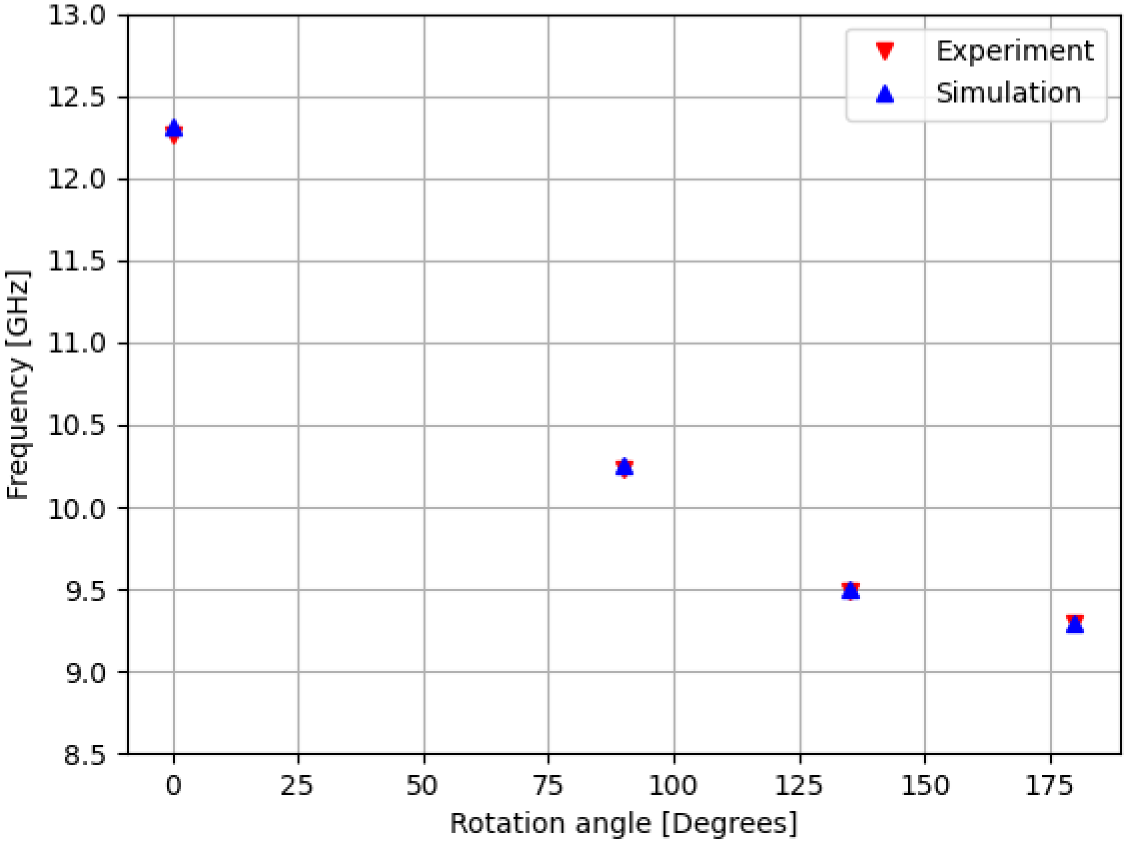
•Large prototype: 9.64 GHz, 10.71 GHz, 11.78 GHz, 12.86 GHz

Tuning range

7.8cm X 7.8cm X 8cm

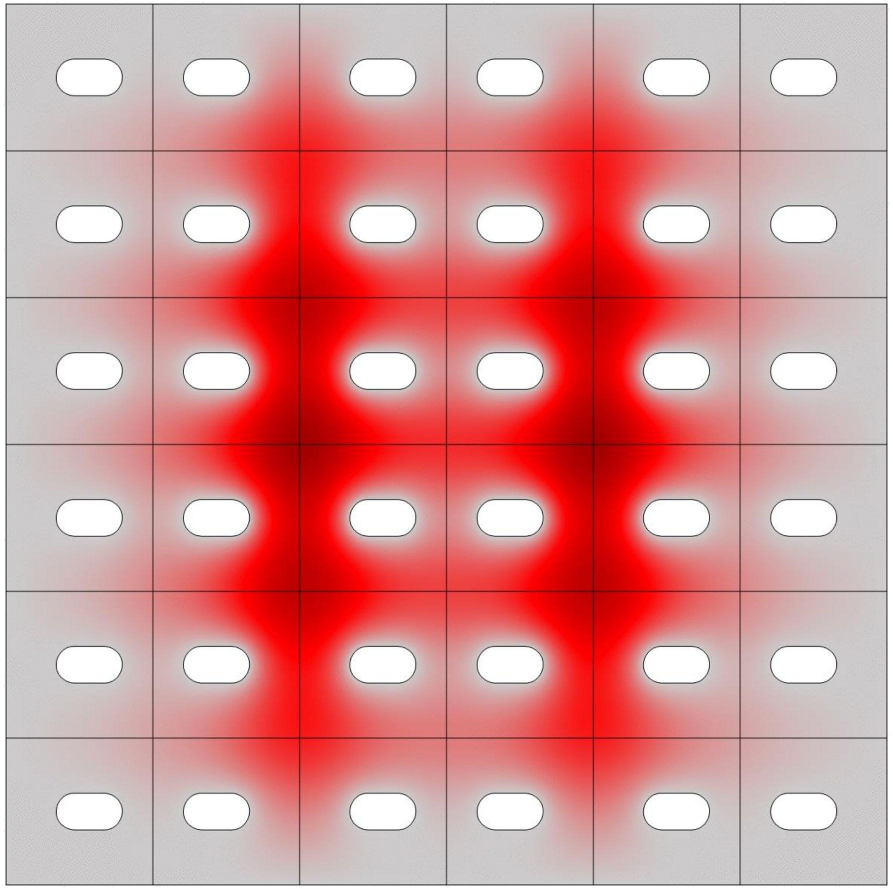


7.8cm X 7.8cm X 16cm

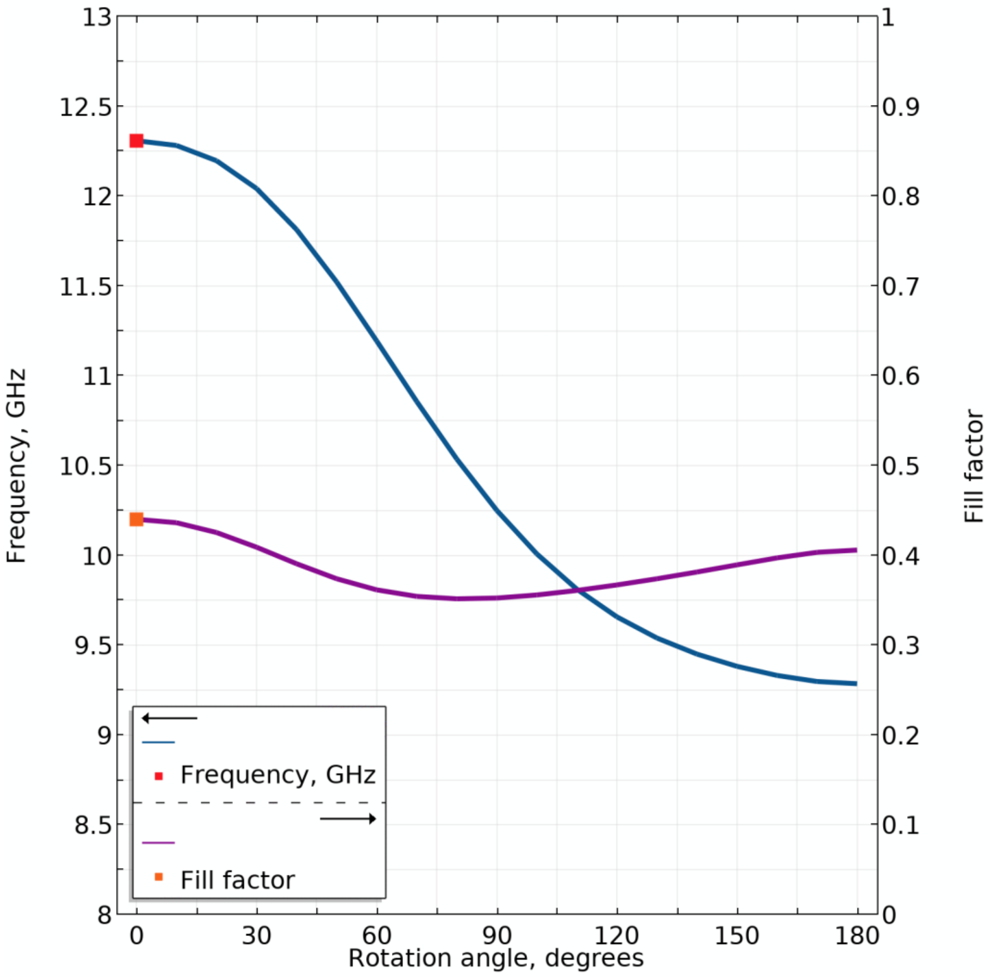


- Good agreement between experiment and simulation for both
- Demonstrate about 28% tuning range for both small and large systems

TM 110 mode

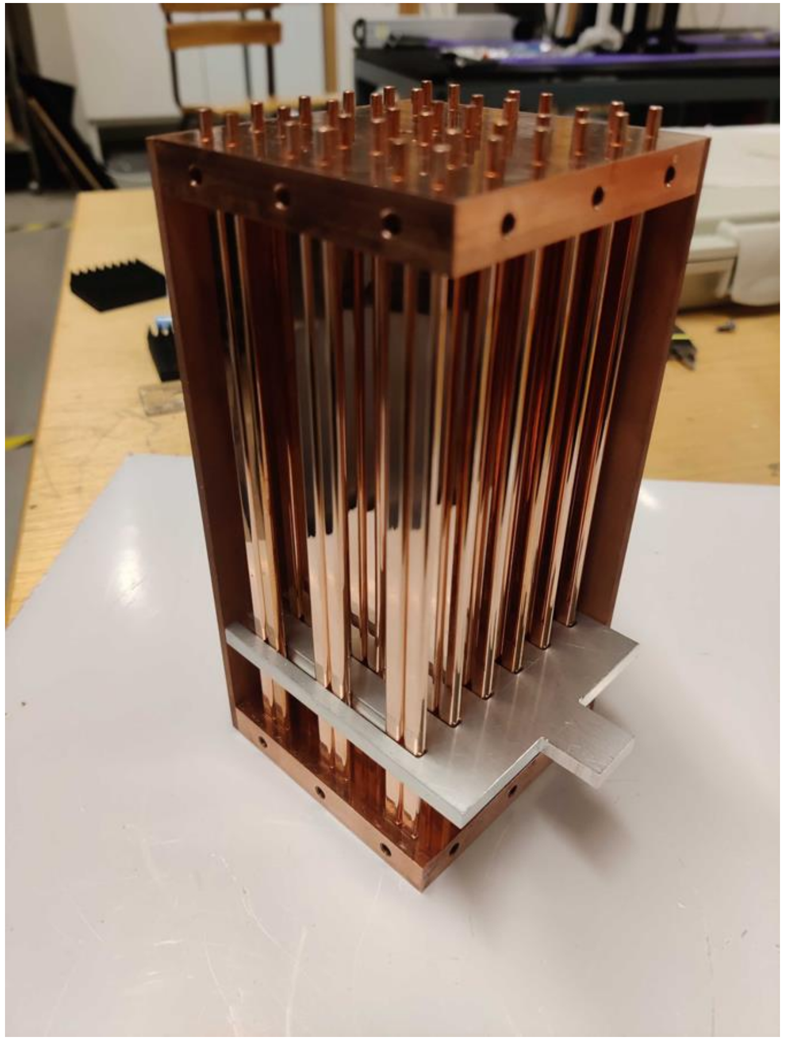


2D field profile of Ez calculated with COMSOL



Credit: Rustam Balafendiev

Optimization and Technical challenges



Critical interface: Oversizing of holes in outer plates

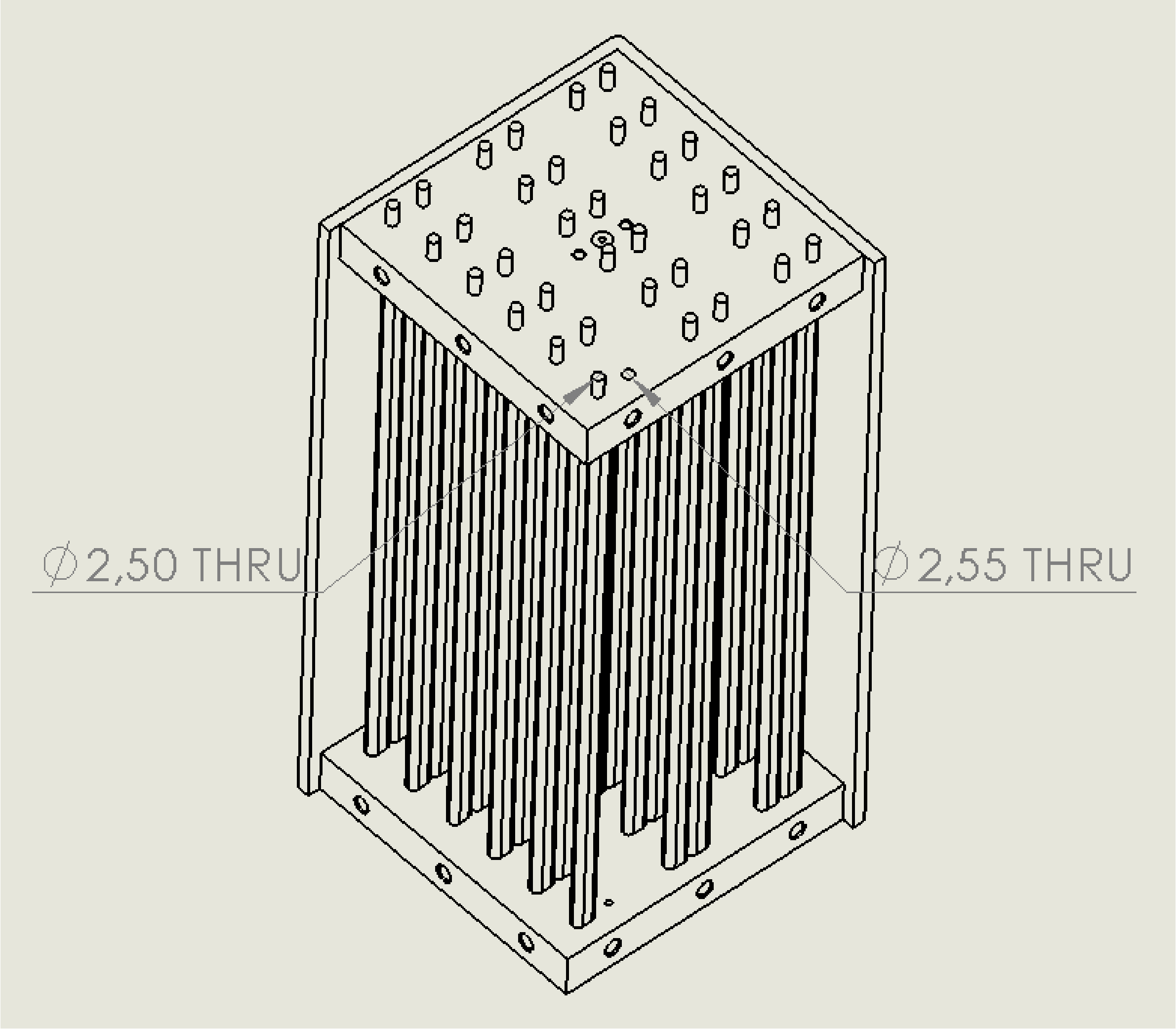
Rod diameter:

2.5mm

Size of holes

in top plate:

2.55mm



Optimization and Technical challenges

Critical interface: Oversizing of holes in outer plates

Striking a balance

- Oversizing needed to facilitate rotational motion
- Oversizing leads to radiation losses in copper plates

Oversizing between 50 um and 70 um

Rotation angle (degrees)	Freq. (GHz)	Coupling coefficient	Unloaded Quality factor
180	9.294	3.82	2154

Oversizing between 30 um and 50 um

Rotation angle (degrees)	Freq. (GHz)	Coupling coefficient	Unloaded Quality factor
180	9.293	4.54	2692

Conclusion

❑ Current status

- Testing 2 different approaches for mechanical tuning in resonator prototypes
- Efficiently built and tested prototype based on rotational tuning (~9-13GHz)
- Rotational prototype quite promising: tunability of about 28%

❑ Future goals

- Tuning at certain angles, working towards robust rotational tuning mechanism
- Design modifications for covering wide frequency range 10-20 GHz
- Cryogenic testing of the prototypes
- Build static prototype with superconducting rods/sails