

Environmental Engineering for Qubit-Based Detectors

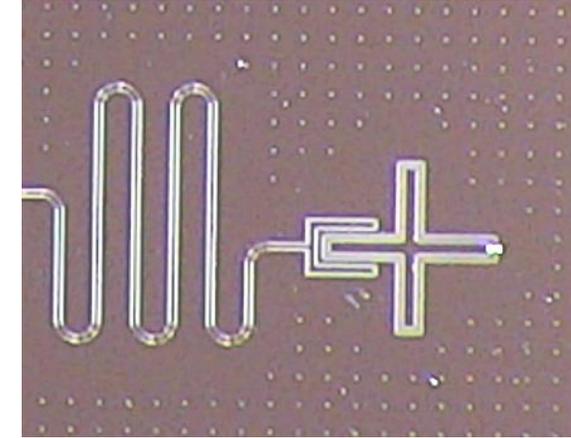
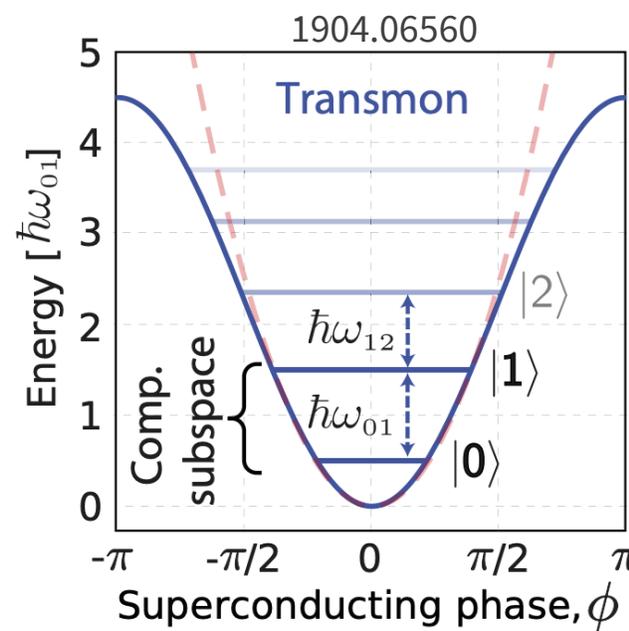
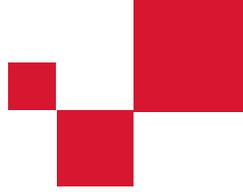
Daniel Molenaar

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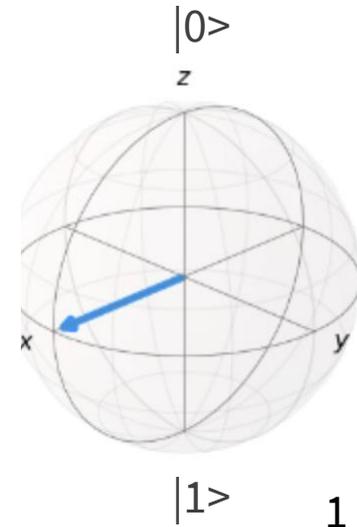
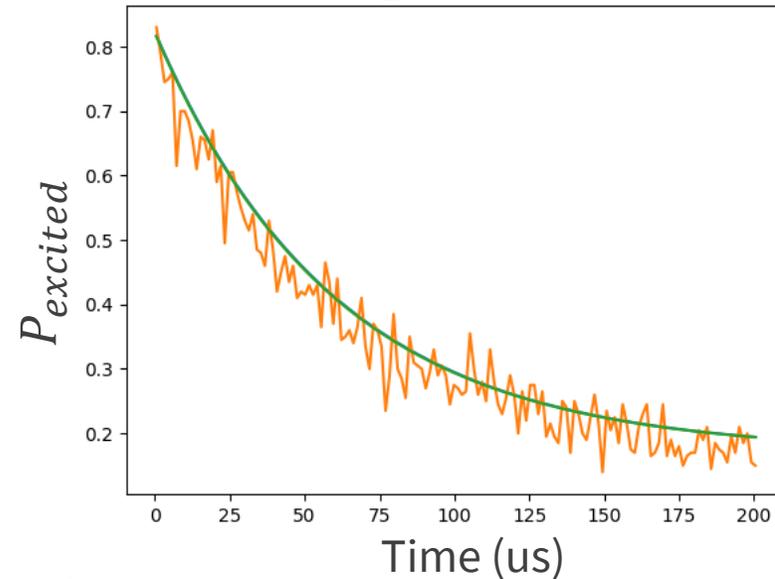
CPAD 2025

Qubit Basics

- Qubits are Anharmonic Oscillators
- Our group focuses on circuit based superconducting qubits
- Two important quantities for Qubits are T_1 and T_2
 - T_1 describes the lifetime of the first excited state; the coherence time
 - T_2 Is the phase decoherence time
 - $T_{2 Echo}$ can be used to remove external phase influences



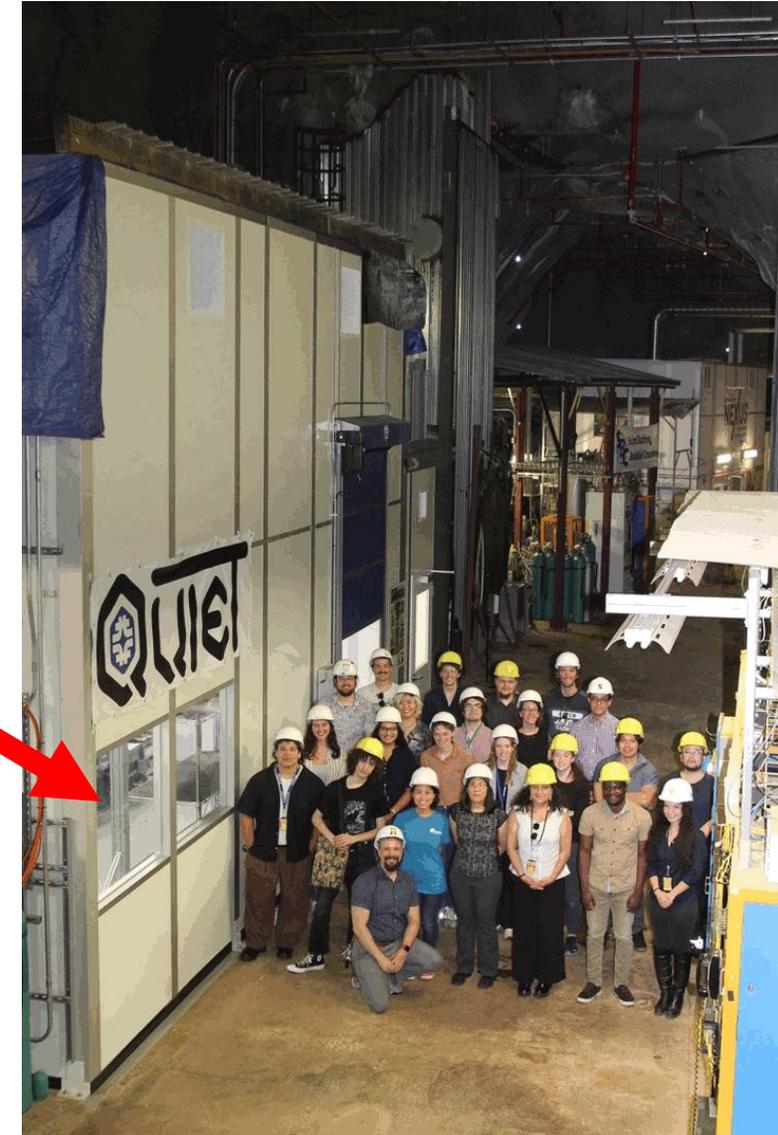
T_1 Curve



QUIET (Quantum Underground Instrumentation Experimental Testbed)

- Located 100 meters underground in the Minos cavern at Fermilab
- Provides a 100x reduction in cosmic ray muons

For a glimpse at some of our recent studies
see Kester Anyang's Talk
Oct 8, 2025, 11:45 AM Woodlands AB



LOUD

- Located on the surface at Fermilab
- Same model fridge as QUIET allowing for simplified A-B tests
- Currently LOUD is our test bed for a MEMS guided laser for qubit energy deposition studies

For more about this see Israel Hernández's Talk
Oct 8, 2025, 11:15 AM Woodlands AB

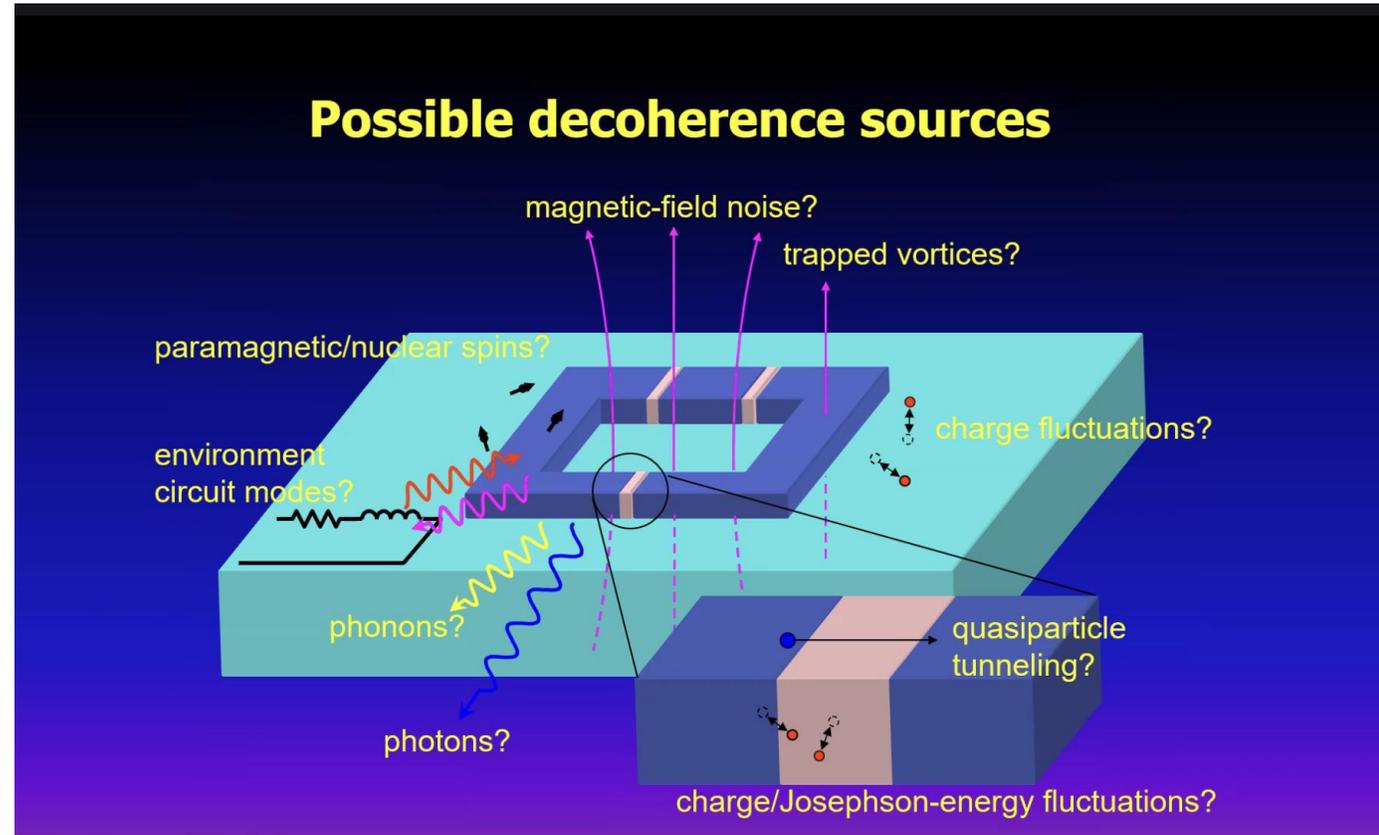


Environmental Background Sources

Problematic Backgrounds:

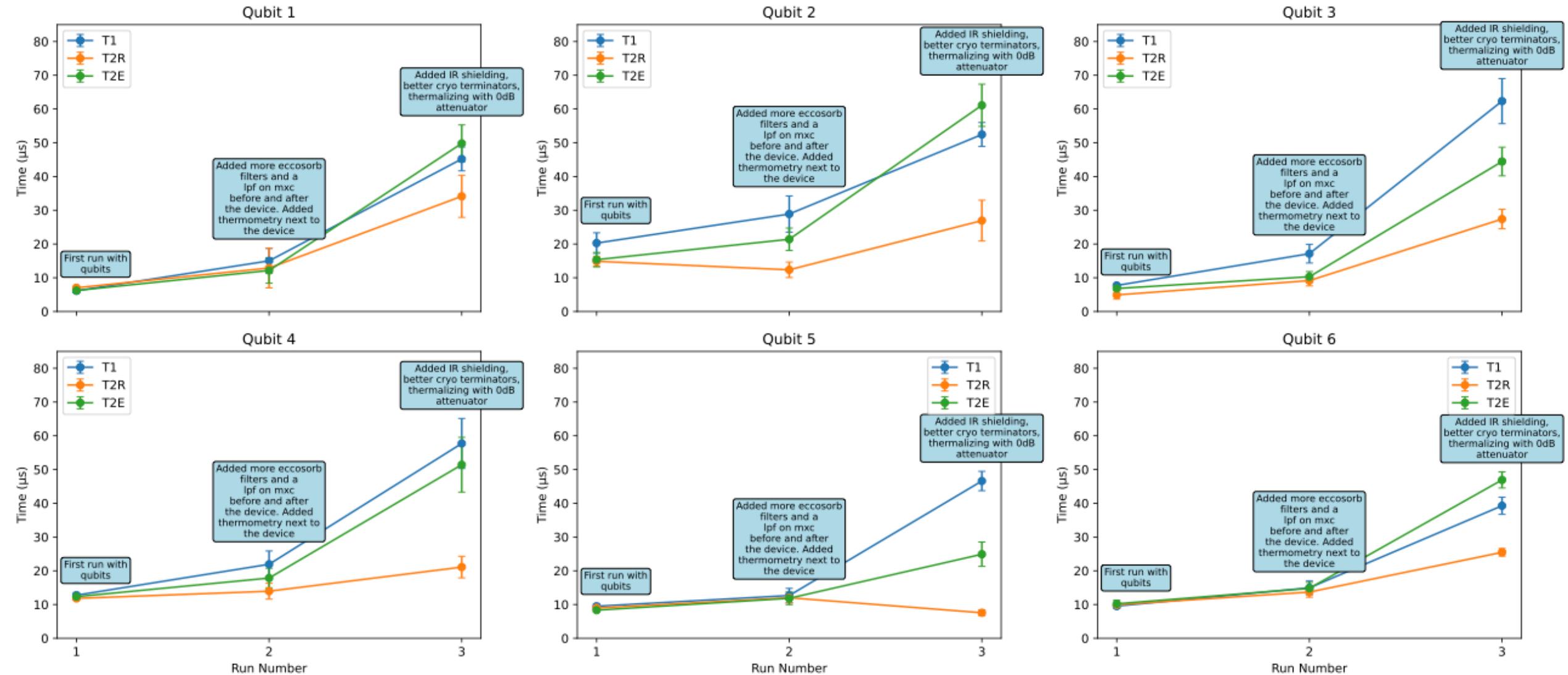
- Temperature Fluctuations
- Gamma Rays
- Cosmic Rays
- Vibrations
- B(H) – Fields
- **IR Photons**

And many more



Schematic from Yasunobu Nakamura's Talk
University of Tokyo, RIKEN

Impact of Shielding Filtering and thermalization on Qubits



IR Photons

- Generally we're concerned about black body radiation leaking from higher temperature stages
- IR photons have a small wavelength and can slip through cracks effectively
- The 4K stage has significant blackbody emission from ~ 10 GHz – THz

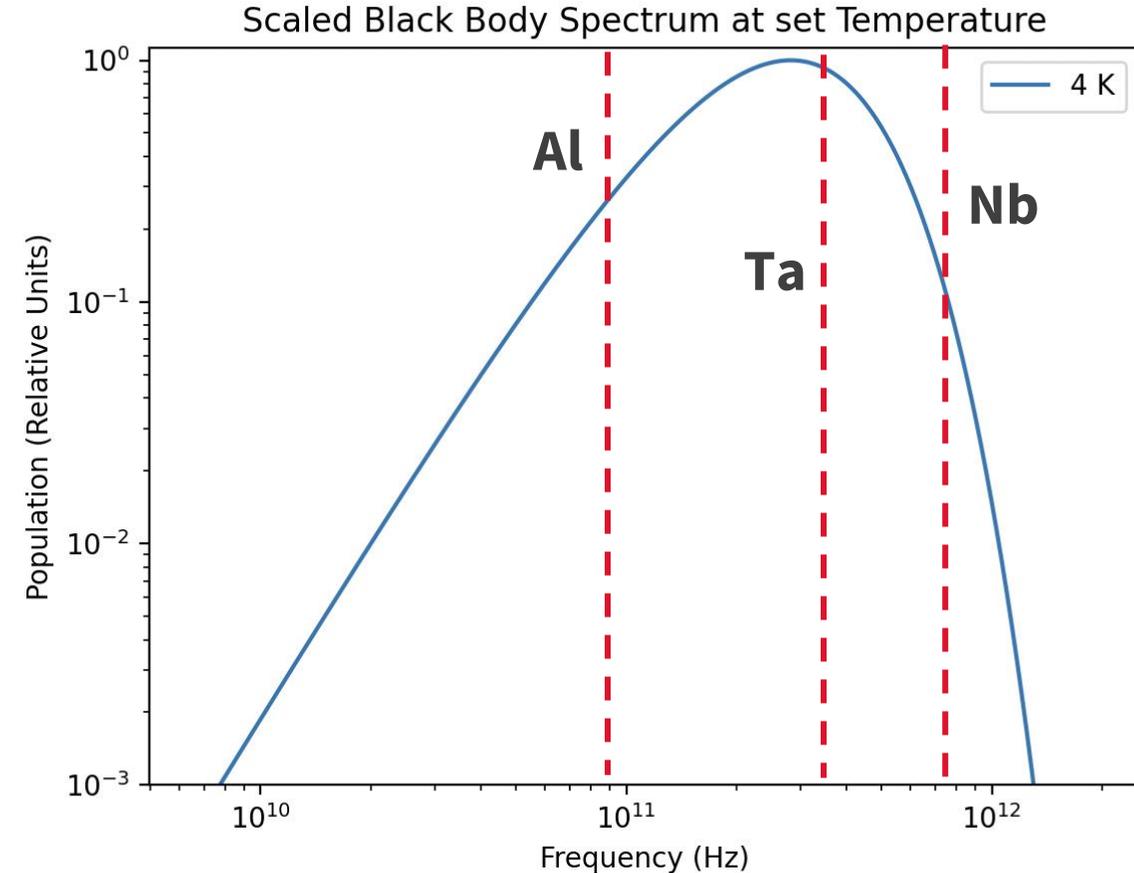
Solutions:

IR shields

IR absorbers (epoxy, foam)



More on this Shortly!



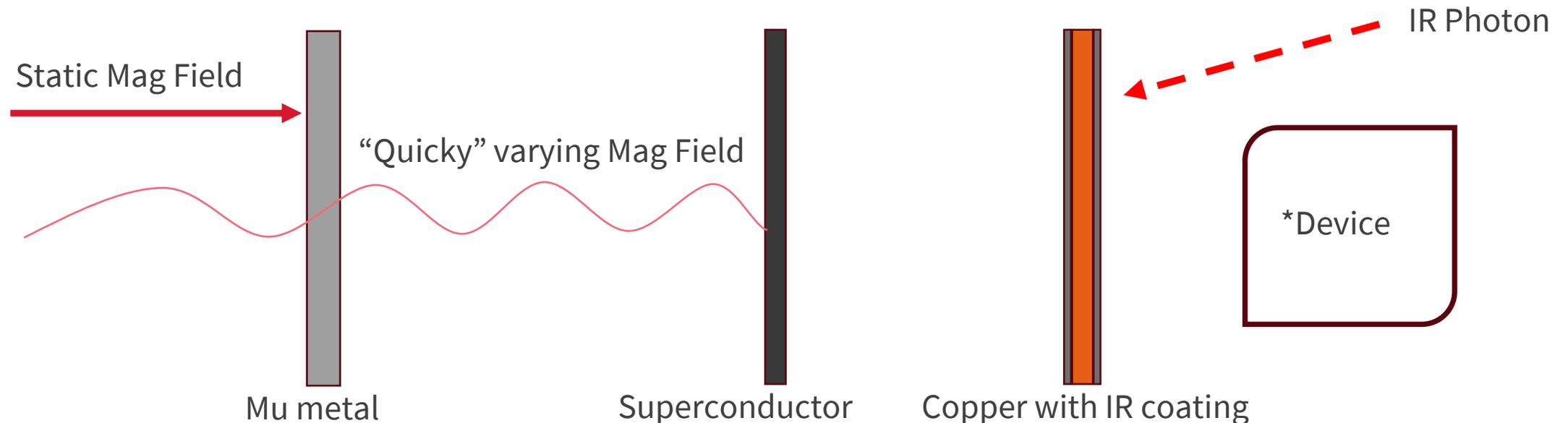
Optimal Shielding

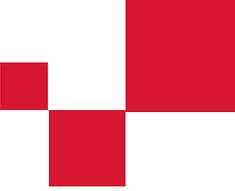
Ideal shielding will generally follow the structure of:

Mu metal -> Superconducting -> IR shield

See 2505.14274 for details

1. Mu metal is fantastic at redirecting static magnetic fields
2. Superconductors are good for more dynamic magnetic fields
3. IR shield Absorbs and thermalized IR radiation





Optimal Shielding

Effective shielding is tough to achieve. In general shields aim for:

- Light tight
- Vacuum compatible
- Non-device specific (reusable)
- Not radioactive
- Non-magnetic
- Effectively Thermalized

Many of these criteria seem “easy” to achieve but at closer inspection are very challenging or mutually exclusive

Let's look into “Light Tightness”

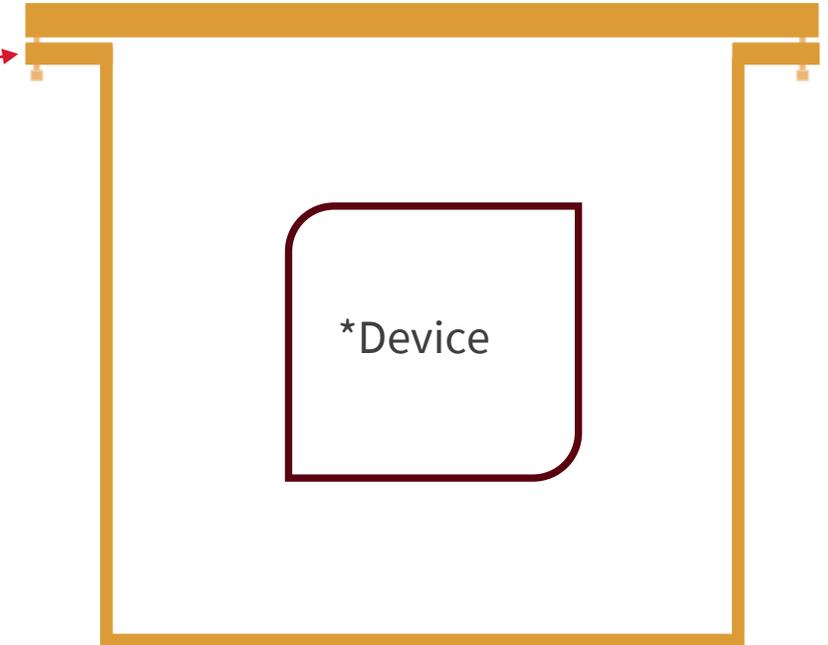
Problematic Seams

In a standard enclosure the device is sealed inside, this generally results in a seam

Indium wire is often used to create a hermetic seal

Indium is weakly **radioactive**.

As a result, this is undesirable for dark matter and or rare event searches



*General Enclosure

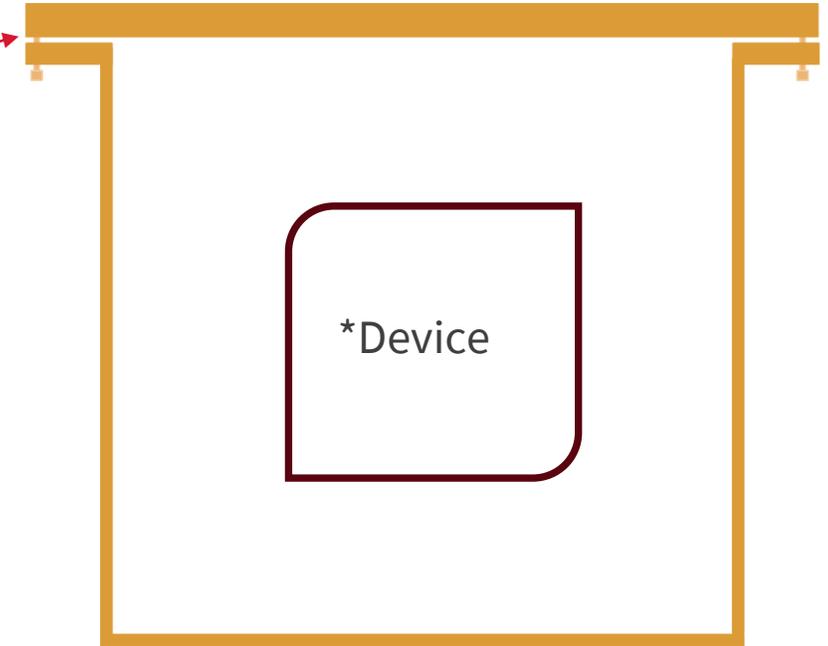
Problematic Seams

We're generally limited to two metal surfaces pressed against each other

At best this seam will have gaps on the order of the surface smoothness

(~150um is a reasonable worst case)

-> Clearly this sort of seam is not “light tight”

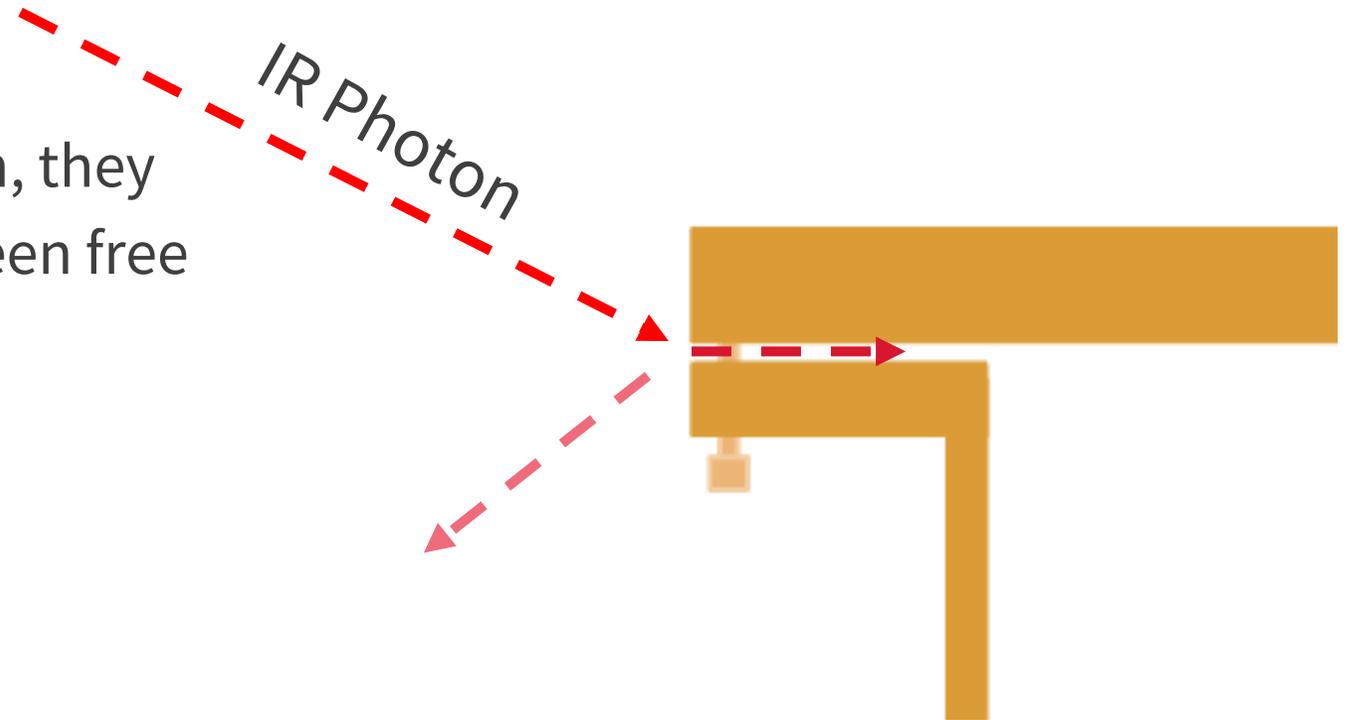


*General Enclosure

Problematic Seams

When photons encounter this seam, they see an impedance mismatch between free space and the flange

- Some photons are reflected
- Others pass into this region

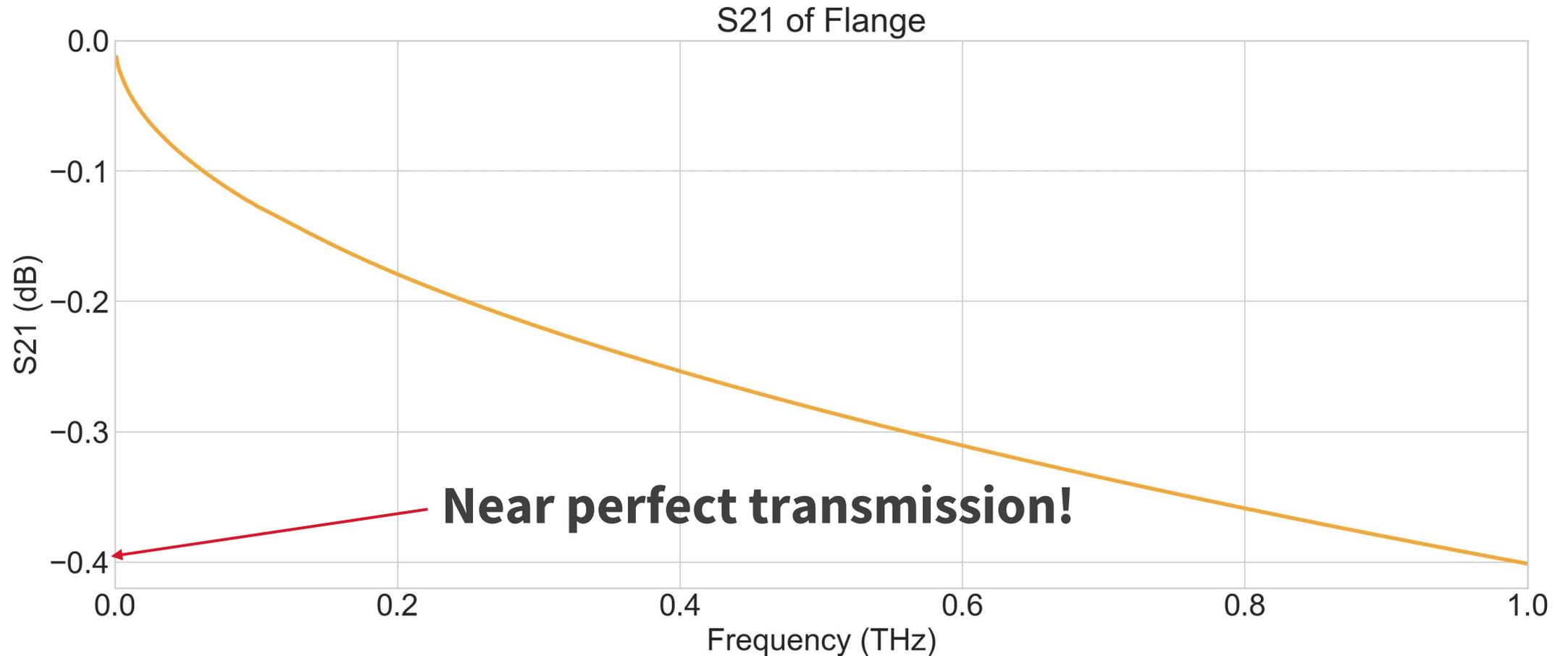


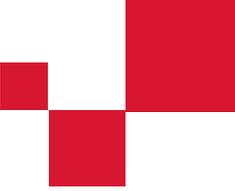
Using HFSS, the transmission S_{21} of the transmitted photons can be simulated

Simulating Seams

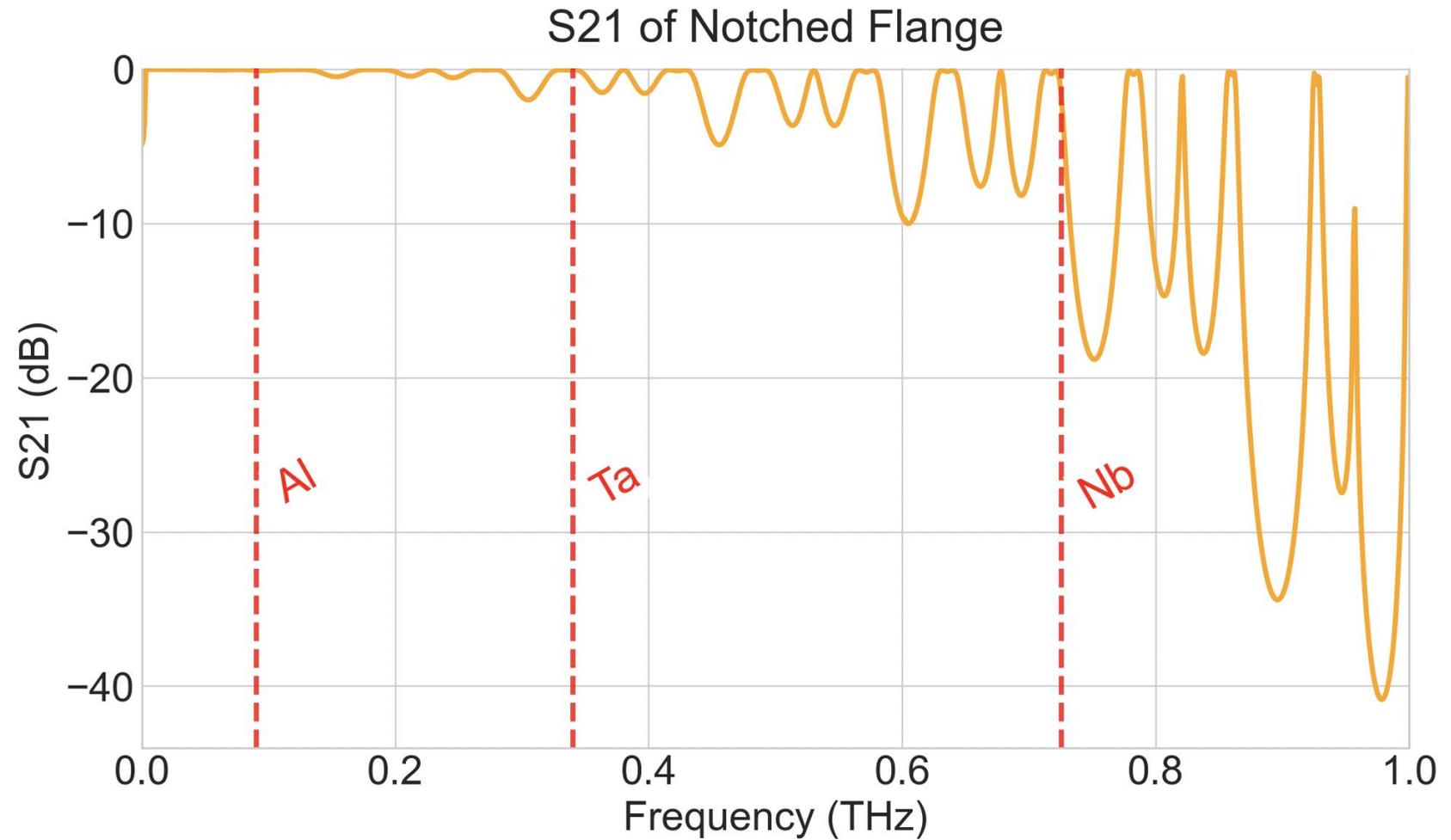
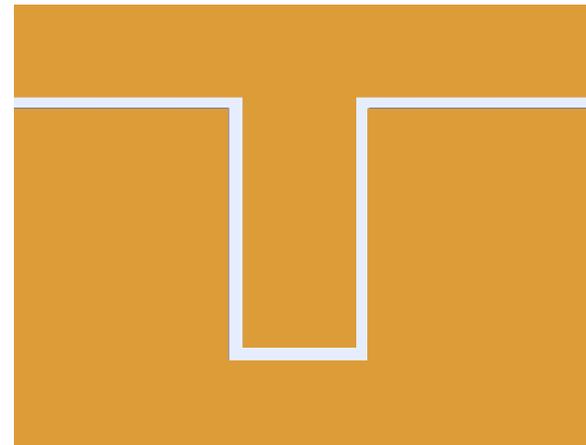


Here a thin slot with a thickness of 150 μm was simulated in HFSS





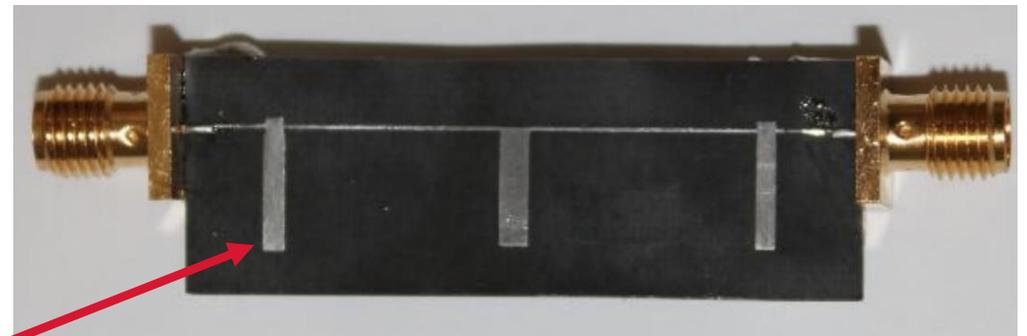
Common Mitigation: Notch



*This high frequency geography is highly notch dimension specific!

Flanges are generally unoptimized

- Flanges are suboptimal for 1 GHz- 1 THz
- Notches kick in around 800 GHz
- What can be done for <800 GHz?
- A general solution comes from RF design and has been demonstrated by **Yen-Yung Chang (Berkeley)**:



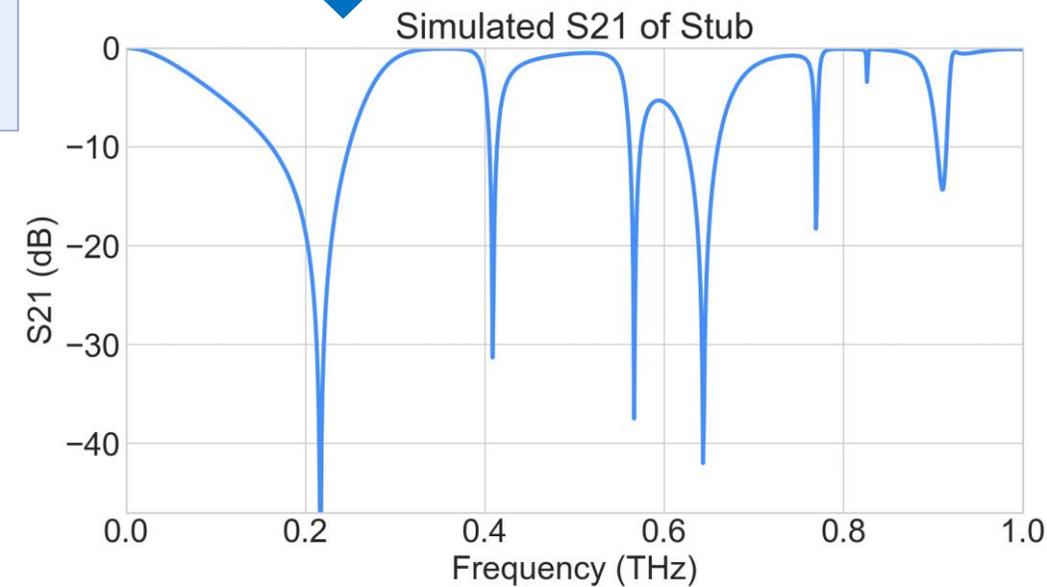
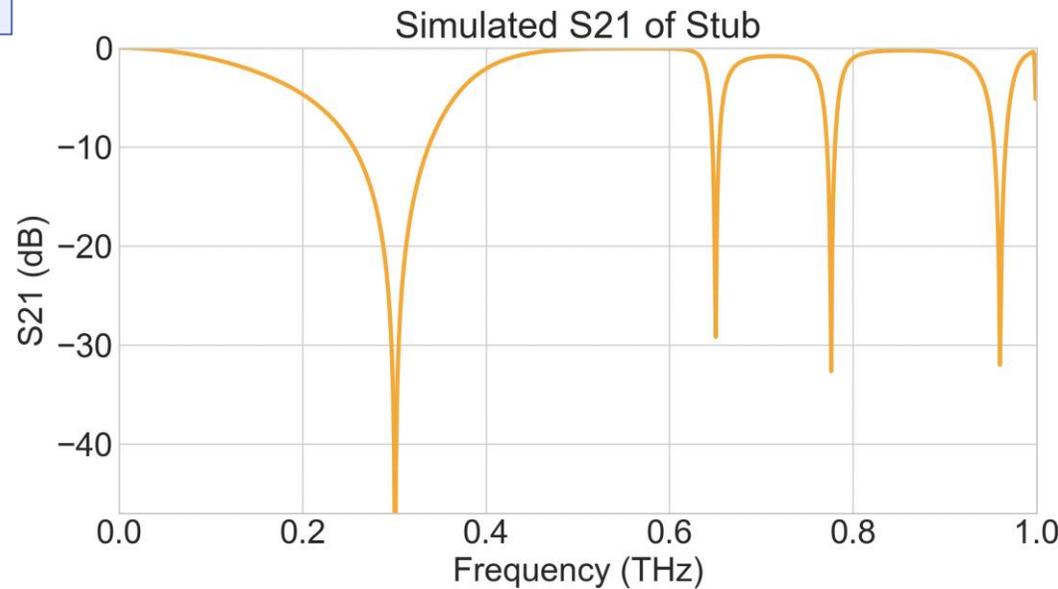
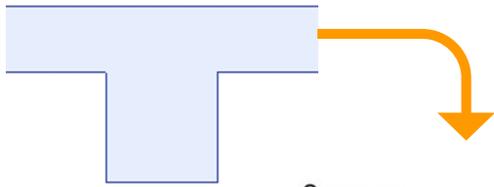
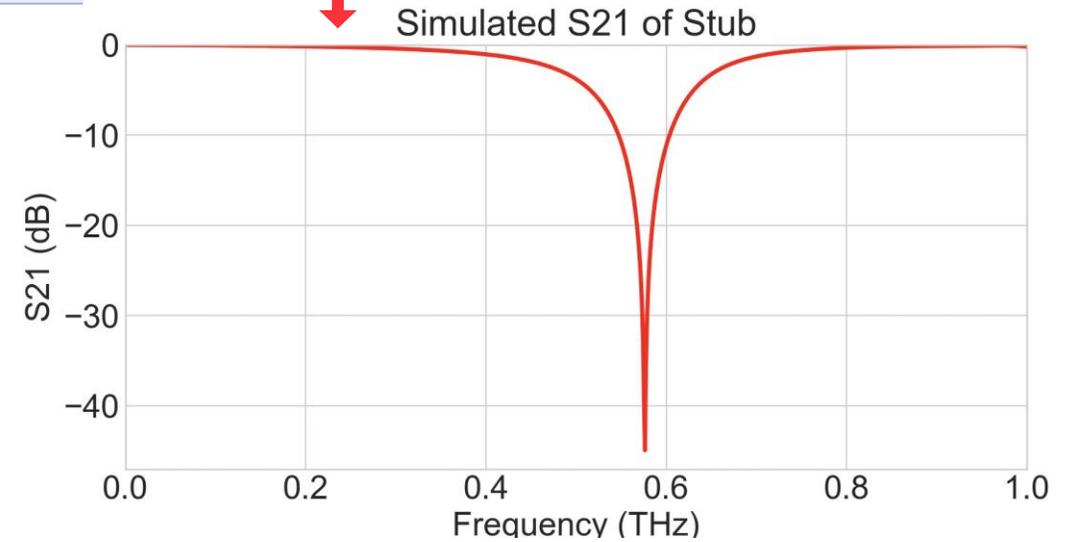
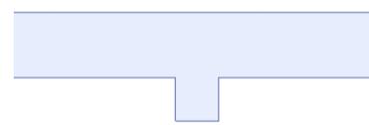
<https://ieeexplore.ieee.org/document/7394533>

Stub Filters

Currently I'm working with Yen-Yung to apply this technique and optimize it further to block lower frequency radiation and have favorable interactions with box modes

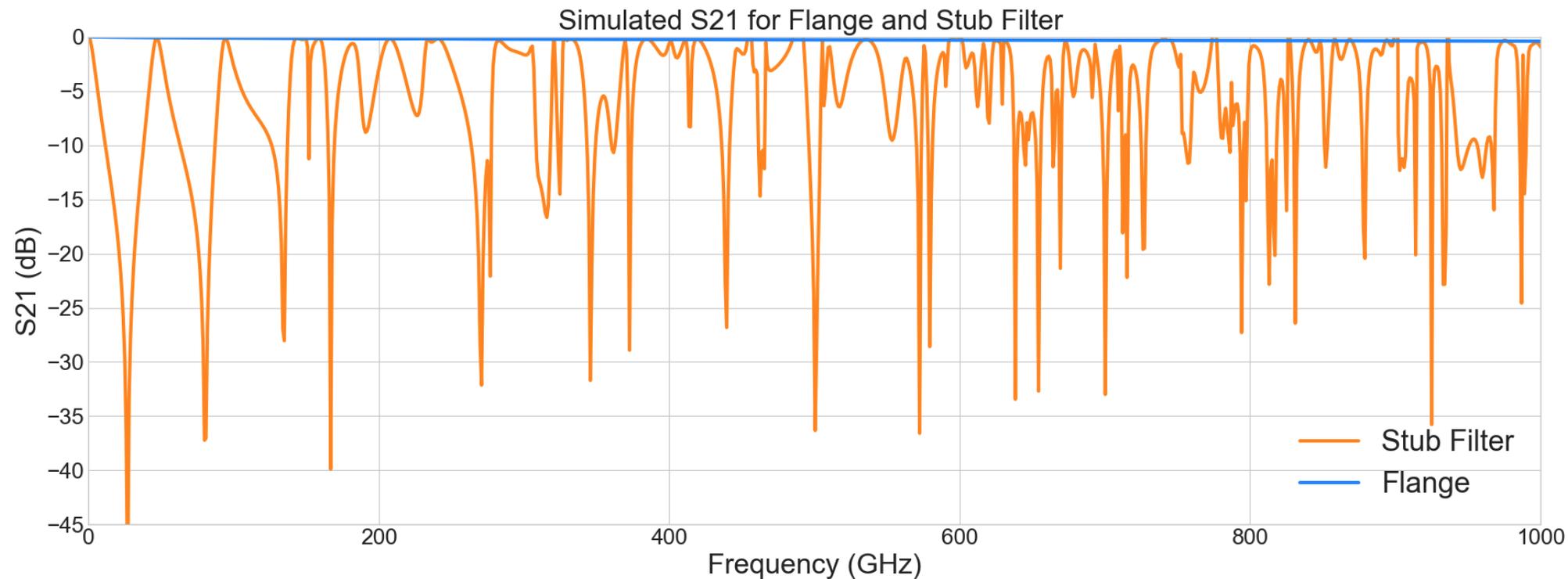
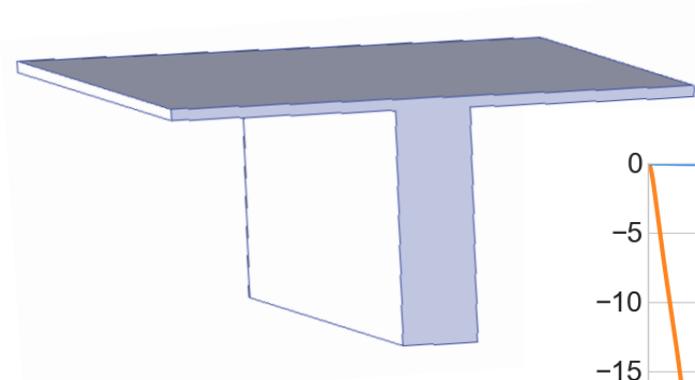
Stub Filters (<1mm)

- Stub Filters can be applied to the flange geometry
- Through stub parameters the transmission spectrum can be tuned!



Larger Stubs (>1mm)

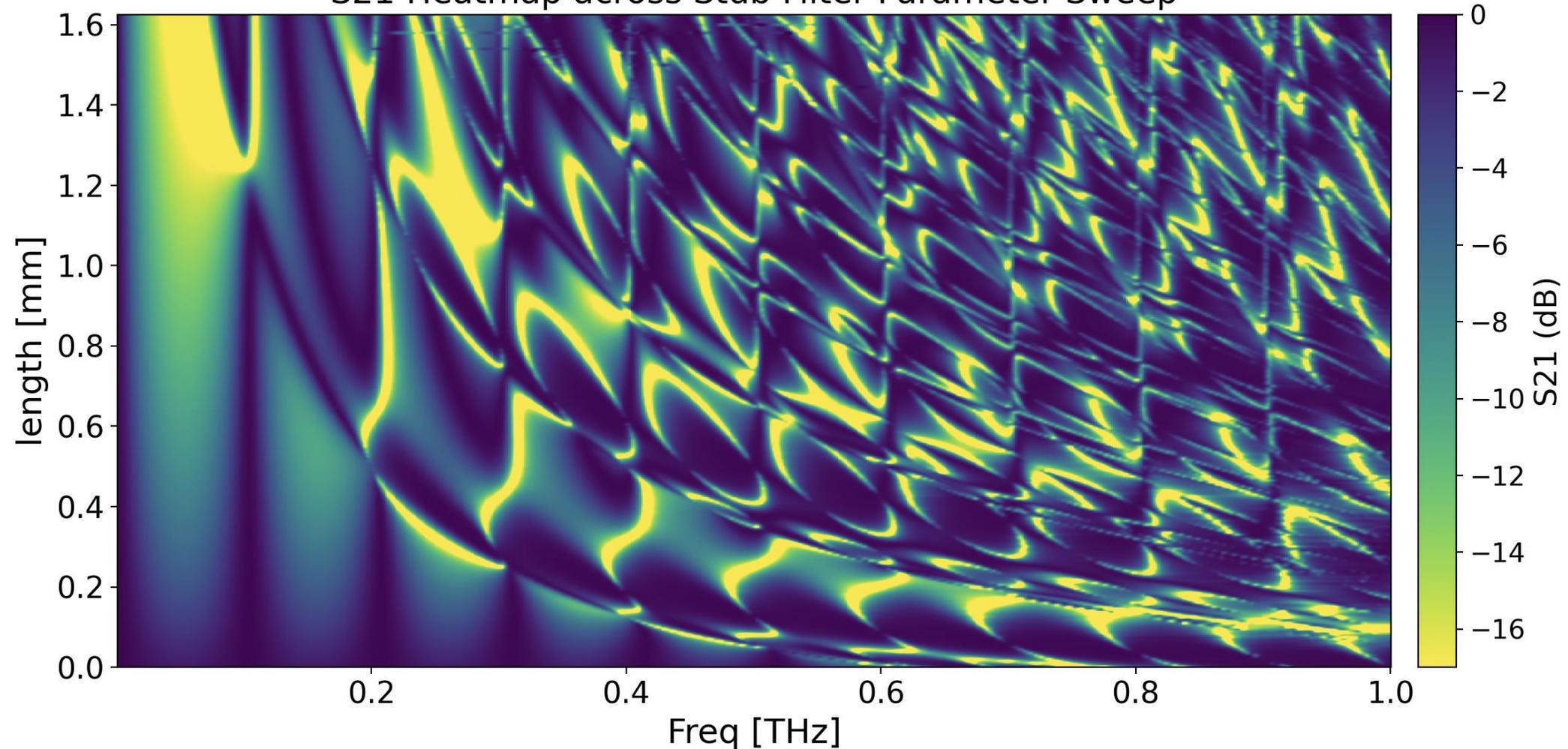
- Larger stubs have a more intricate spectrum
 - Combining small and large stubs provides a toolbox for Terahertz regime filtering!



Stub Filter Parameter Space

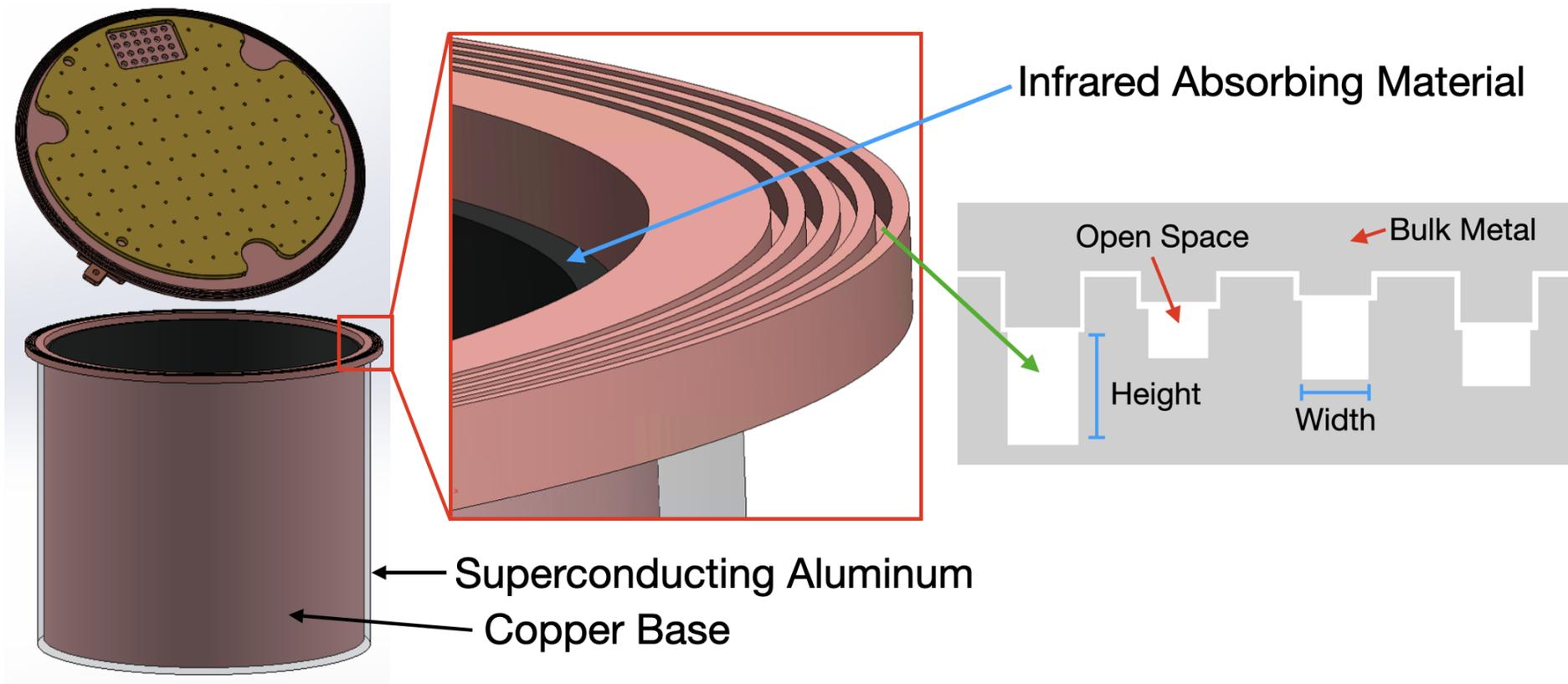
Wealth of parameter space to tune the spectrum!

S21 Heatmap across Stub Filter Parameter Sweep

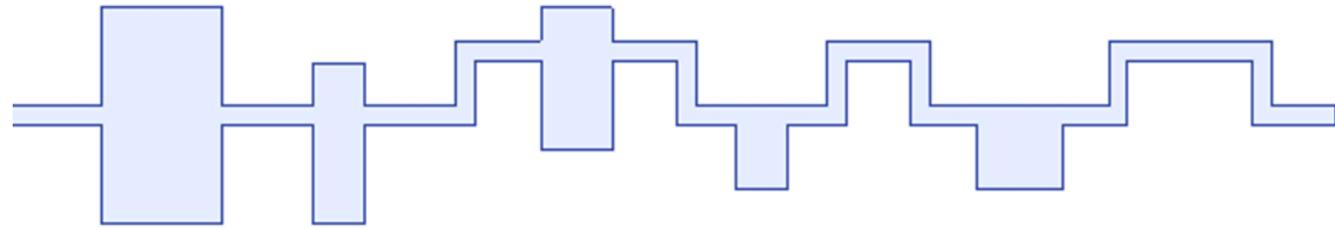


Stub Implementation

- The scale of these filters is well suited for shielding and device enclosure
- These filters can be retrofitted into an existing shield

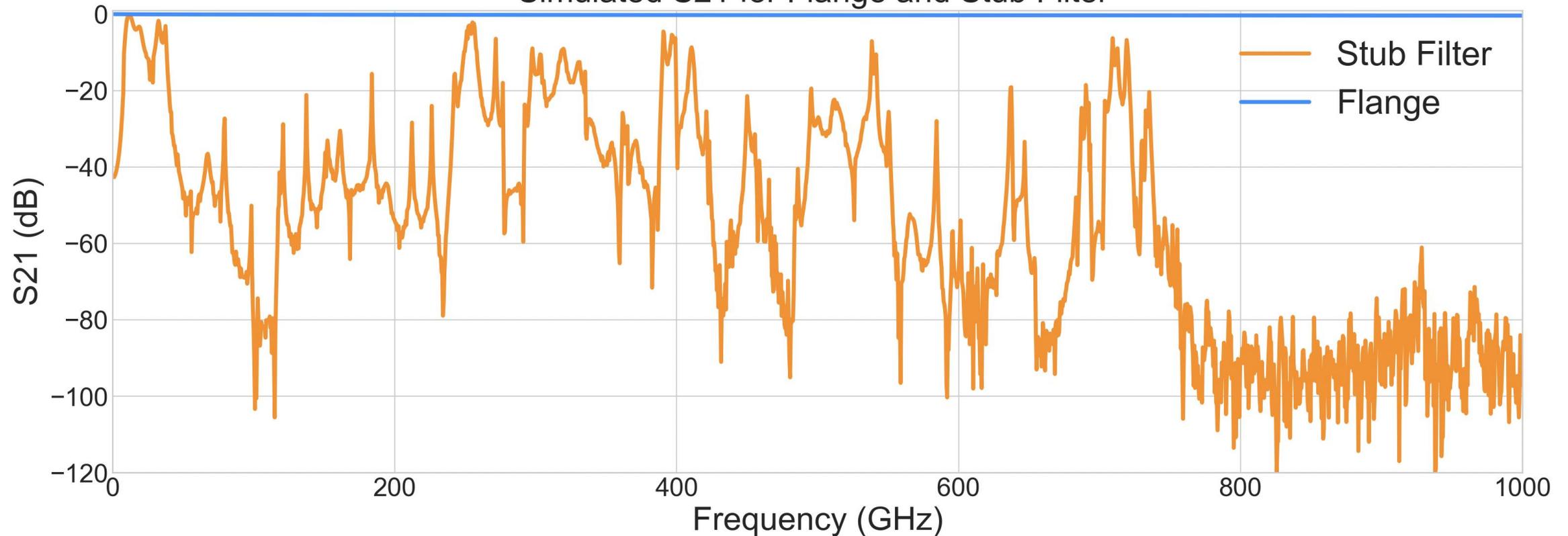


Stub Filter

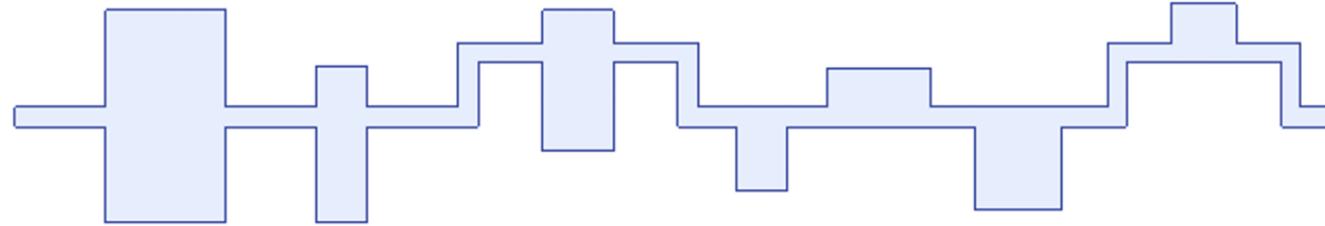


Preliminary design made for the RF Box Consortium, currently finalizing the design before production

Simulated S21 for Flange and Stub Filter

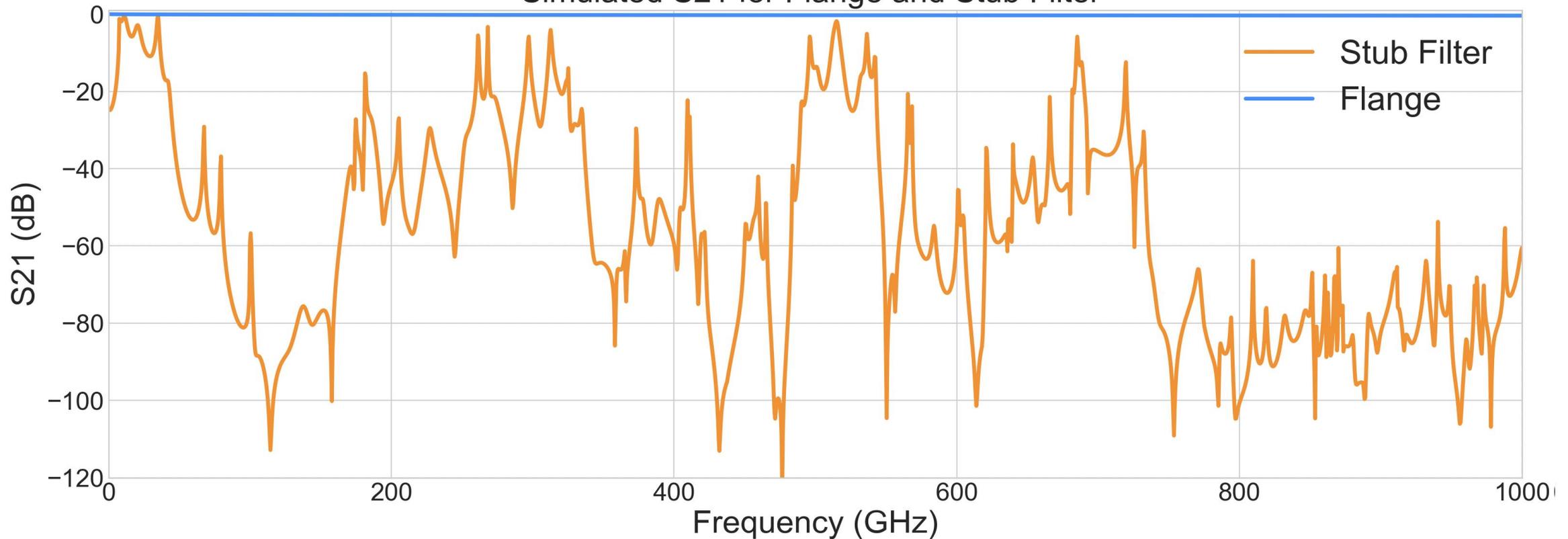


Stub Filter

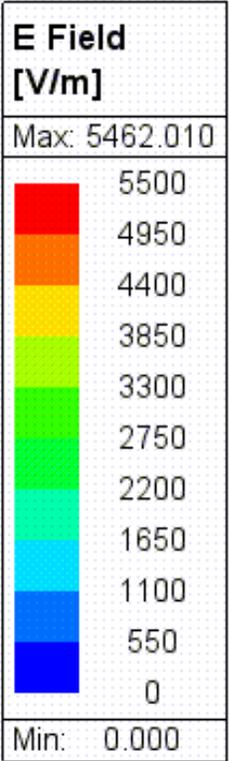
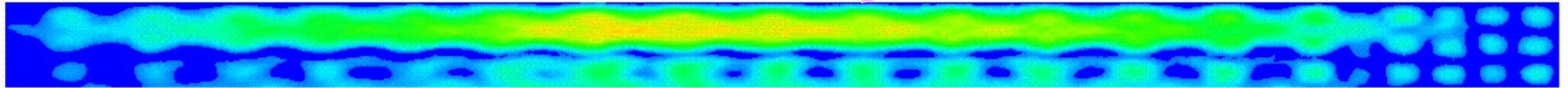
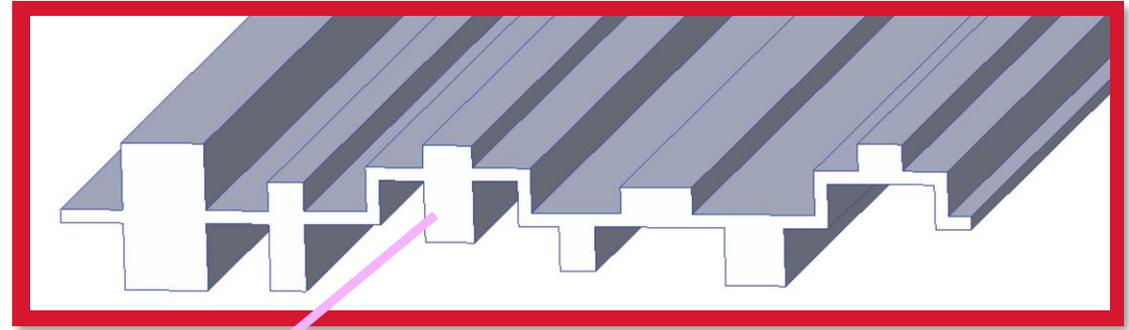


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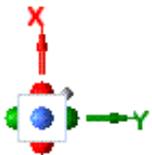


Resonant Mode Example



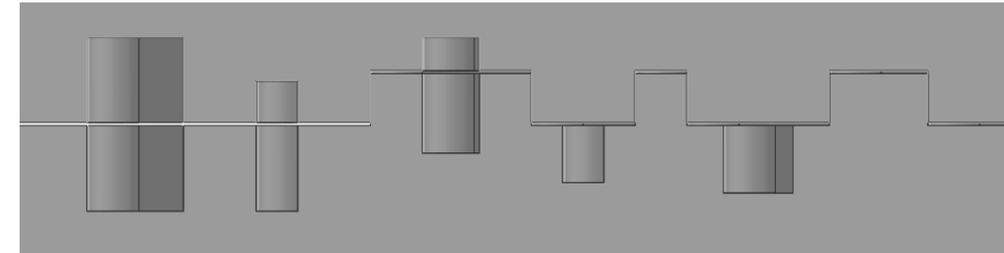
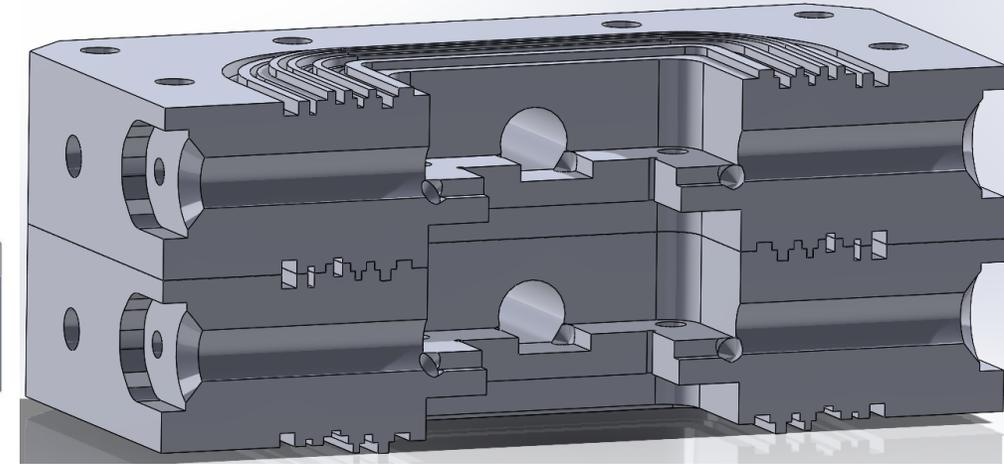
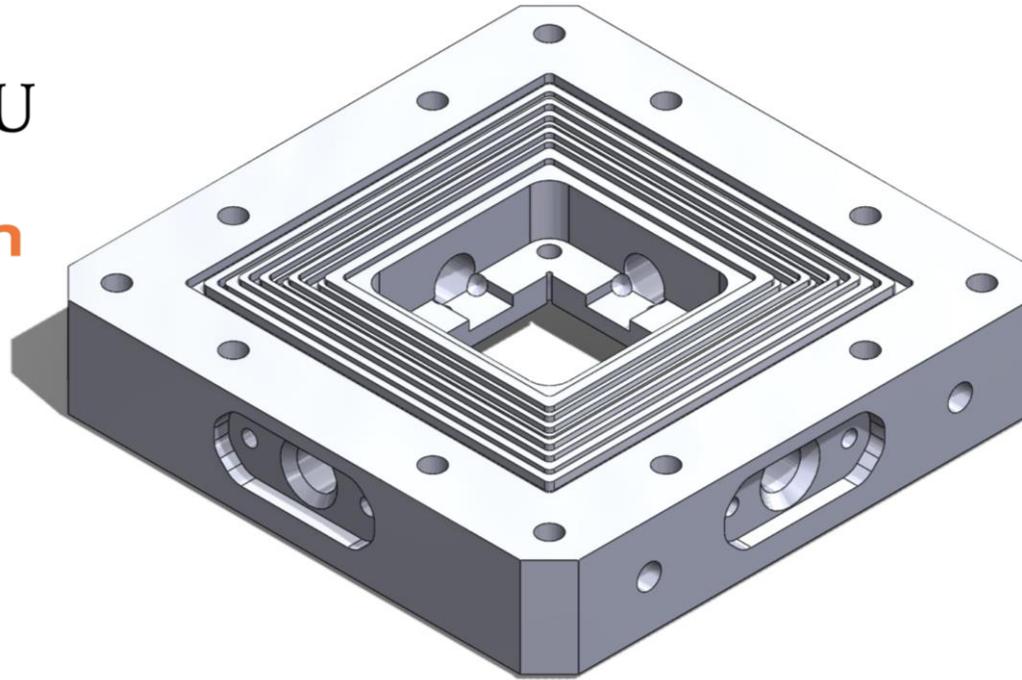
Phase = 0deg

This is a cross section of the indicated Stub, Resonant Mode!
The resonances will appear as peaks in S21



RF Box Consortium

- Through this group we're hoping to create a general device enclosure compatible with TES, Qubits, MKIDs, and other superconducting/quantum devices



Credit: Yashwanth Balaji & Arian Gashi of LBNL

For More in depth details please go to Xinran Li's talk on behalf of Yen-Yung:
Oct 9, 2025, 2:00 PM. Woodlands AB RDC 7

Conclusion

- Improving backgrounds is important to push our devices performance
- Shielding effectiveness improvements are expected through use of stub filters
- Plans to implement the RF box and study qubit performance in QUIET are taking shape
 - Stay tuned for RF box results



Acknowledgements

•**IIT:** Rakshya Khatiwada (joint w/ FNAL), Kester Anyang, Israel Hernandez, Jialin Yu, Ziyu Cai

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Thank you!

**ILLINOIS
TECH**

Magnetic Fields

- common cryo components are often weakly magnetic
 - SMA connectors are made of stainless steel (magnetic) are common
 - Many copper SMA connectors contain a layer of nickel
- Some passive components are innately magnetic (Circulators!)



Solutions:

Use non-magnetic lines*

Mag shields (Mu metal / superconducting)

Properly isolate natively magnetic components