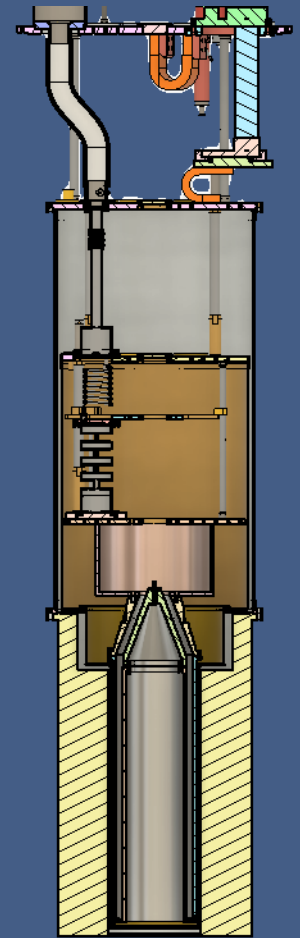


CAL-Pathfinder

Shreya Puranam
CPAD October '26



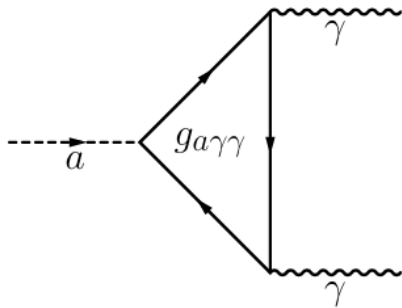
Axions

Axions are a highly motivated dark matter candidate, first proposed to solve the strong CP problem in QCD!

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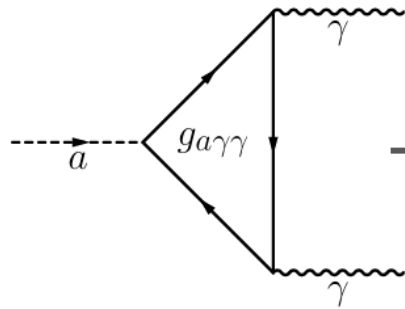
- Search for the axion using its coupling to photons



Axions

Axions are a highly motivated dark matter candidate, first proposed to solve the strong CP problem in QCD!

- Search for the axion using its coupling to photons
- Low mass = wave-like $\rightarrow$ searching for an effective current



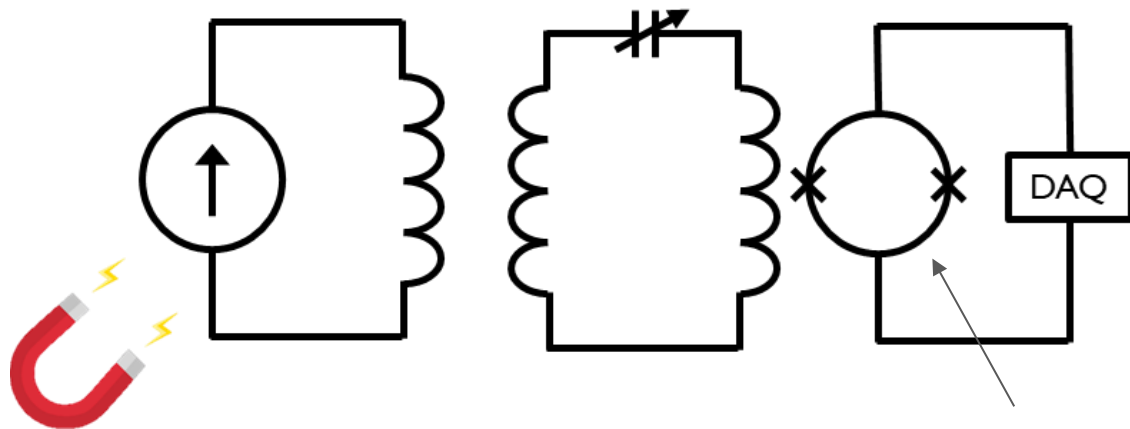
$$\mathbf{J} \sim g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}} \cos(m_a t) \mathbf{B}$$

- $\rightarrow g_{a\gamma\gamma}$ = coupling strength to photons
- $\rightarrow \rho_{\text{DM}}$ = dark matter density
- $\rightarrow m_a$ = axion mass

Lumped Element Detection

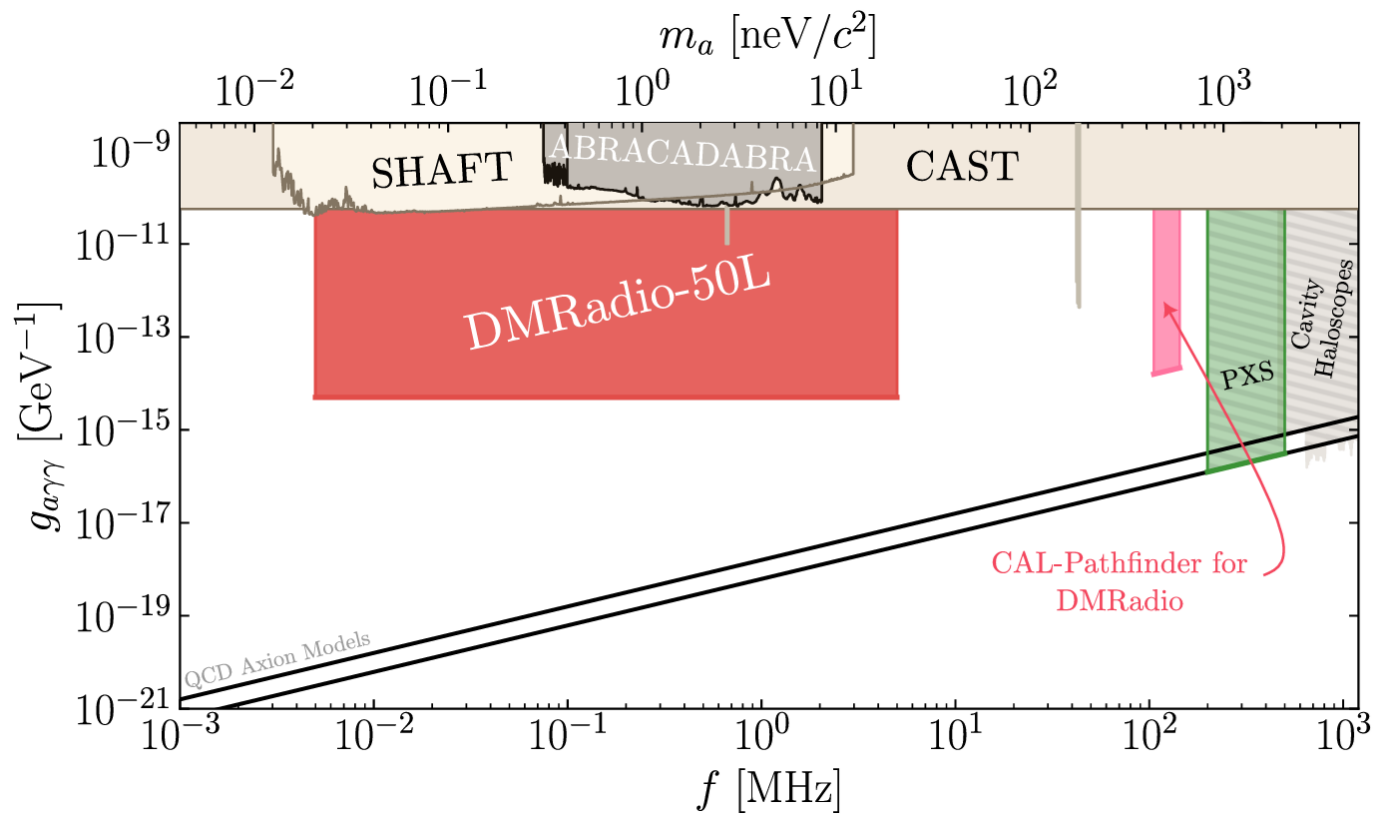
Lumped element: $\lambda_{\text{axion}} > \text{detector size}$

- Resonant modes are given by inductive and capacitive elements
- Use an LC resonator with the axion effective current acting as a current source

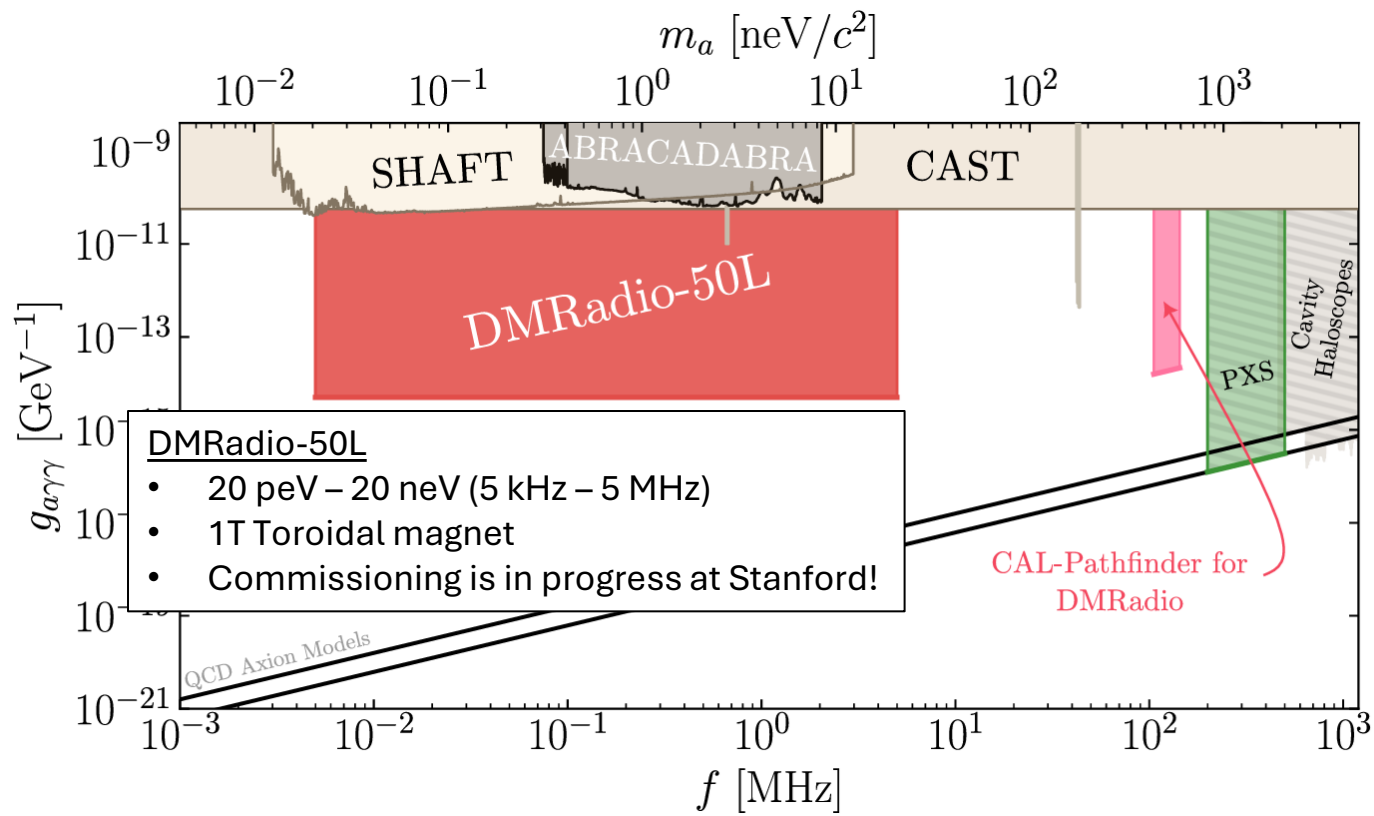


flux to voltage amplifier

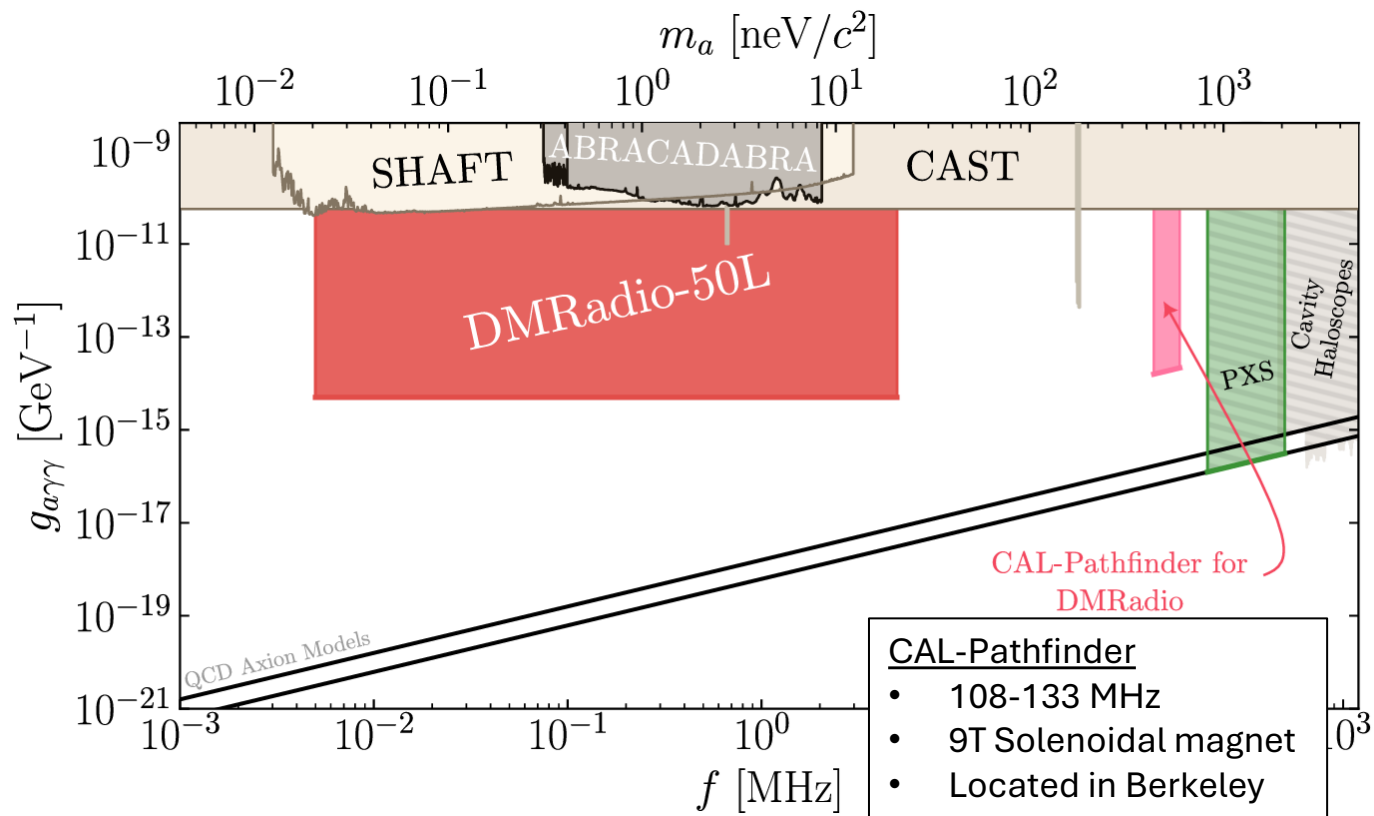
DMRadio Program



DMRadio Program



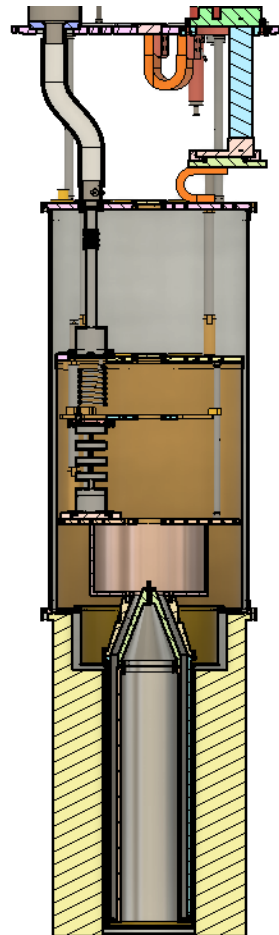
DMRadio Program



CAL: Cal Axion LC

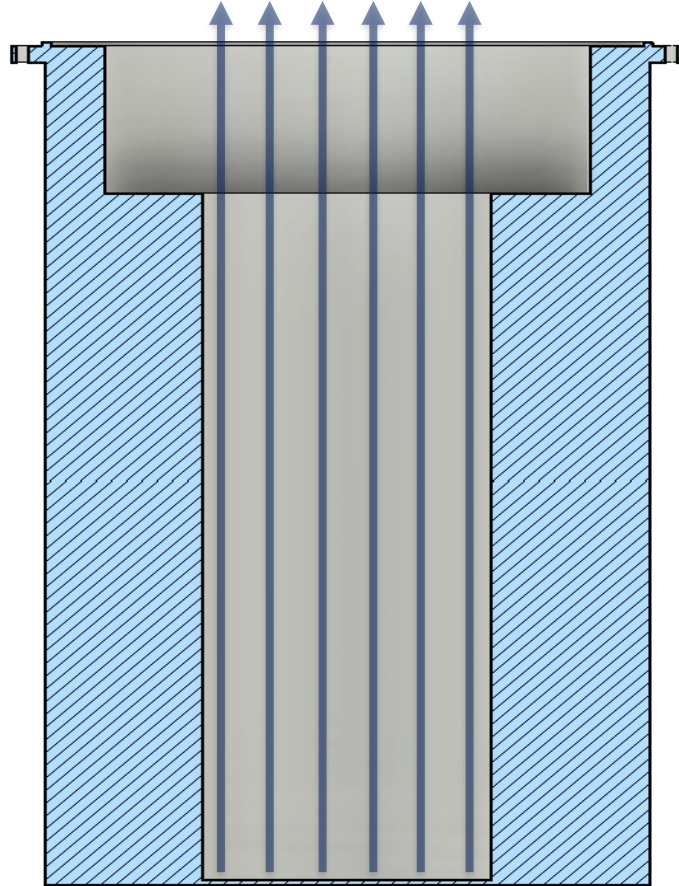
Demonstrate solenoid geometry for axion searches while holding discovery potential for axions and high frequency gravitational waves

- Building on existing DMRadio expertise and infrastructure
- Initial phase (CAL-Pathfinder) is funded by Templeton
- Hosted in a BlueFors LD400 dilution refrigerator at Berkeley

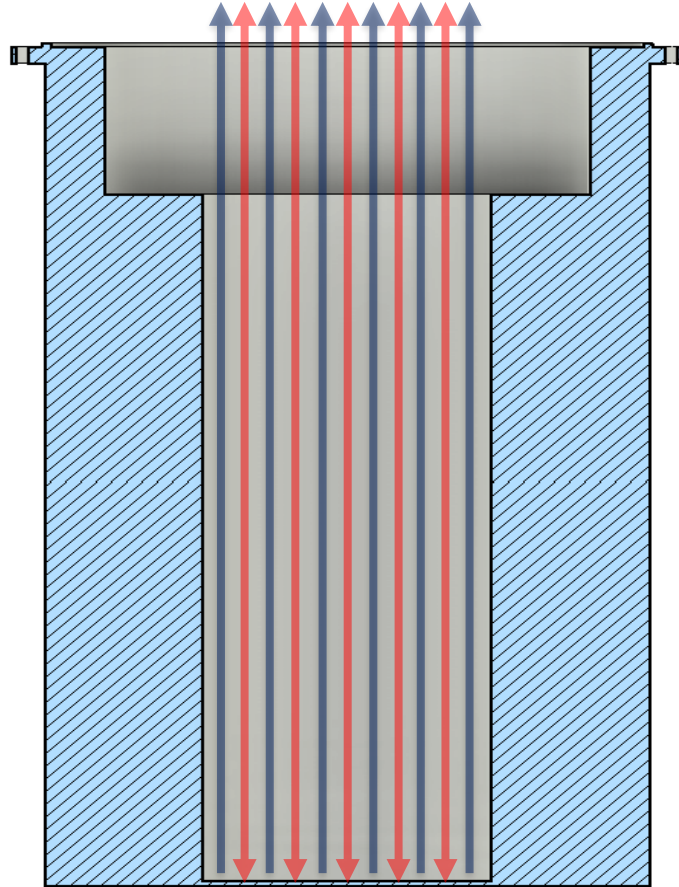


How CAL Couples to Axions

Solenoidal B-Field



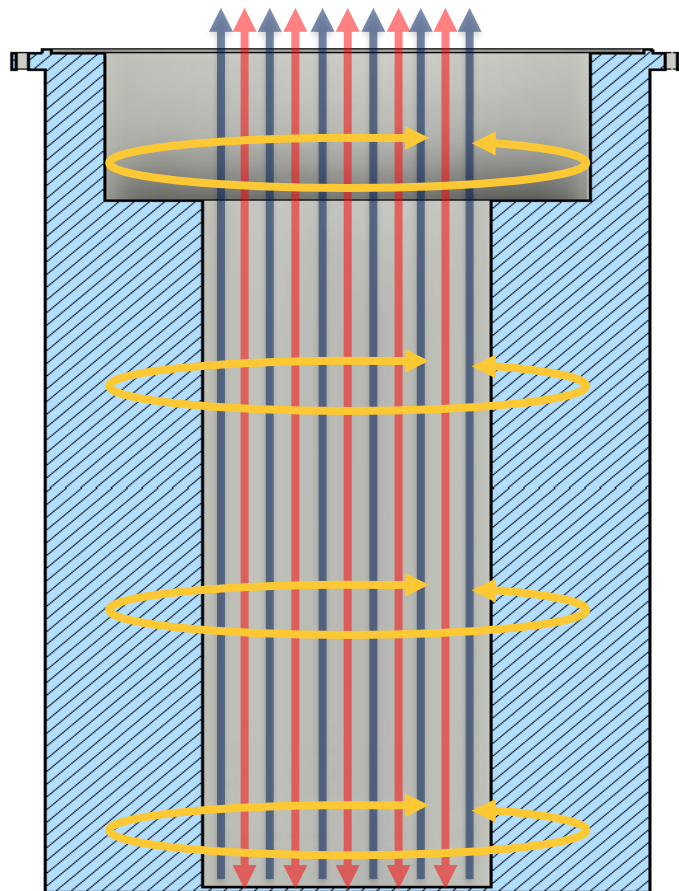
Solenoidal B-Field



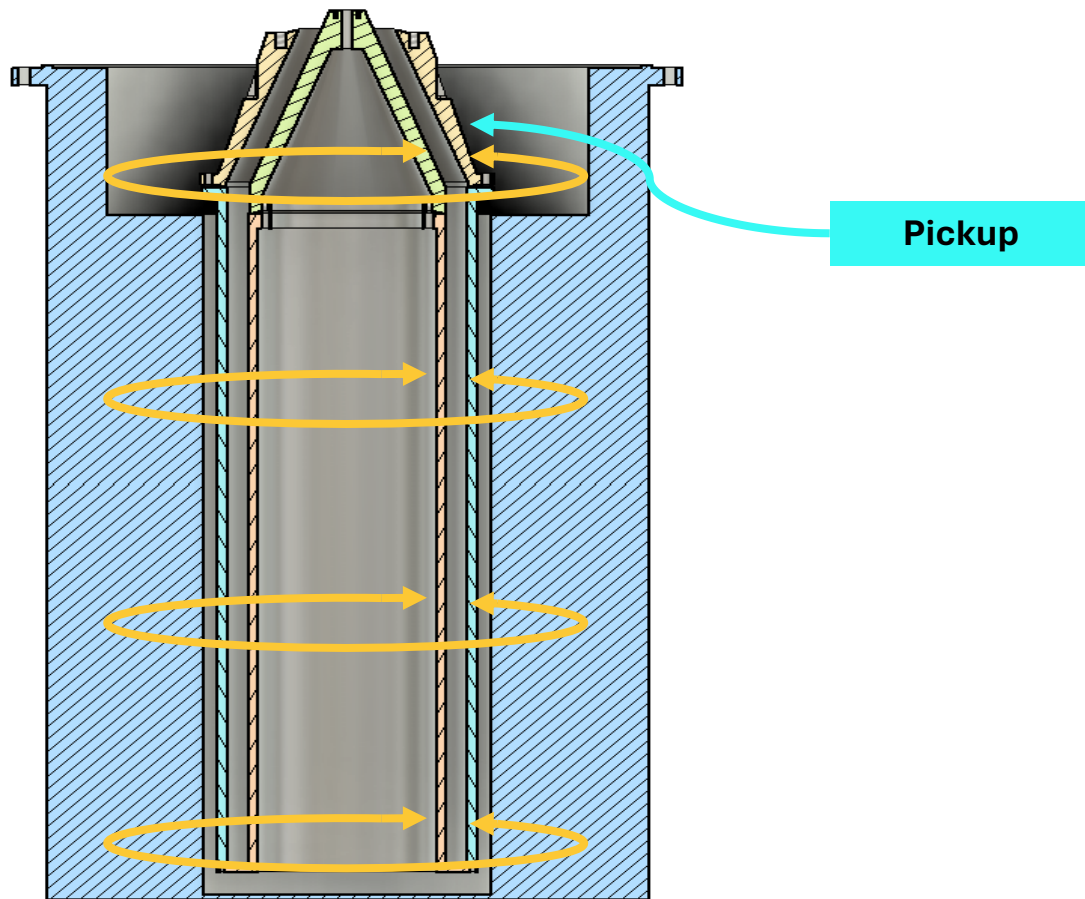
Axion Effective Current

Solenoidal B-Field

Axion Induced B-Field

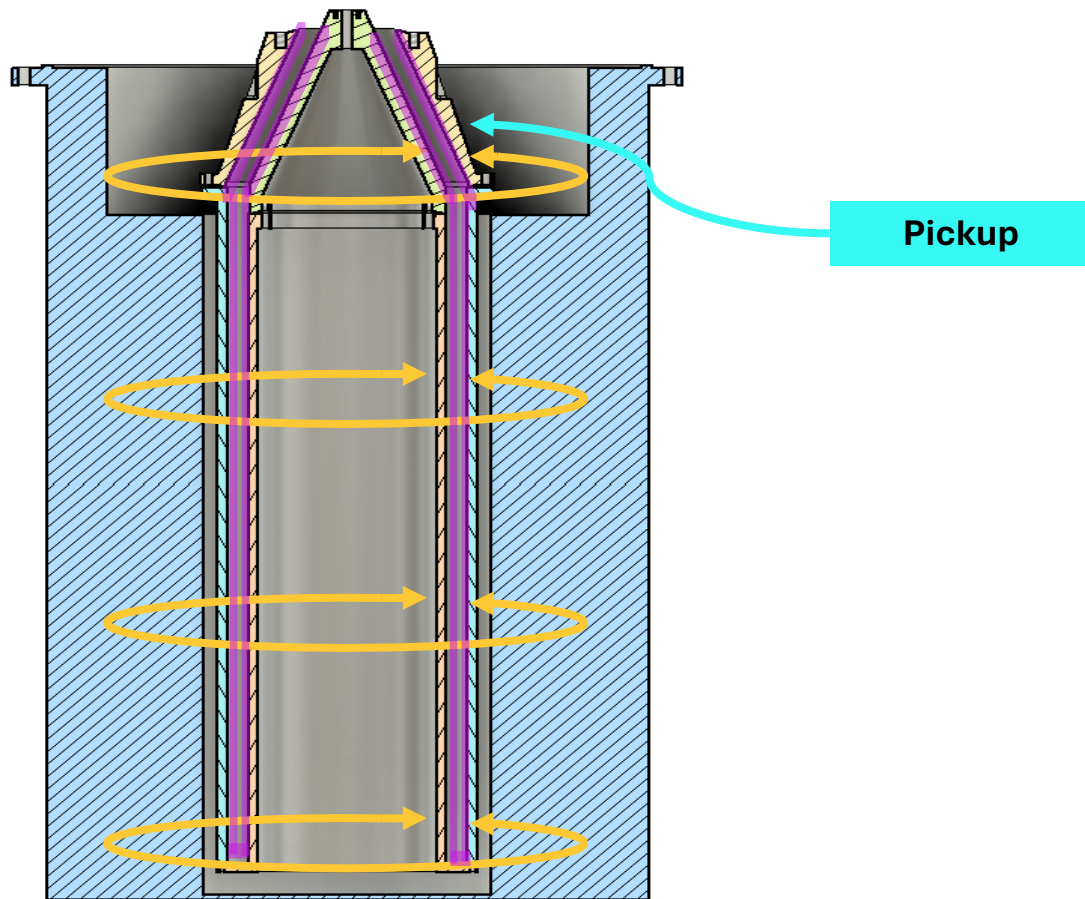


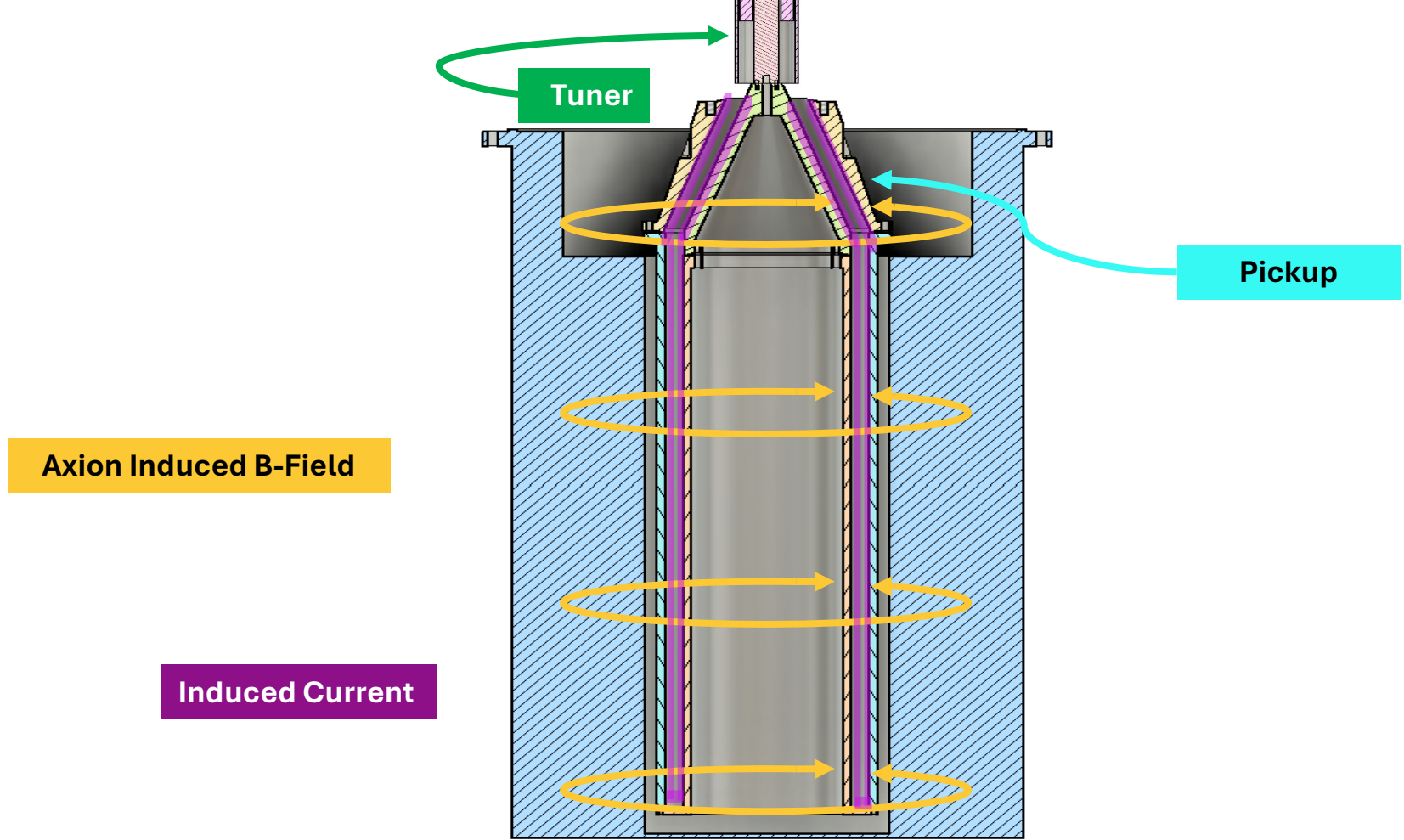
Axion Effective Current



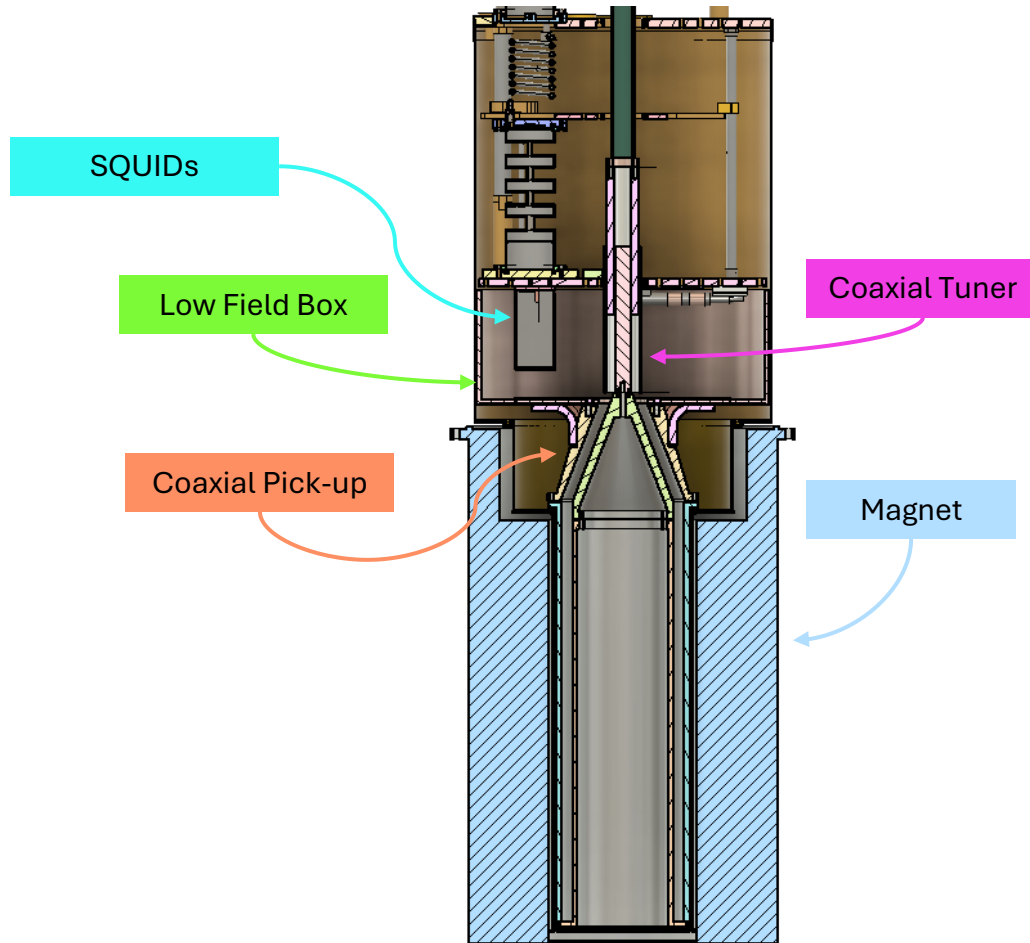
Axion Induced B-Field

Pickup

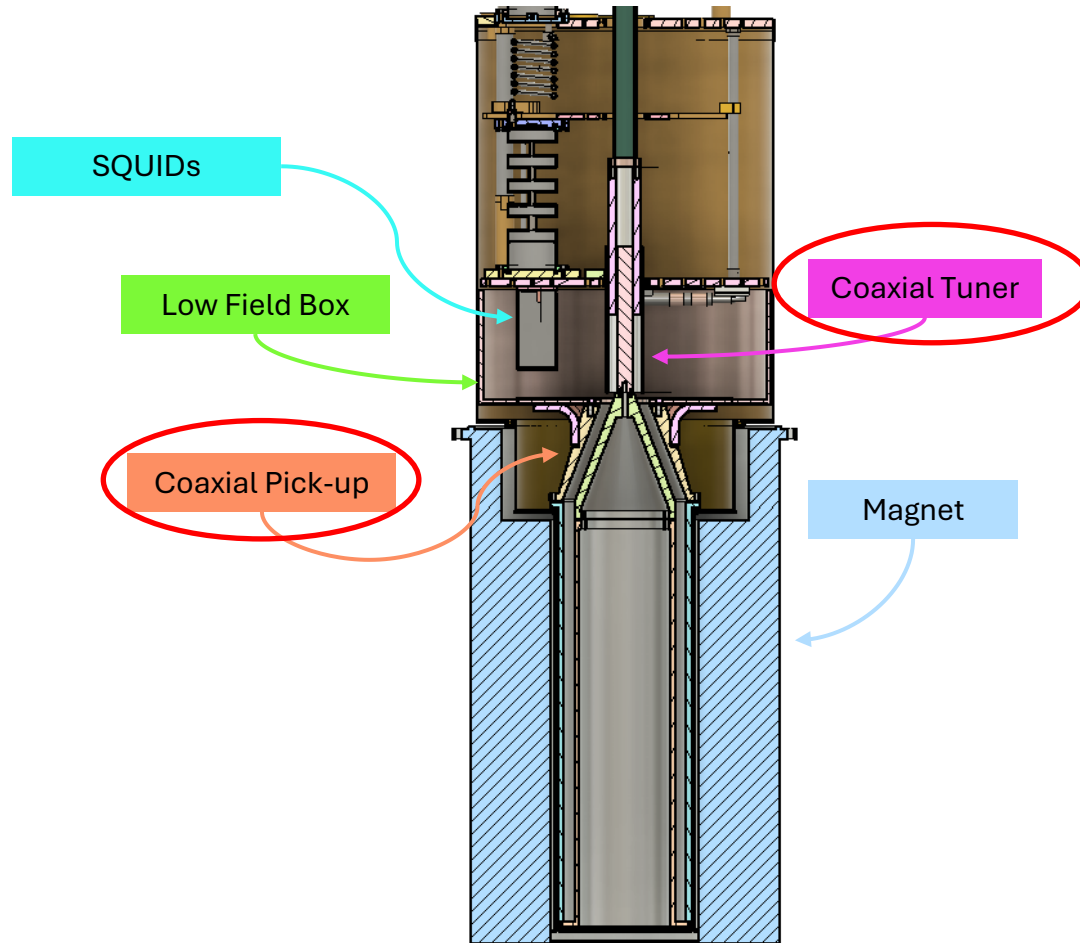




The CAL-Pathfinder Detector

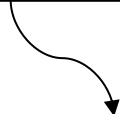


The CAL-Pathfinder Detector



What is Scan Rate for CAL-Pathfinder

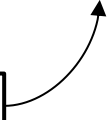
Magnitude of the induced voltage


$$\frac{d\nu}{dt} \propto \frac{|V(m_a, \mathbf{B}, g_{a\gamma\gamma})|^4 Q(\nu_r) \bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]}{L_{eff}(\nu_r)^2}$$

What is Scan Rate for CAL-Pathfinder

$$\frac{d\nu}{dt} \propto \frac{|V(m_a, \mathbf{B}, g_{a\gamma\gamma})|^4 Q(\nu_r) \bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]}{L_{eff}(\nu_r)^2}$$

Total effective inductance



What is Scan Rate for CAL-Pathfinder

Quality factor of the resonator



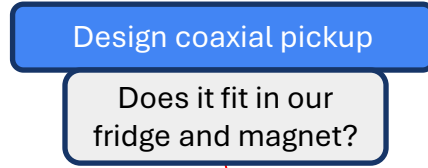
$$\frac{d\nu}{dt} \propto \frac{|V(m_a, \mathbf{B}, g_{a\gamma\gamma})|^4 Q(\nu_r) \bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]}{L_{eff}(\nu_r)^2}$$

What is Scan Rate for CAL-Pathfinder

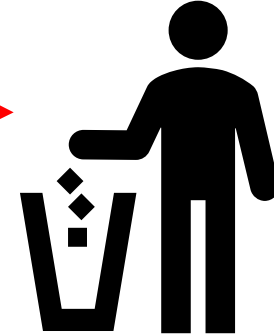
$$\frac{d\nu}{dt} \propto \frac{|V(m_a, \mathbf{B}, g_{a\gamma\gamma})|^4 Q(\nu_r) \bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]}{L_{eff}(\nu_r)^2}$$

Parameterizes the noise physics.

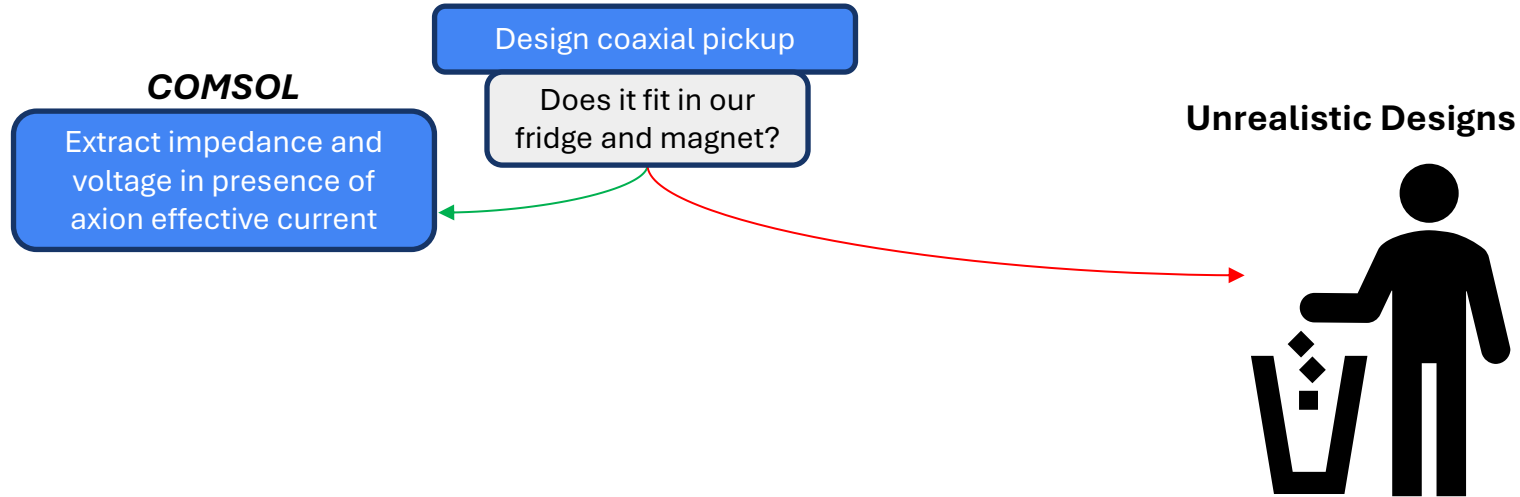
Designing the Coaxial Pick-Up and Tuner



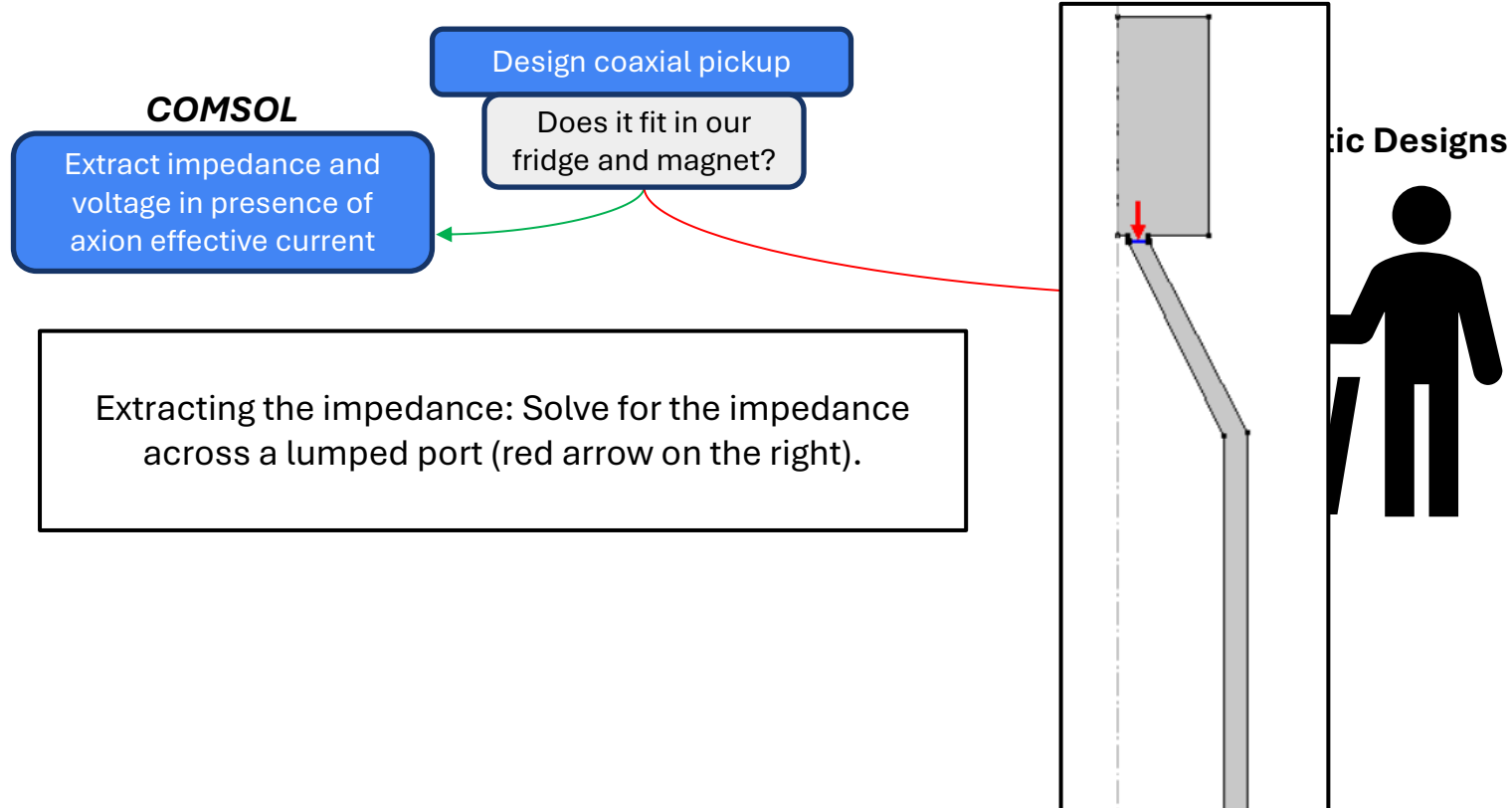
Unrealistic Designs



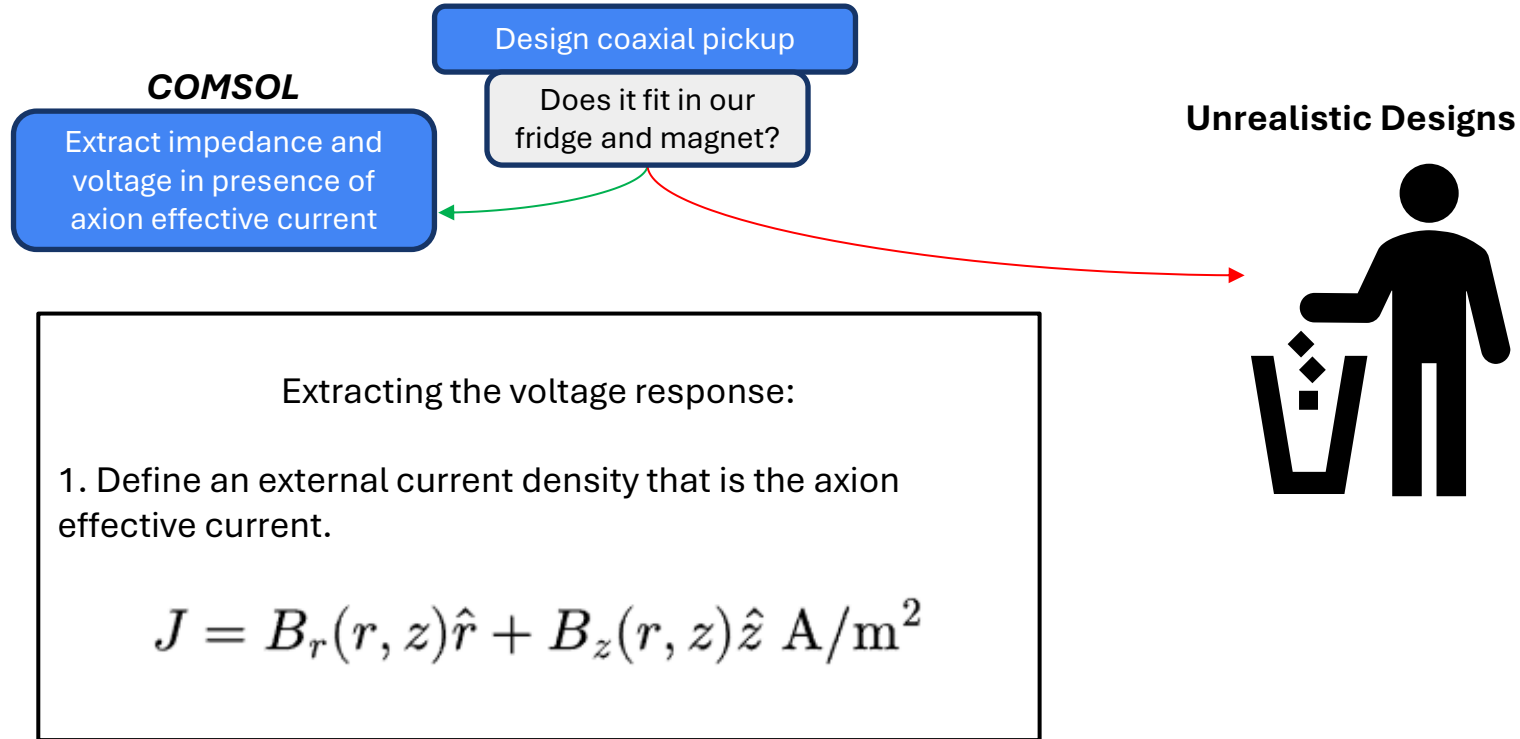
Designing the Coaxial Pick-Up and Tuner



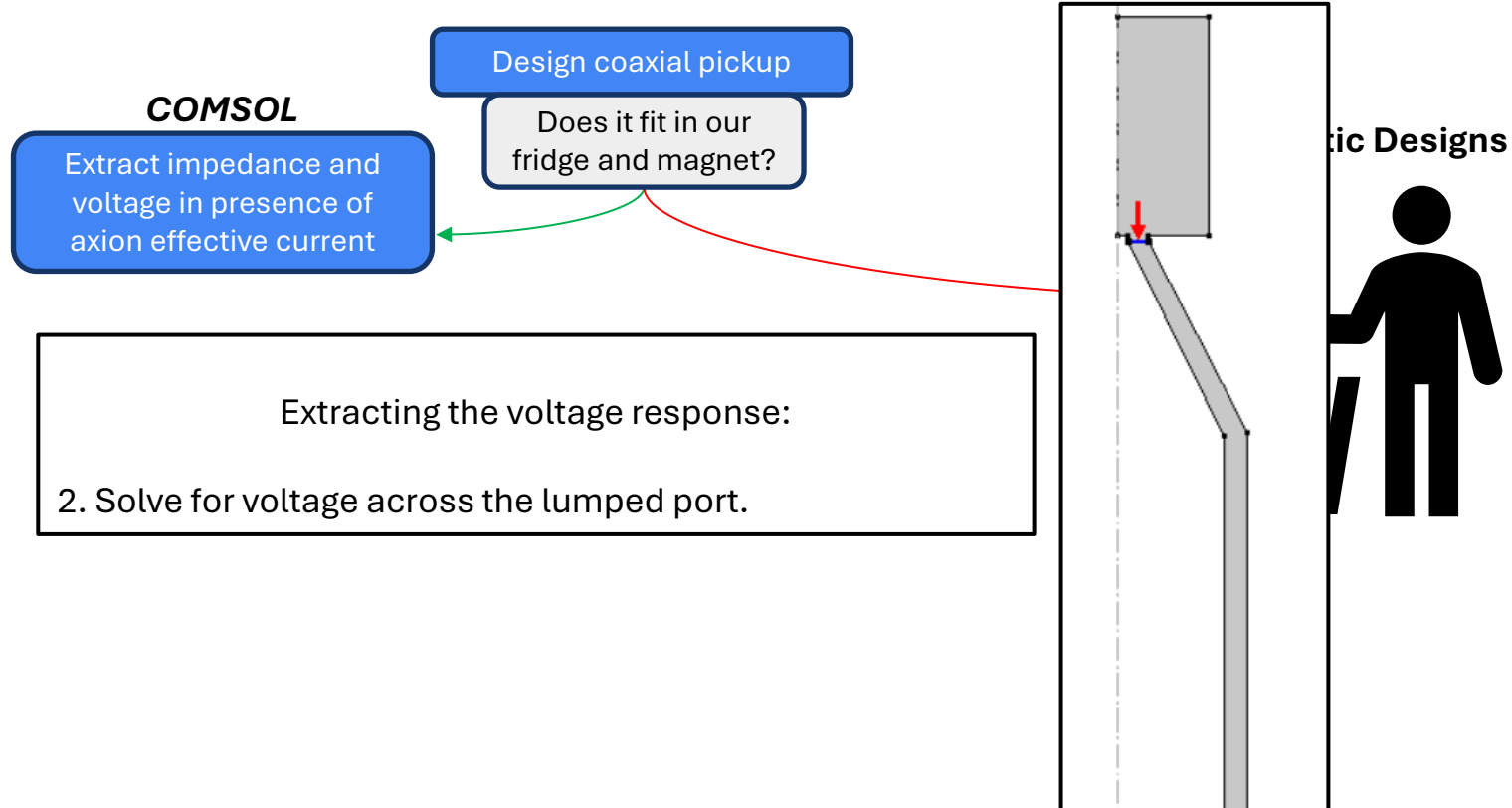
Designing the Coaxial Pick-Up and Tuner



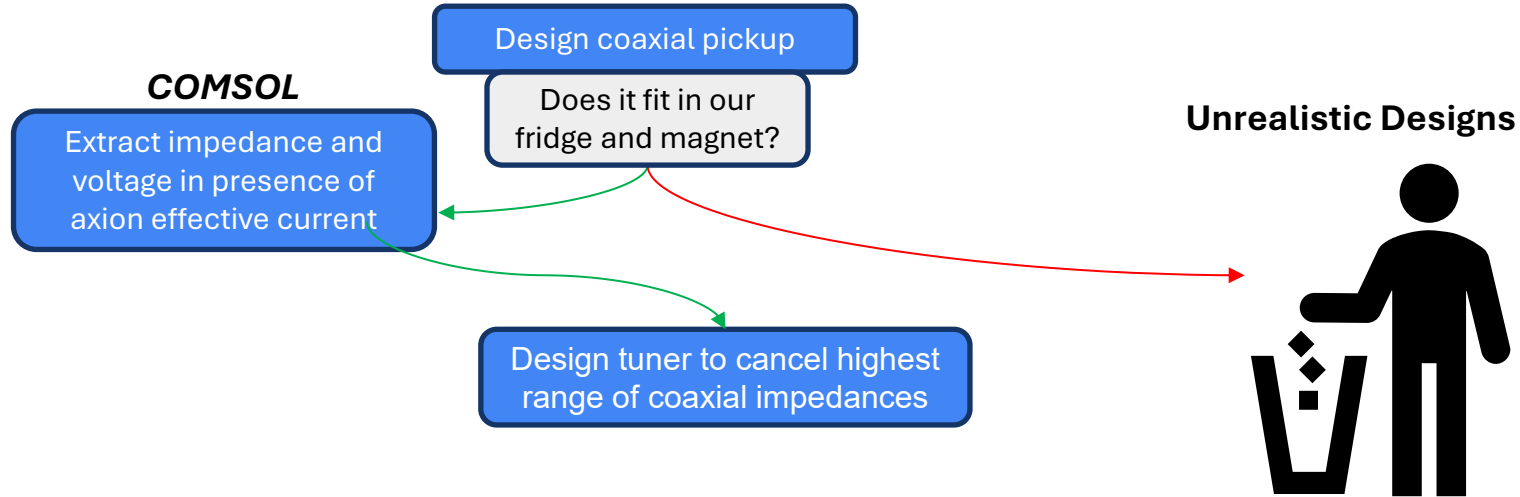
Designing the Coaxial Pick-Up and Tuner



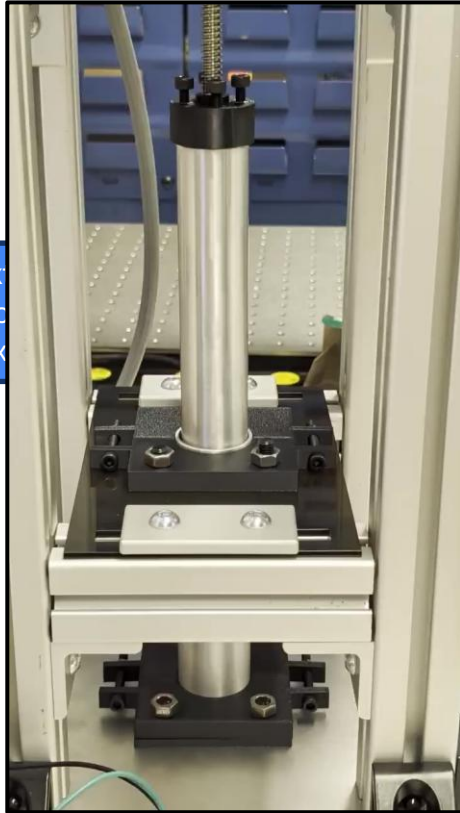
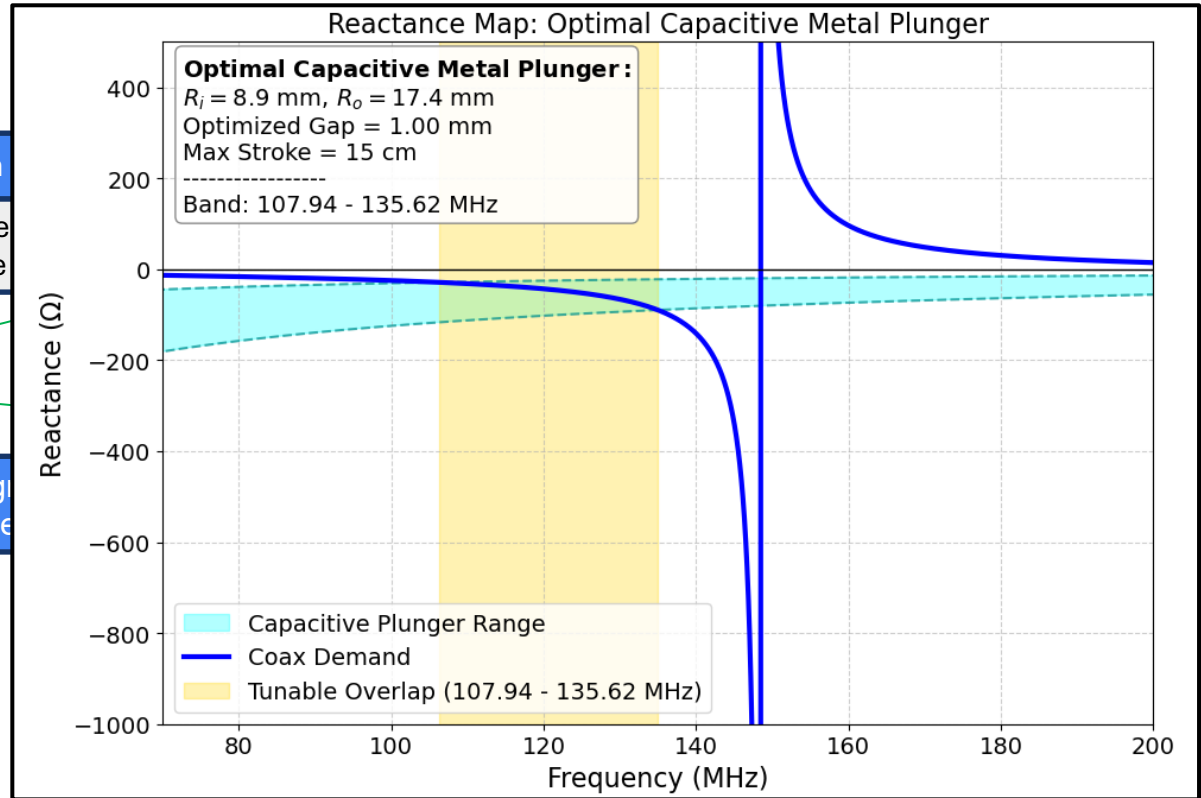
Designing the Coaxial Pick-Up and Tuner



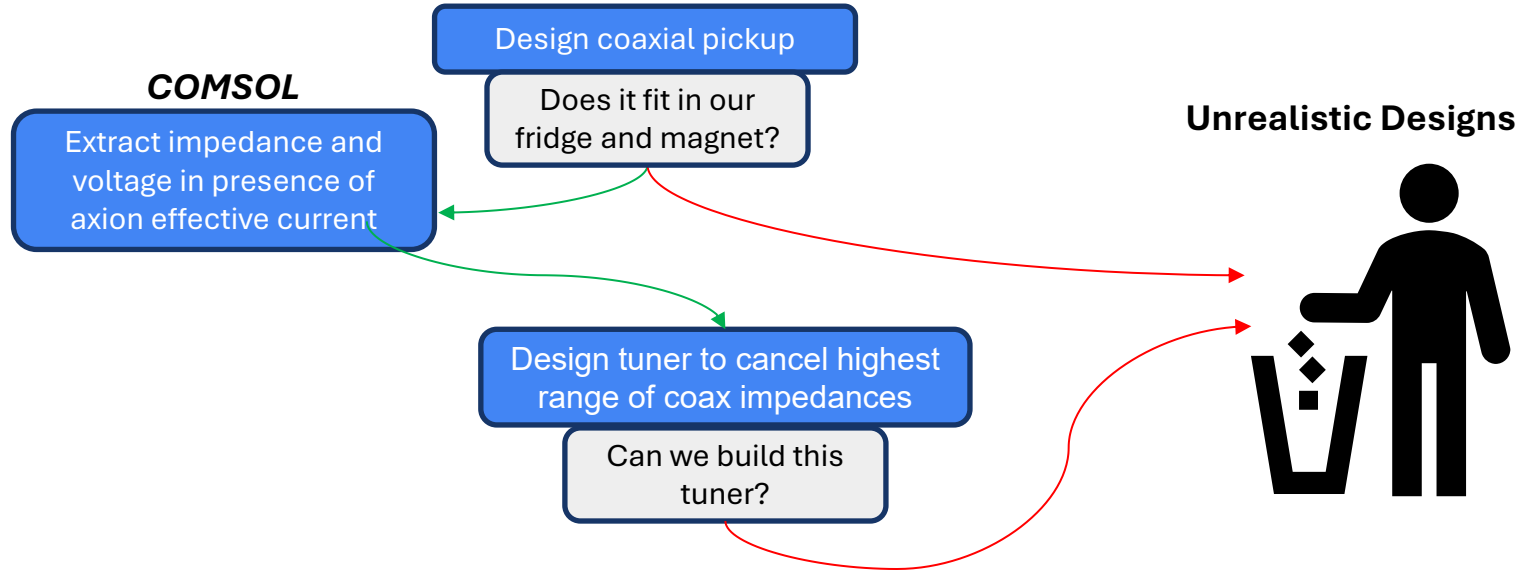
Designing the Coaxial Pick-Up and Tuner



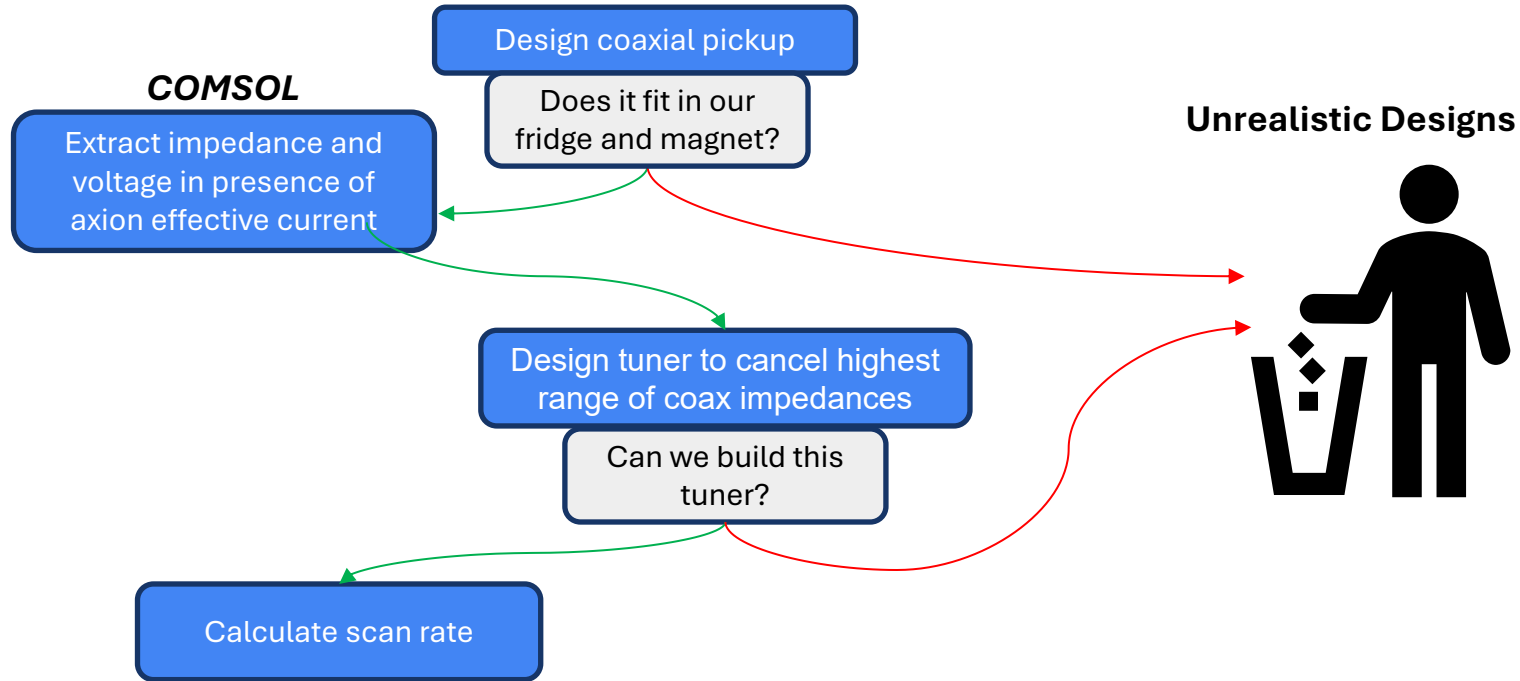
Designing the Coaxial Pick-Up and Tuner



Designing the Coaxial Pick-Up and Tuner

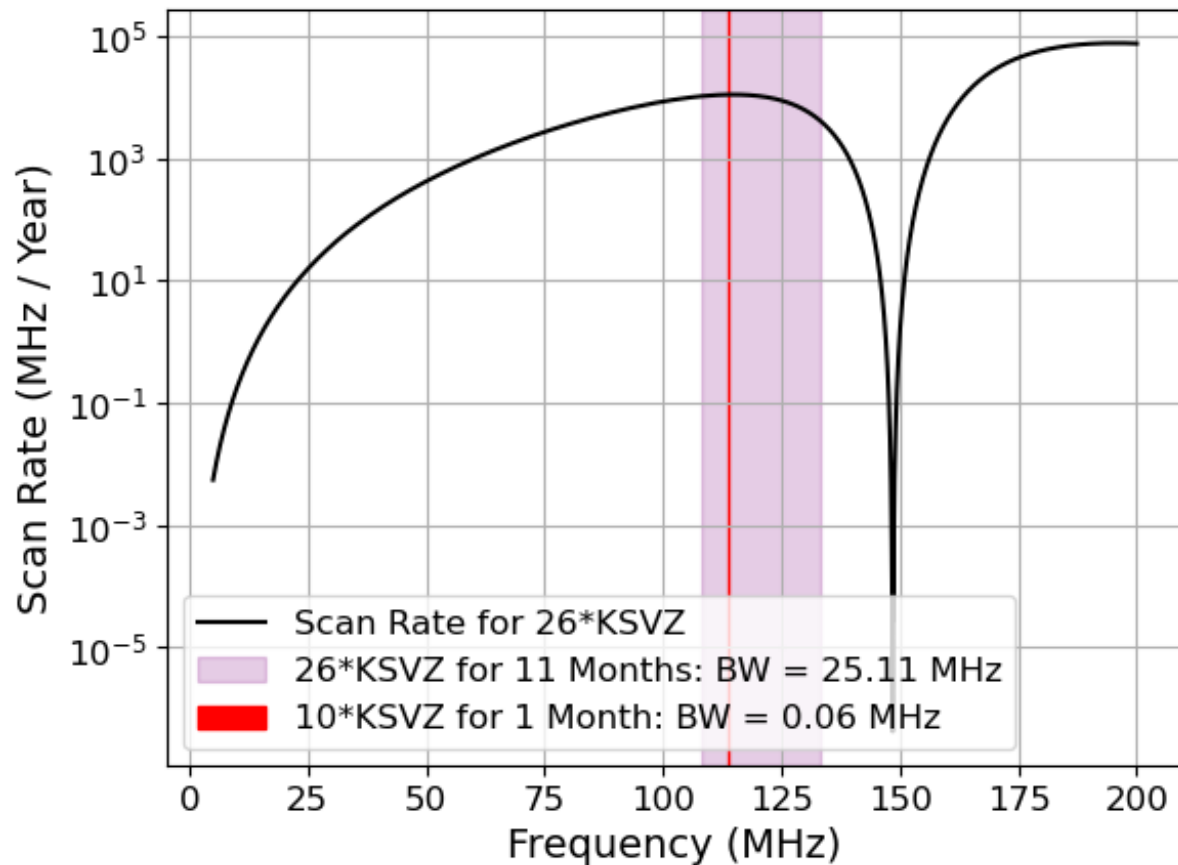


Designing the Coaxial Pick-Up and Tuner



Final geometry chosen is the one that gives us the best scan rate

Expected CAL-Pathfinder Scan Rate

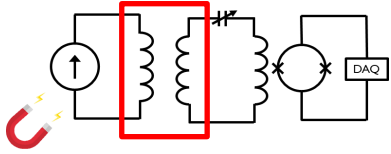
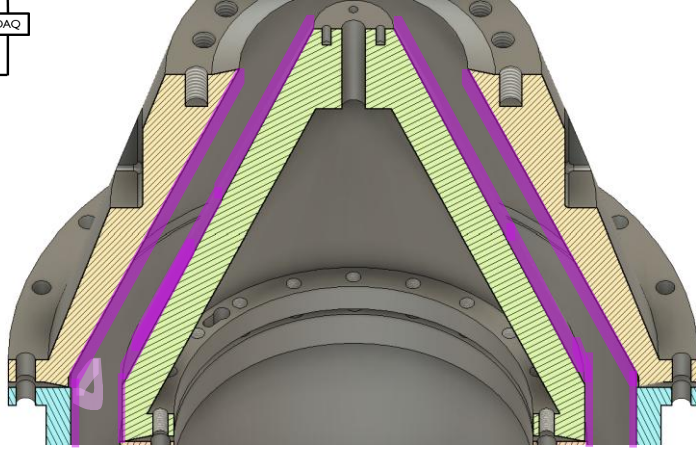


Current Run Plan

- Axion sensitivity of 26*KSVZ for 11 months spanning 108-133 MHz
- Axion sensitivity of 10*KSVZ for 1 month at 114 MHz

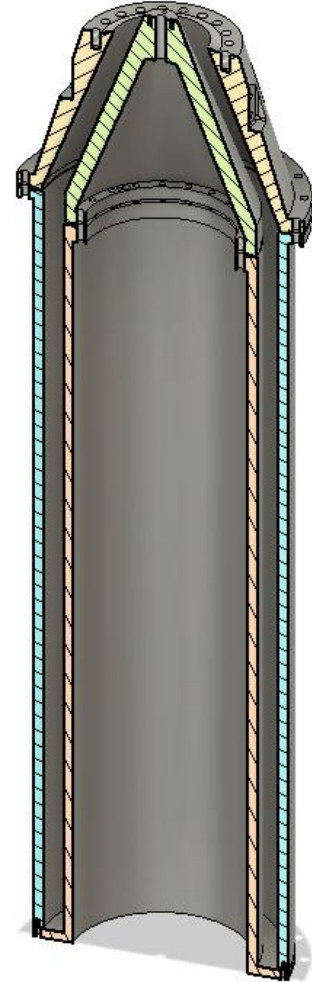
Note: this assumes a sensitivity bandwidth of 10 kHz

Building the Coaxial Pick-Up

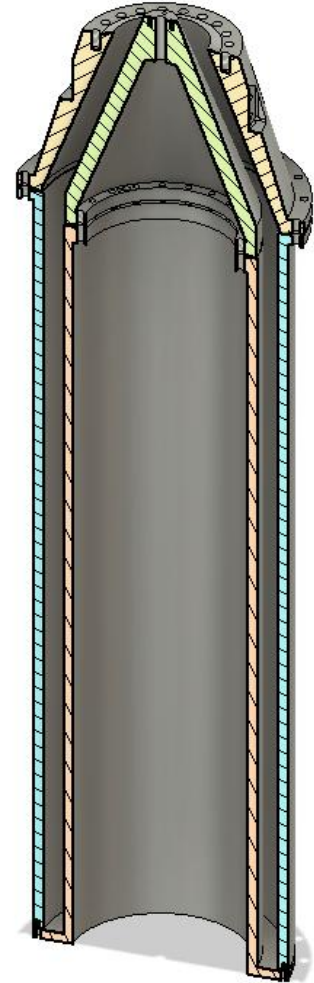


Material: Copper coated stainless steel

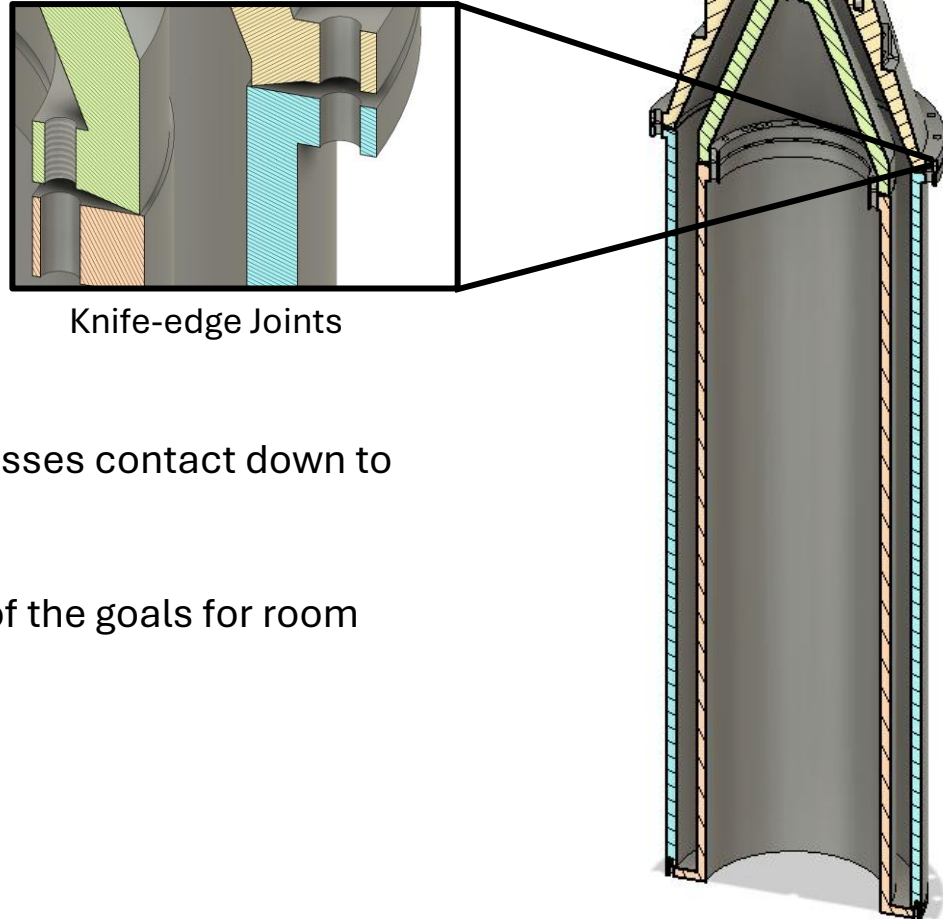
- Copper coating for high Q
- Stainless steel bulk for quench protection



Building the Coaxial Pick-Up



Building the Coaxial Pick-Up



Knife-edge Joints

Knife-edge Joints:

- Pressure of screwing in compresses contact down to eliminate interface loss

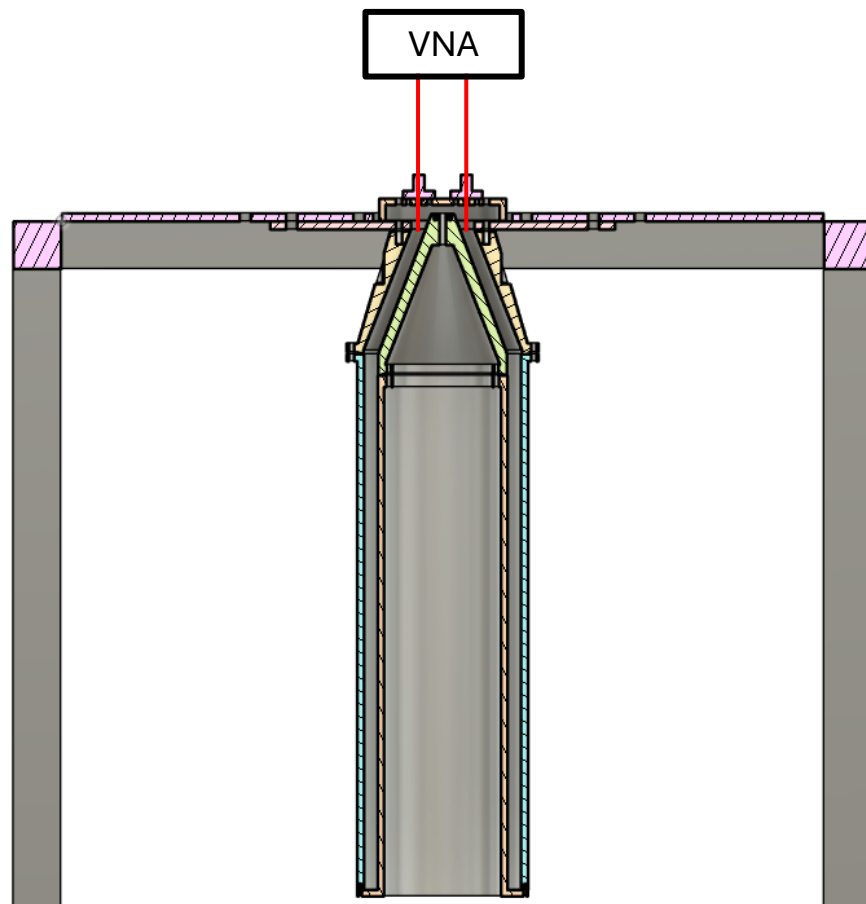
Testing the quality of these is one of the goals for room temperature testing of the pickup.

Testing the Coaxial Pickup

Goal: Measure the cavity properties of the coax and compare to COMSOL simulations.

1. Cavity Quality Factor Measurements

- Transmission measurements (S21)
- Weakly coupled antenna regime



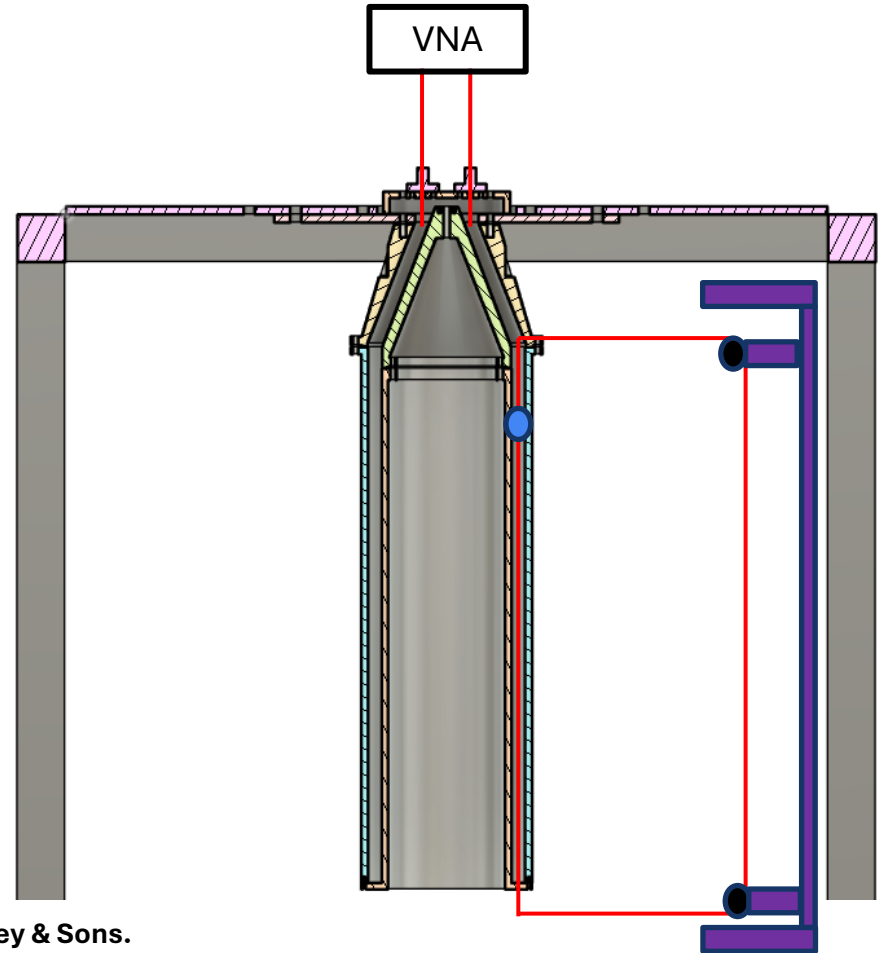
Testing the Coaxial Pickup

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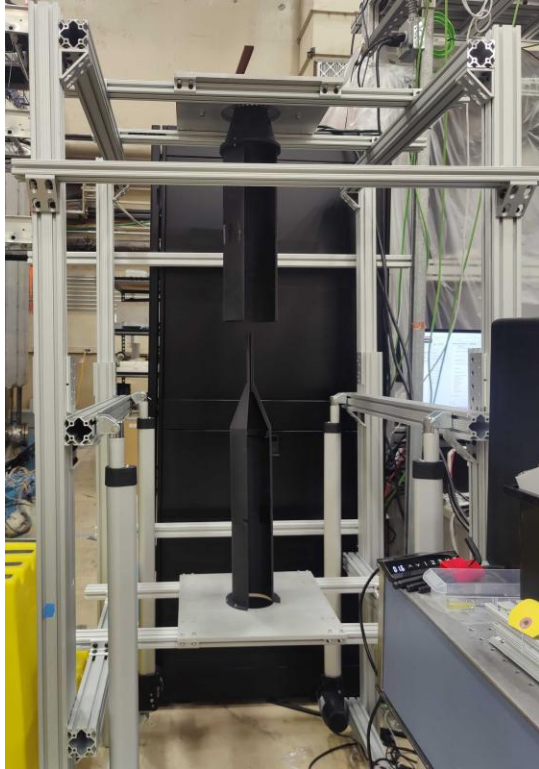
2. Mode Mapping: Bead Pull

- Introduce a small bead (PTFE) to perturb the field inside of a cavity
- Measuring a change in resonance frequency maps to field strength in that location

$$\frac{\Delta\omega}{\omega_0} \propto \frac{\epsilon_r - 1}{\epsilon_r + 2} \times \epsilon_0 |E|^2$$



Current Status of Coaxial Pickup and Tuner

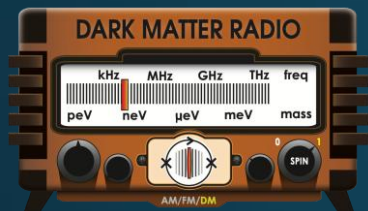
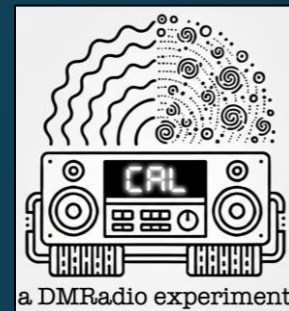


Tuner

- Prototype has been manufactured
- First room temperature capacitance measurements are underway!

Pickup

- Assembly procedure tested with 3D print
- Coated and arriving back today!
- Room temperature tests starting next week.



DM RADIO

Berkeley
UNIVERSITY OF CALIFORNIA



NATIONAL
ACCELERATOR
LABORATORY

Stanford
University



GORDON AND BETTY
MOORE
FOUNDATION



HEISING-SIMONS
FOUNDATION



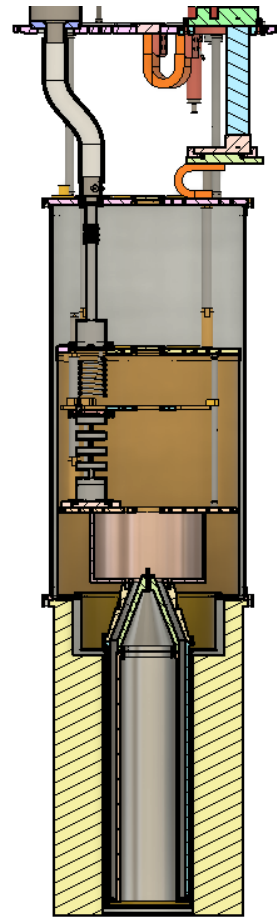
Summary

- CAL-Pathfinder is a solenoidal lumped element experiment
 - Novel coaxial pick-up
 - Targeting axions in the 108-133 MHz range
- Many critical parts of CAL-Pathfinder are being designed and tested
 - Coaxial pick-up is being tested
 - Tuner prototype is being tested
 - SQUIDs are being designed and tested
 - Shielding box is under design
 - Cryo-actuation methods are under design

Goal is to have first science data in 2027!



a DMRadio experiment



Backup Slides

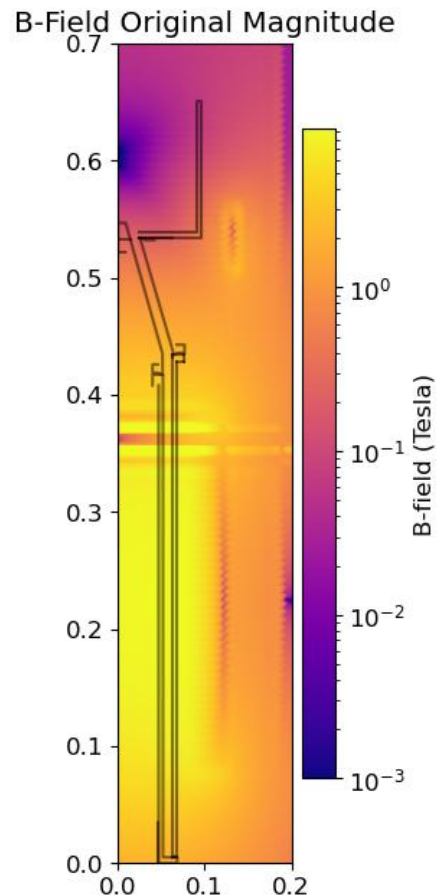
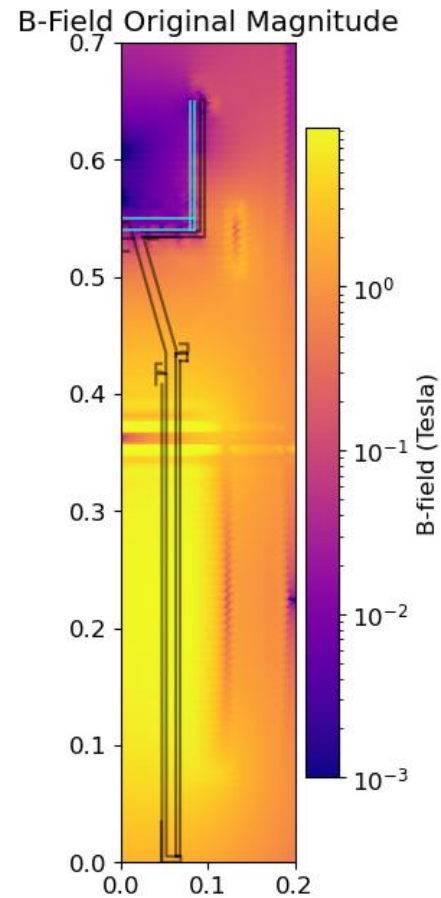
Shielded Box Design

Need to reduce fields from 0.3T to below HC1 of Nb (~ 0.1 T) such that the tuner can be superconducting and the SQUIDS can be placed in a Nb box to sit in a field free region.

Methods being explored:

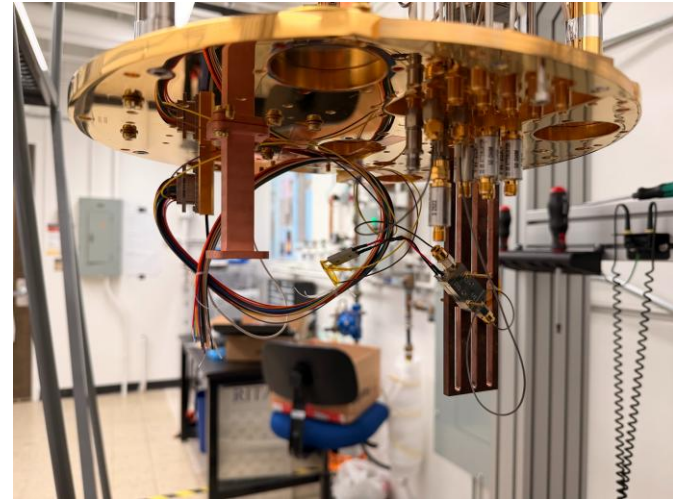
- Passive/Active cancellation coils
- Cryoperm shields
- Medium permeability nickel alloy shields

Problems: Need to be able to design a structural support that will tolerate the forces felt on any shielding in the presence of our magnet.

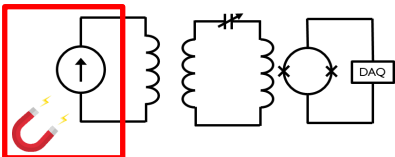
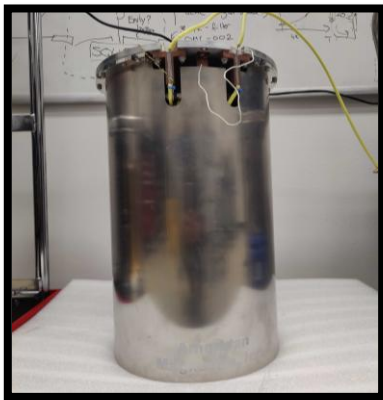


SQUID Readout Chain

- Design custom DC SQUIDs being manufactured at NIST → Initial design chosen
- Set up biasing and readout infrastructure → Ongoing
 - Magnicon, SQUID wiring and shielding, cryoamp, thermal clamps, etc.
- Test system with CMB SQUID Arrays
- Incorporate custom SQUIDs into the system



Magnets: Solenoid versus Toroid

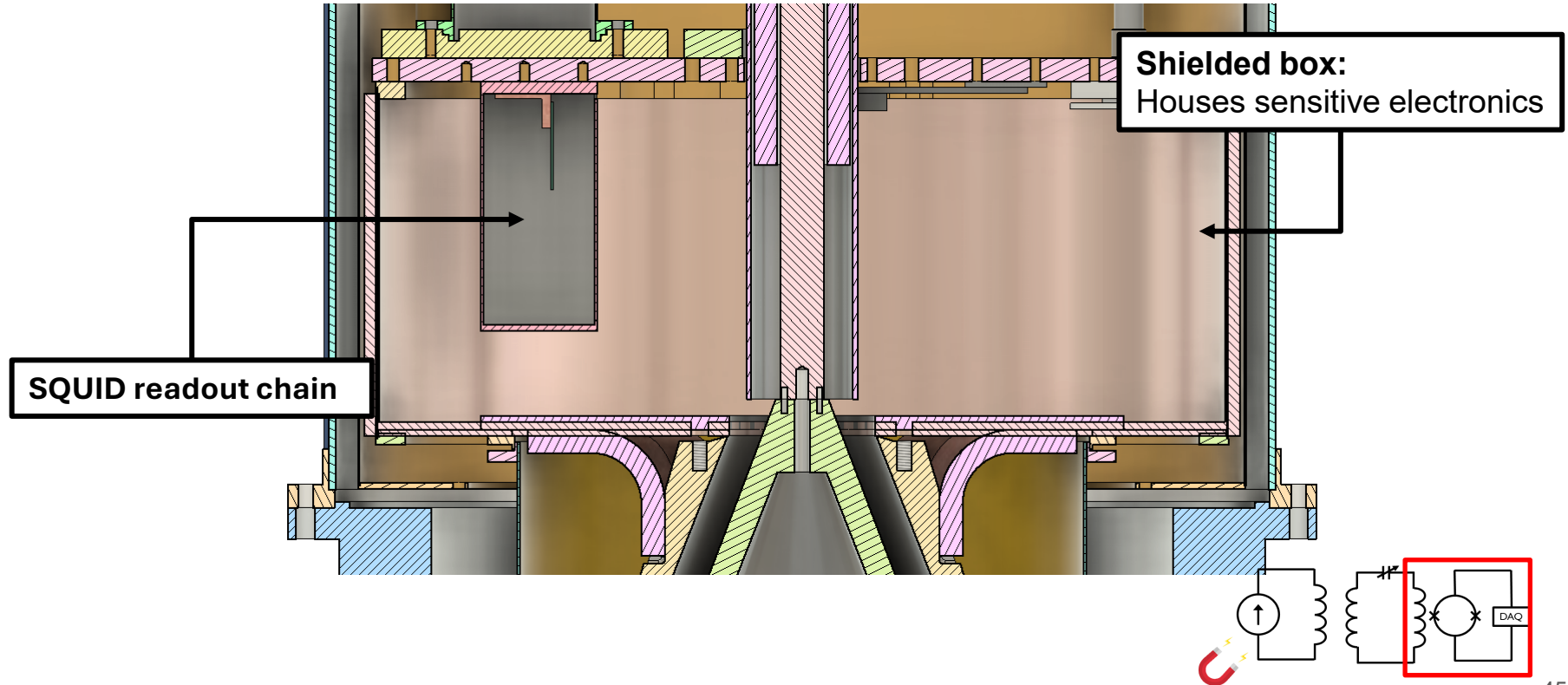


	Toroid (used in 50L and ABRA)	Solenoid (used in CAL)
Pros	Magnet Bore fully contains field.	Available commercially so typically cheaper!
Cons	Needs to be custom built, expensive :(	Large fringe fields

Building towards a GUT scale experiment, we need to scale up magnetic fields. One option to do this is **solenoids!**

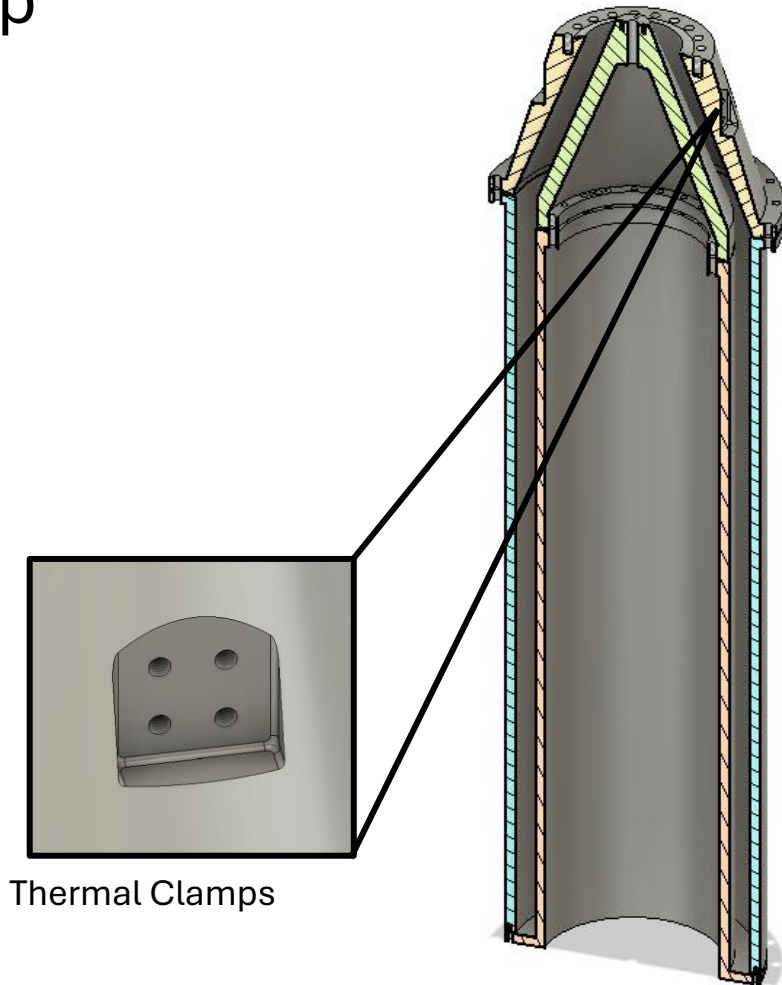
Readout Design

Building off DMRadio-50L infrastructure for DAQ software and calibration plan



Building the Coaxial Pick-Up

Estimating the cooldown time of the coated pickup alone is over a day, not including cooldown time of magnet and fridge itself. Goal is to speed this up using copper braids between the MXC and the pickup.



Building the Coaxial Pick-Up

