Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Dielectric tuning of cavities

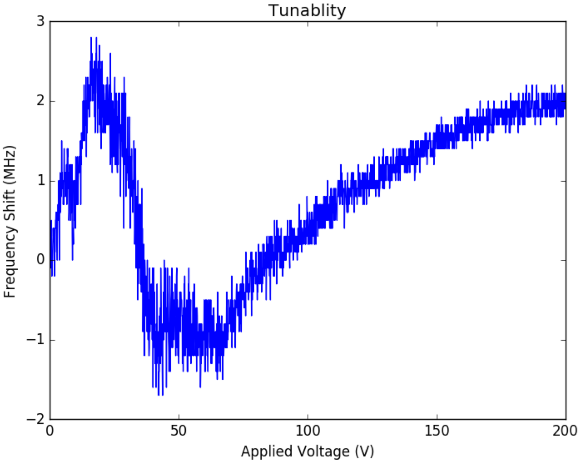
D. Bowring

3rd Workshop on Cavities and Detectors for Axion Research

August 21, 2018

On behalf of T. Connolly, M. Kang, M. Ortega, S. Priya, C. Salemi, M. Silezin, A. Sonnenschein, and A. Tollestrup.

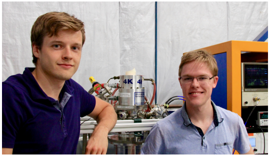
Headline: We can tune a 4.5 GHz cavity by a linewidth using an STO crystal.



Before we start, I want to brag about our students.

Chiara Salemi (MIT, Physics)

Marlene Ortega (Brown, Physics)

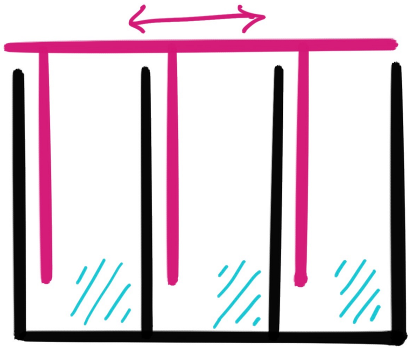


Michal Silezin (UIUC, Engineering) and Thomas Connolly (U.Mass-Amherst, Physics)

Overview

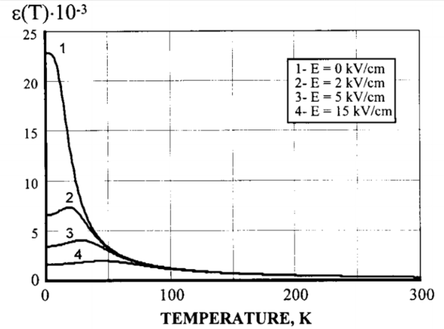
1. Simultaneous tuning of many cavities is hard.
2. Ferroelectric materials have variable ϵ, depending on applied voltage.
3. We can tune our prototype cavity via this method.
4. Still some work to be done.

Concept: Coarse mechanical tuning + fine tuning via ferroelectrics



Tuning cartoon, showing **cavity array**, **coarse-tuning rod assembly**, and **fine-tuning ferroelectric material**.

Strontium titanate (STO) exhibits $d\epsilon/dV \neq 0$.



O.G. Vendik *et al.*, J. Supercond **12**, 2 (1999).

- $\tan\delta \lesssim 10^{-3}$ for single-crystal STO at 10 GHz
- Significant loss introduced w/ electrodes. We see this too. (More later.)

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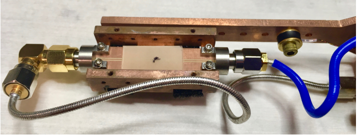
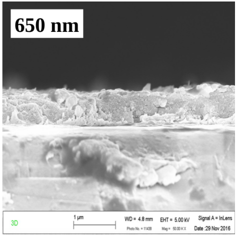
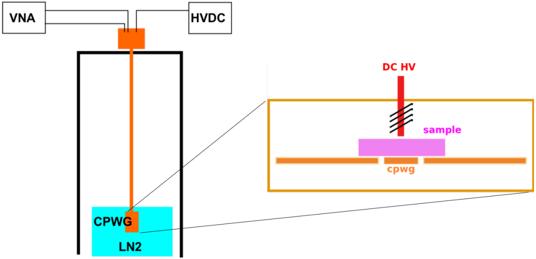
Prior work on 2D resonators



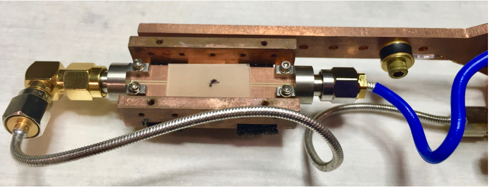


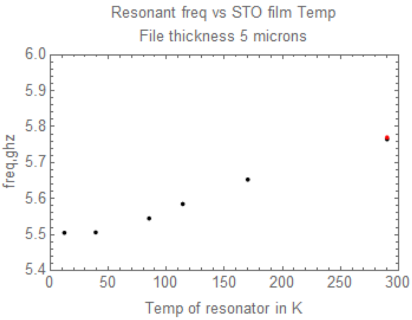
S. Priya, M. Kang (Va Tech)

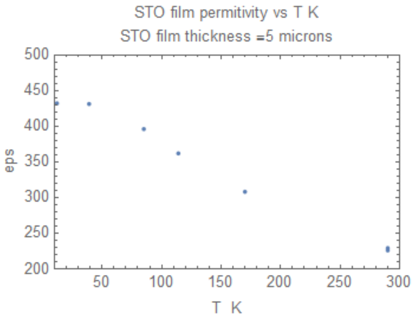


- Prior work on 2D resonators.
- Possible to measure ϵ.
- Thin film process development ongoing.

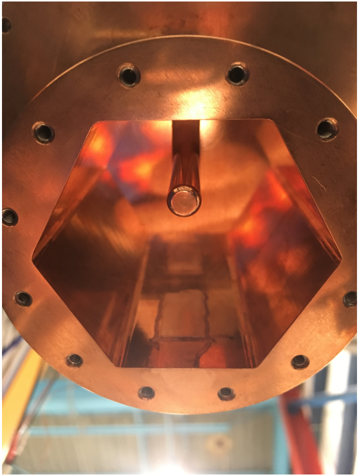
Prior work on 2D resonators







(Relatively) New Prototype Cavity



- $f_{010} \gtrsim 4.4$ GHz for empty cavity.
- Linear rod path; 25 mm throw; 6.25 mm rod diameter
- TM_{010} mode has ∼300 MHz of "clean" tuning range.
- Can be loaded with STO samples.

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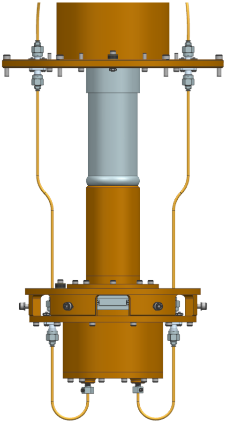
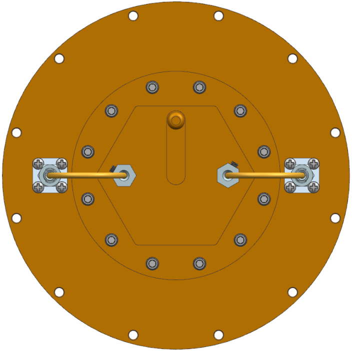
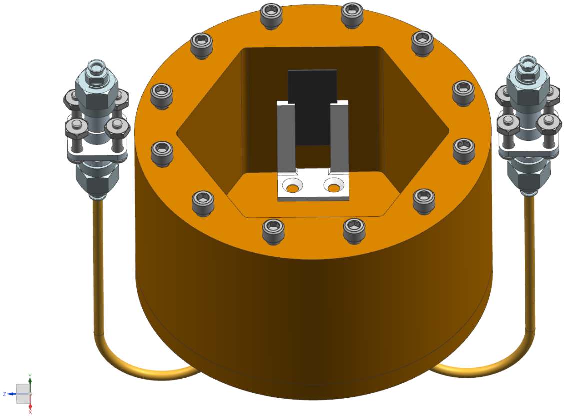
(Relatively) New Prototype Cavity





For this work: remove tuning rod & insert crystal



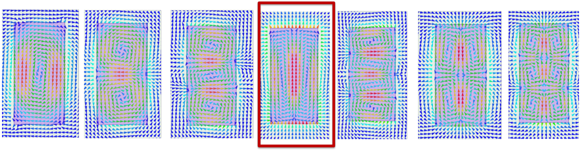
3D-printed L-bracket + single-crystal STO sample. **The tuning rod was not installed during the measurements described here.**

Progressively lossy interventions

	Q_L	f_{010} **at room temp. (GHz)**
Empty Cavity	11,000	4.36
Uncoated Sample	10,000	4.28
Ti Coated Sample	1,300	4.36
With Electrodes	900	TBD

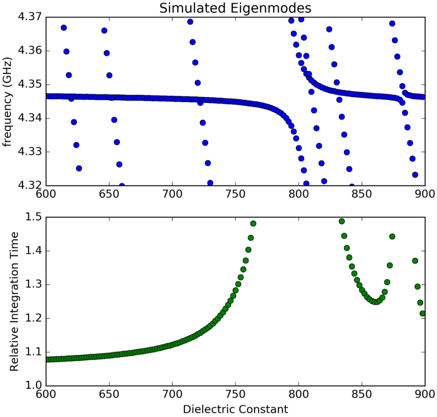
- Currently large systematic errors. We need a screw torque standard, e.g.
- 10x drop in Q when Ti coating applied.
- Straightforward explanation (see next slide).
- NB: No effort made to optimize cavity Q (polishing, RF joint design, etc.)

Crystal modes hybridize with cavity modes.

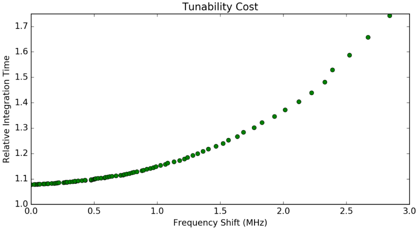


- Coating w/ metal film turns this into a planar resonator.
- Crystal is 20 x 10 x 0.3 mm (ripe for mode crowding).
- Highlighted mode couples strongly to cavity TM_{010}.
- Remediation: spoil crystal mode *Q*s via thin, *patterned*, resistive films.

Simulate hybridization & effect on C_{010}.



HFSS simulation.



Effect on C_{010} translated into integration time penalty.

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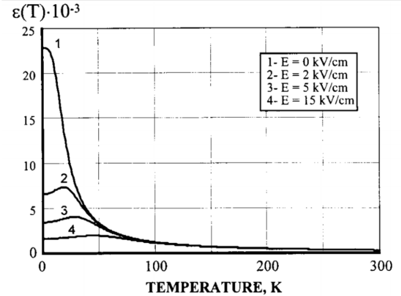
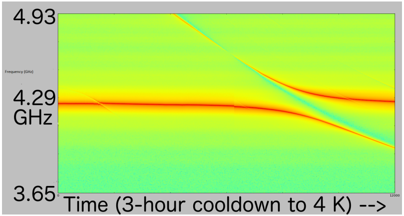
We can demonstrate tuning via temperature control.



O.G. Vendik *et al.*, J. Supercond **12**, 2 (1999).



Cavity loaded with single-crystal STO sample at wall.

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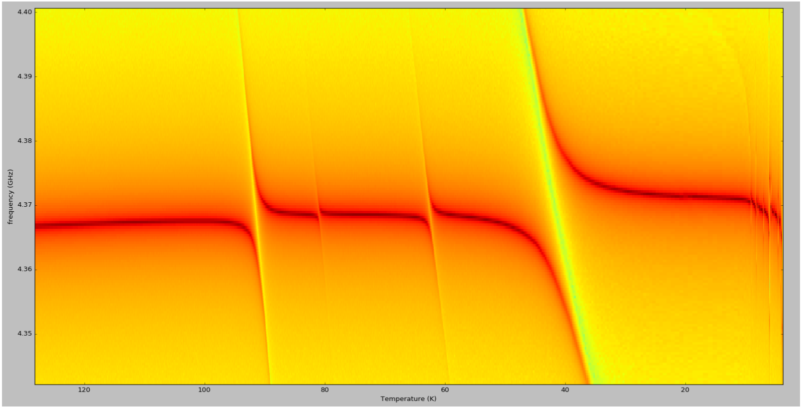
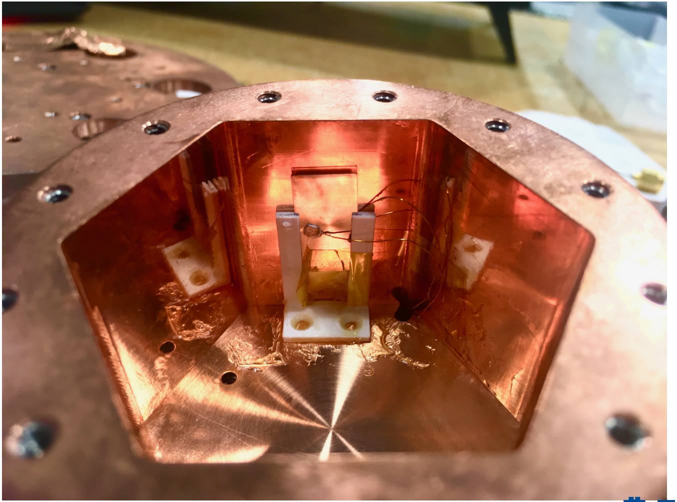
Qualitatively, simulated and observed mode mixing agree.

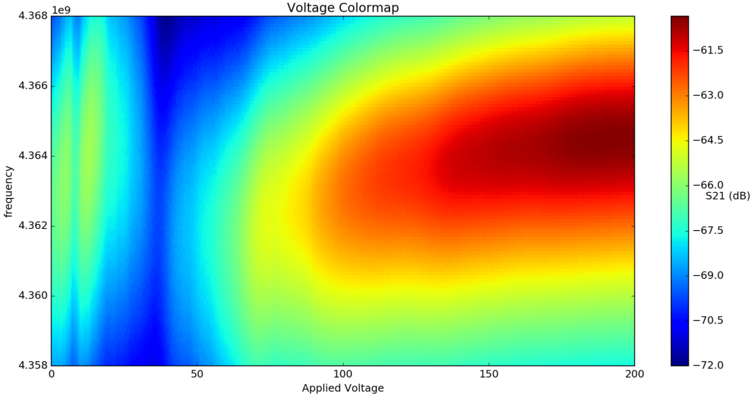


$\sim$ 40-50 dB of difference between dark red (high) and green (low).

Attach electrodes to Ti-coated crystal, tune with voltage.

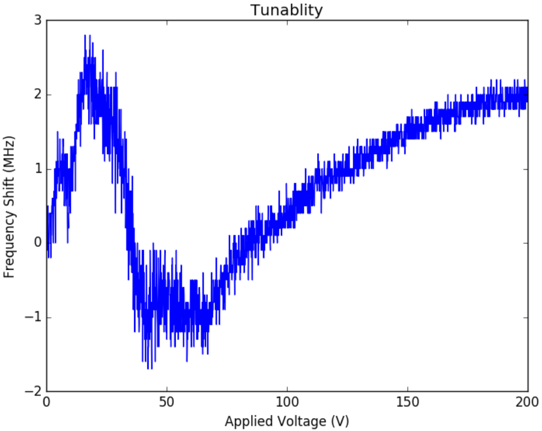


$Q \sim 900$ means the spectrum colorplot is not as clean.



Leakage current $\lesssim 1\ \mu$A below 600 V.

Δf_{010} (MHz) vs Voltage



Low-voltage structure probably due to charging. Monotonic above $\sim$75 V.
Approximately one linewidth of voltage-based tuning!

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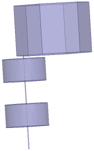
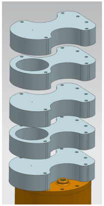
Still lots of work to be done, of course.



Bandstop on DC probe "port"



- Bandstop filter reduces coupling losses by $\gtrsim$200x.
- *Patterned* electrodes (c.f. A. Dixit) reduce crystal/cavity hybridization.
- Crystal position/size optimization.
- Understanding systematics, improving DAQ & instrumentation. . .

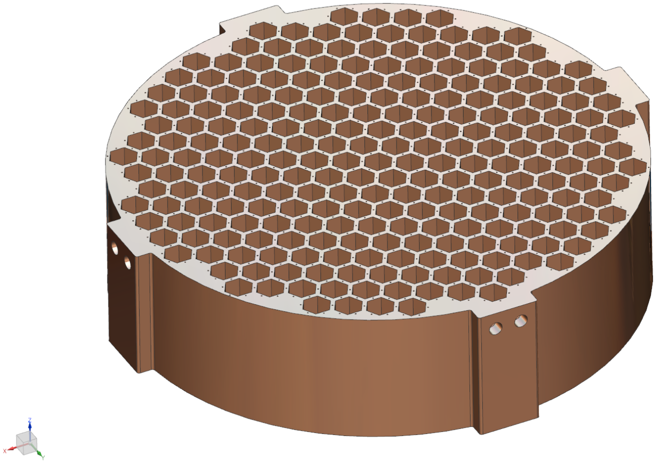
We have a conceptual design that integrates this into a multi-cavity array.

- Via Michal Silezin, summer engineering undergrad
- Assume a magnet with a 1-meter bore, 50 cm long.
- How many 50-mm dia. cavities can we fit in this space? How should they be tuned? How cooled?

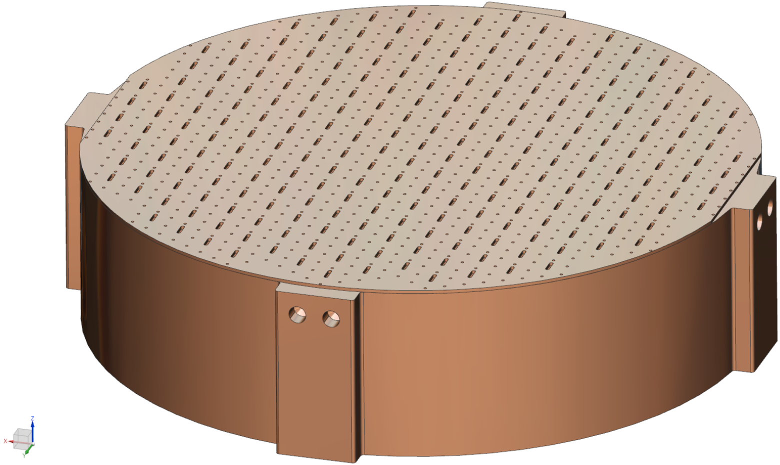
What this design is/is not:

- This is *not* an engineering design ready for review.
- First-pass attempt to show various subsystems
- Hypothetical fridge scaled from ADMX
- Much thermal & electrical design work remains.

Multi-cavity array: 241 50-mm cavities

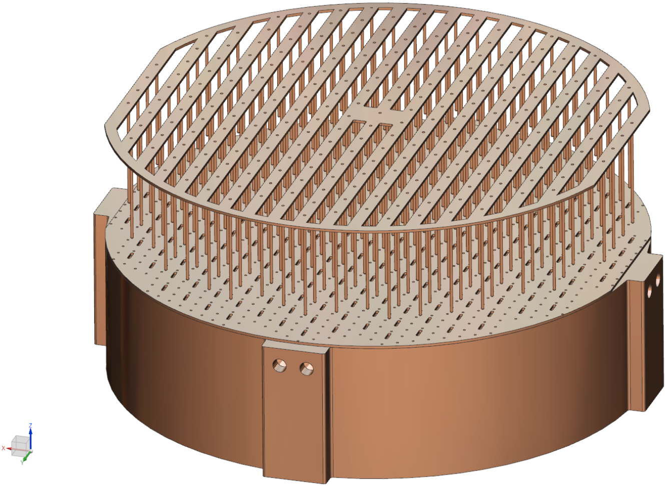


Multi-cavity array: 241 50-mm cavities



"Honeycomb" closed by lid with holes for tuning rods, cabling.

Coarse tuning via simultaneous motion of all rods



Tuning rods move together as part of a single piece.

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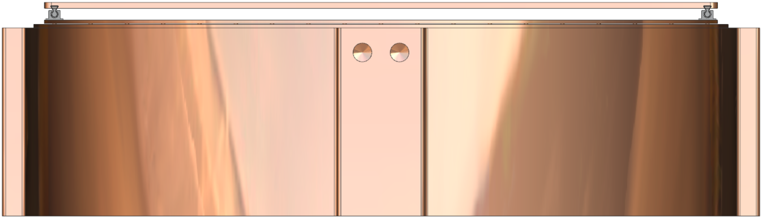
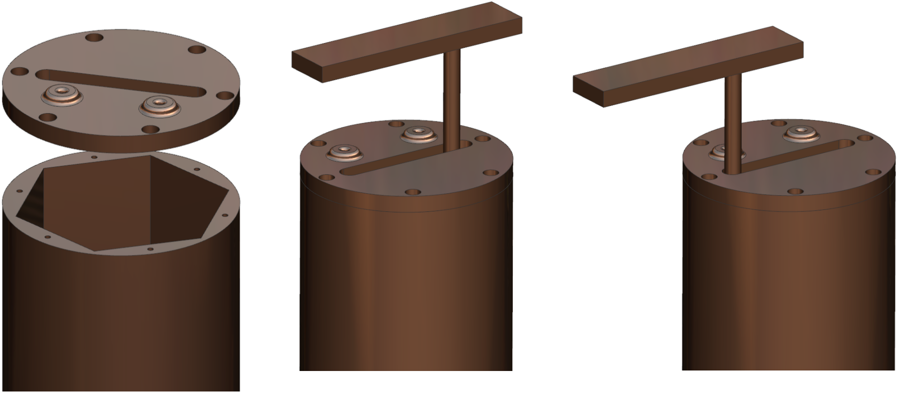
Coarse tuning via simultaneous motion of all rods

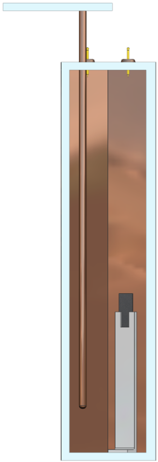


Rod assembly moves on linear bearings.
One piezo actuator can push the entire rod assembly.

Single-cell closeups



Each cell can be loaded with a crystal.



http://www.preperm.com sells stock with $2.5 < \epsilon/\epsilon_0 \lesssim 25$.

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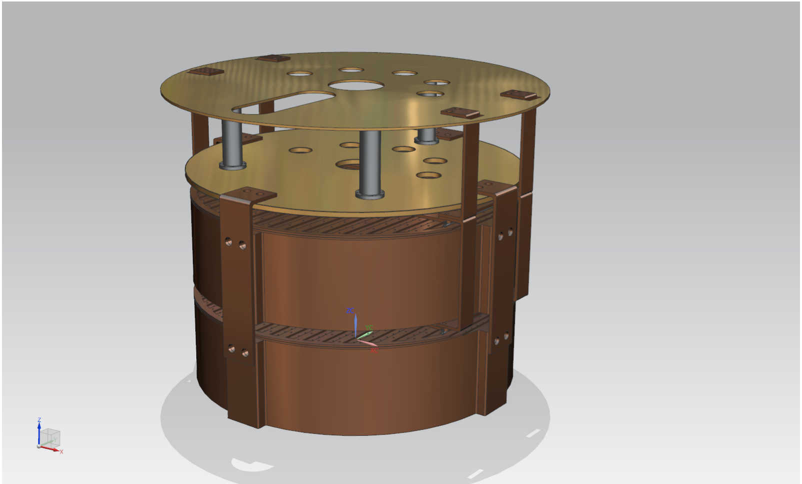
Doubling the array preserves $L \sim 5R$ and maximizes volume.



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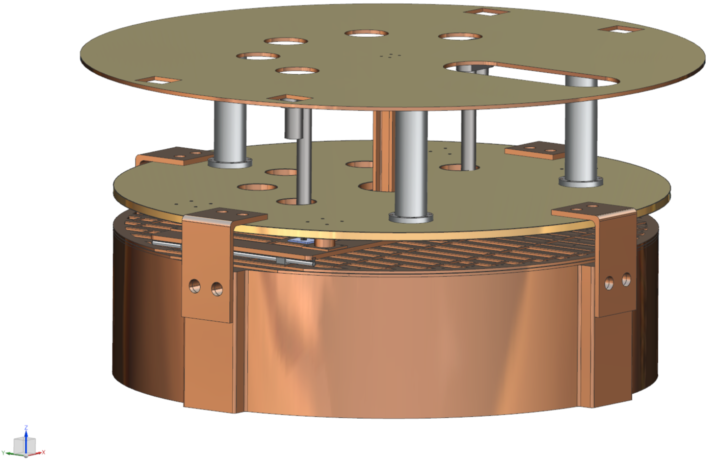
Thermal straps and insulations direct heat flow to correct temp. stages.



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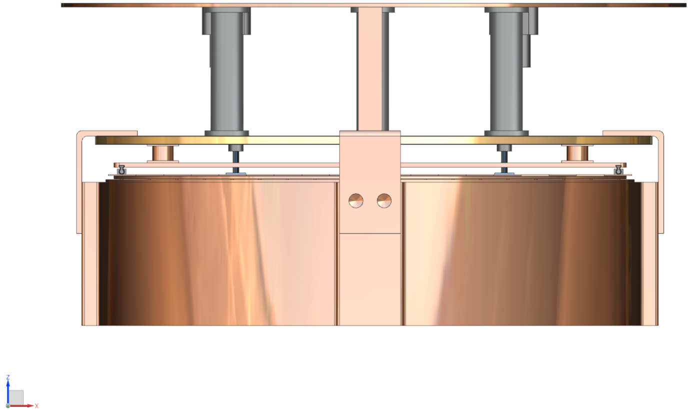

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Thanks for your attention!