Microwave Cavity R&D for Axion Cavity Searches

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Advanced Detector Group

Physical and Life Sciences

Lawrence Livermore National Laboratory

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LLNL-PRES-542472

Current R&D on microwave cavities

- Split Cavity System (U. of Florida)
- ADMX-HF Baseline Cavity
- Multi-post cavity R&D (Harvey Mudd College Clinic team)
- Slow-wave cavity (U. of Washington)
- Hybrid Cavity R&D

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*This work currently funded through DOE Early Career Program

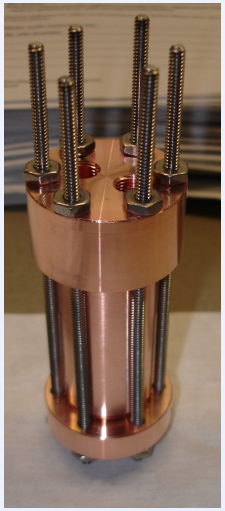
Problem with sampling higher frequencies/mass

- **Higher Frequency requires smaller cavities – sample smaller volume!**
- **Quality factor goes down as frequency increases!**

Radius – 19 inches
Frequency ~ 540 MHz
Q – 200,000
Axion Mass ~ 2 μeV
Volume – 220 liters

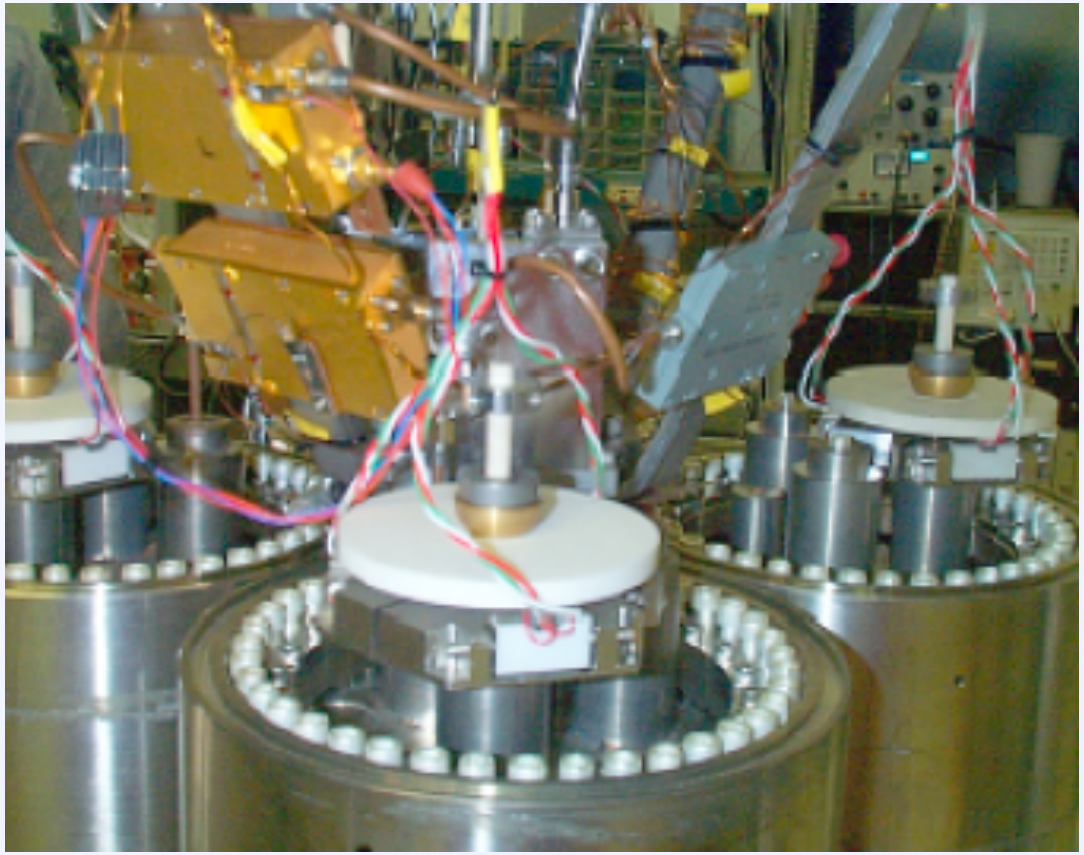
Radius – 2.5 inches
Frequency ~ 2.4 GHz
Axion Mass ~ 9 μeV
Q – 120,000
Volume ~ 2.6 liters

Radius – 0.5 inches
Frequency ~ 10 GHz
Axion Mass ~ 36 μeV
Q – 50,000
Volume – 0.025 liters



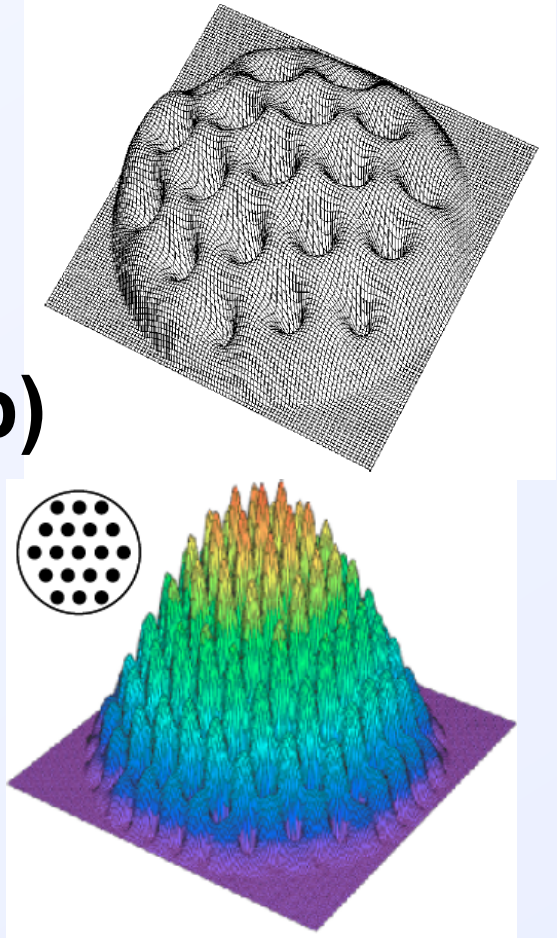
Goal: Higher frequencies without sacrificing volume

4 cavity array operated



D. Kinion Thesis

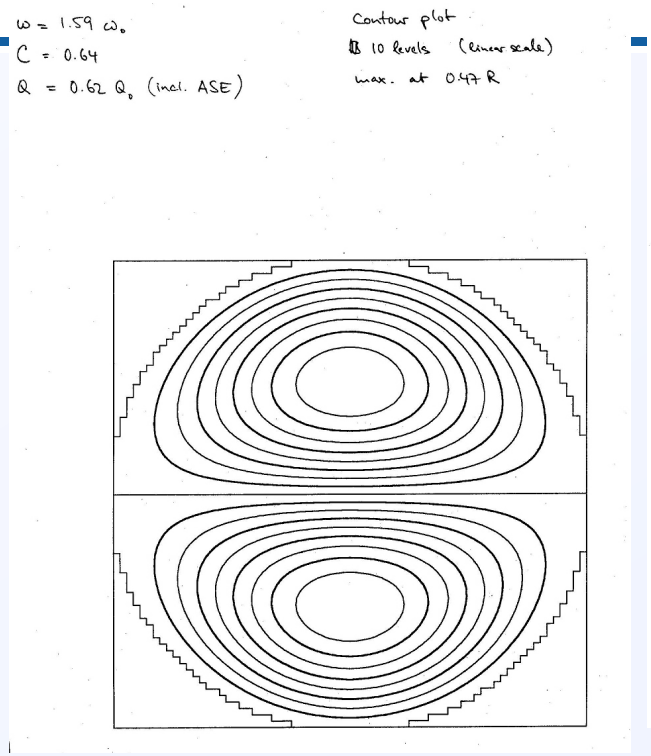
(b)

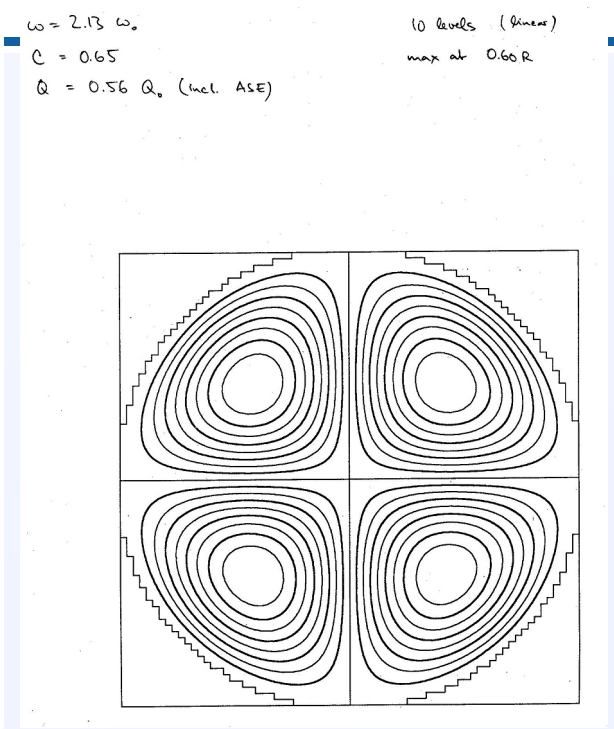


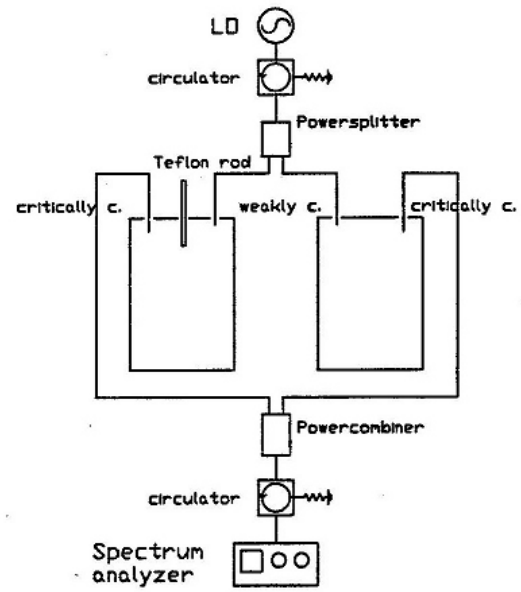
C. Hagmann simulation

Multipost systems possible

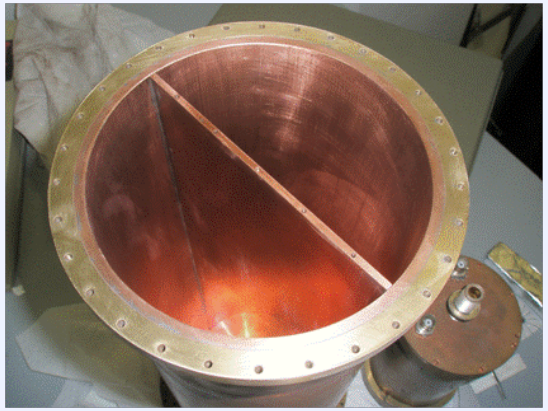
Multi-cavity array – work at U. of Florida

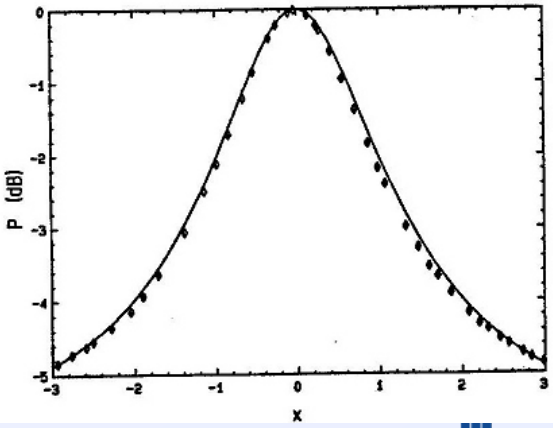






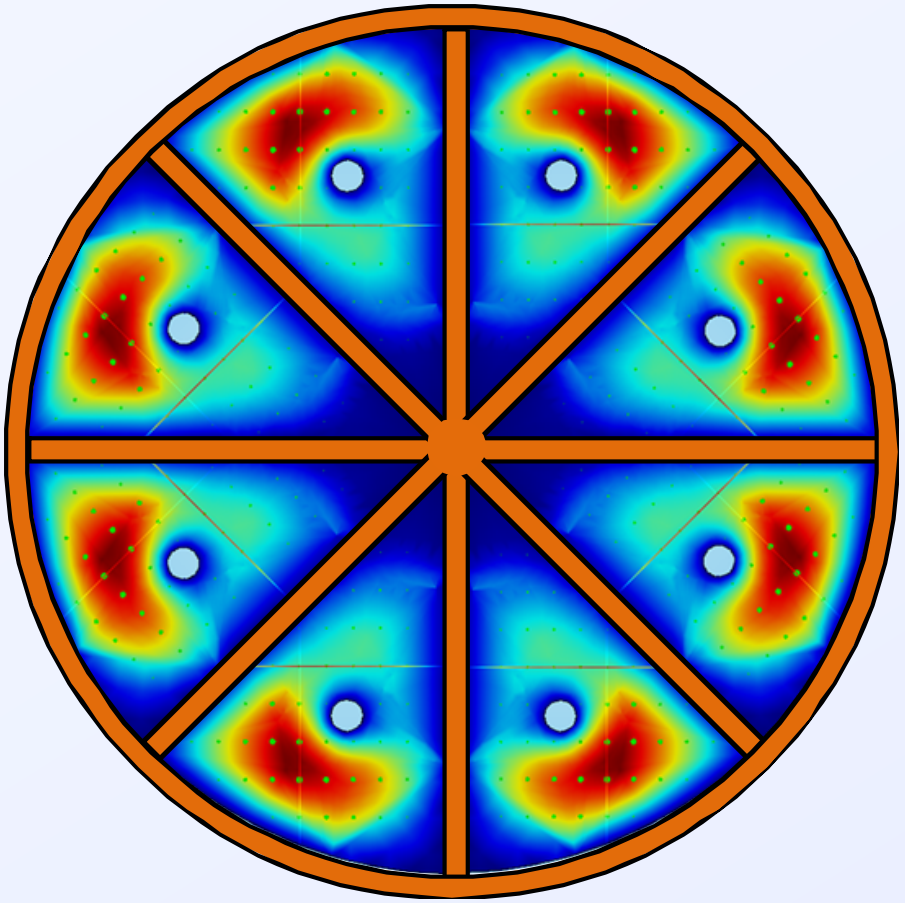
- Partitions reduce scale, increase frequency
- Efficient use of magnetic volume compared to, e.g., 4 parallel cylinders.
- Tune by moving rods from corner to center in each partition
- Issues with Q, coupling





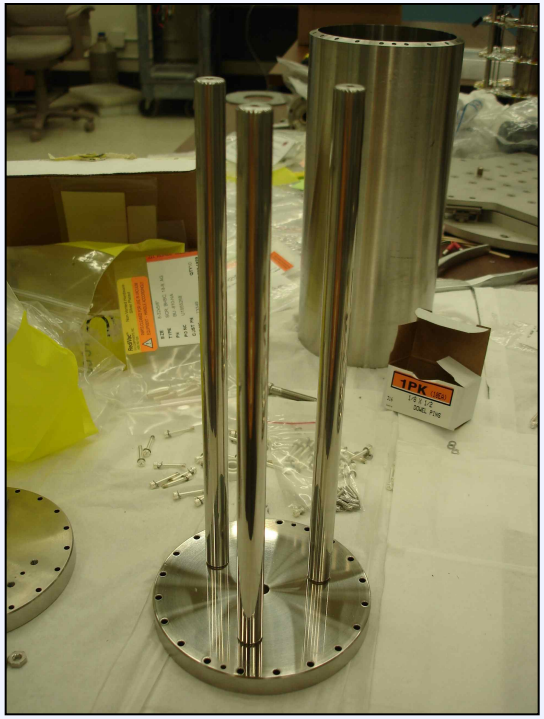
Segmented Resonator

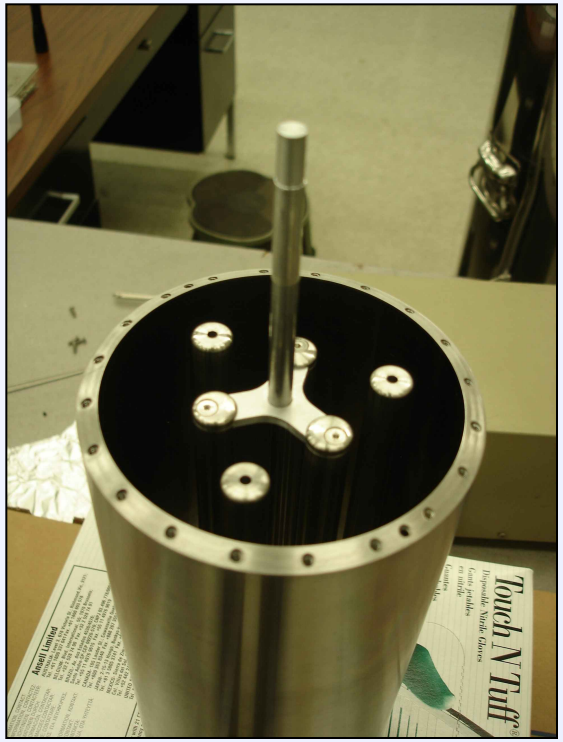
- Method becomes highly complex above 8 segments
  - Maximum TM_{010} Frequency for full scale cavity: ~2.2 GHz (9μeV)
- Project going through cavity redesign and improvements… continued R&D effort



ADMX-HF Baseline Cavity

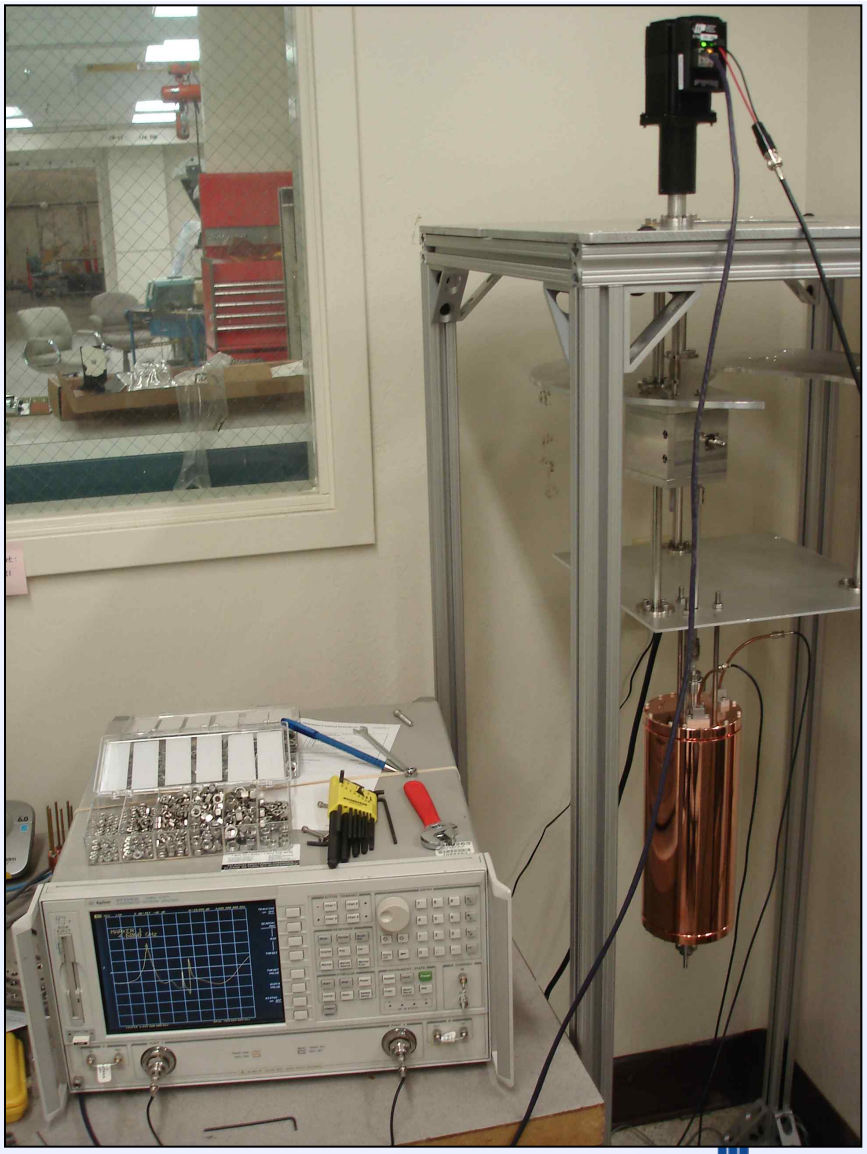
- Multi-post system that consists of 3 rotors connected on common axis and 3 stators.
- 4” ID cavity: Six 0.5” diameter rods
- Freq. span 4.7-5.6 GHz



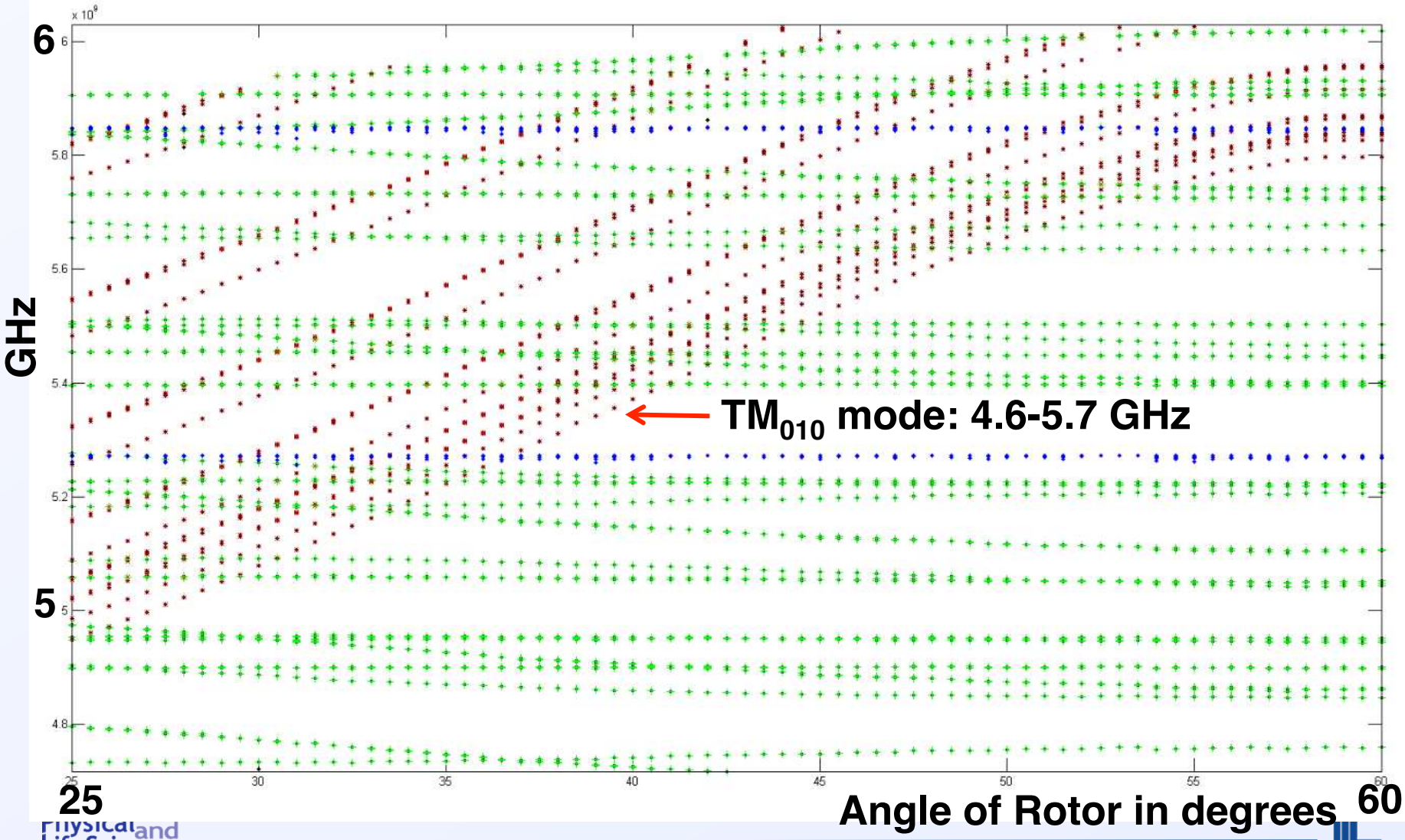


ADMX-HF Baseline Cavity

- Back from plating & annealing shop.
- Will be tested at cryogenic temperatures before delivery to Yale.



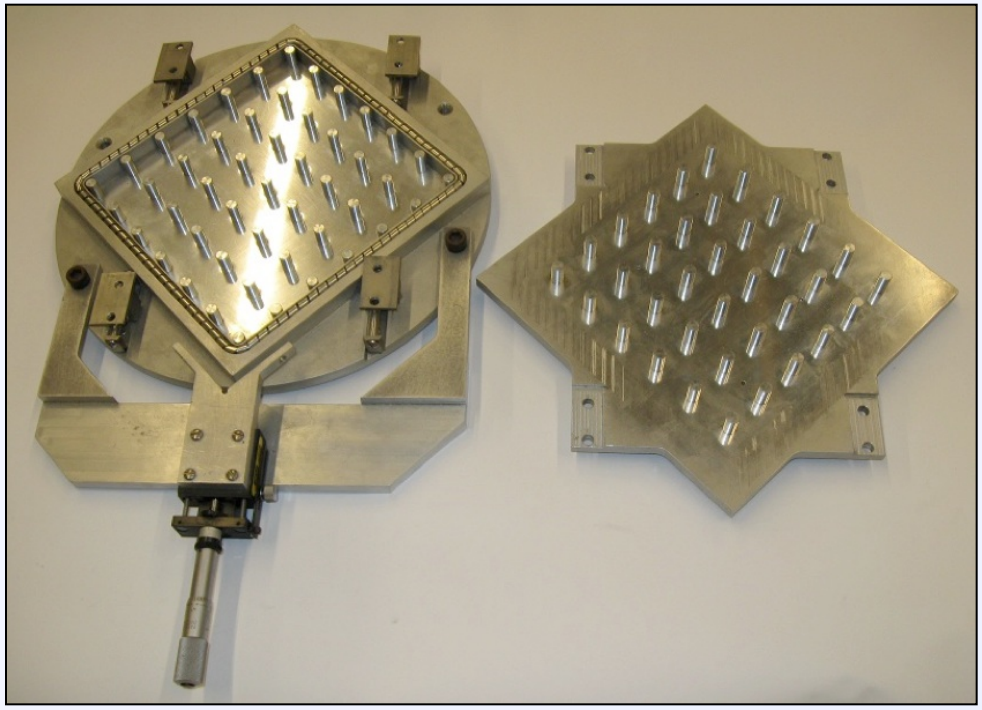
ADMX-HF Baseline Cavity – CST MWS simulation ~ 19 mode crossings



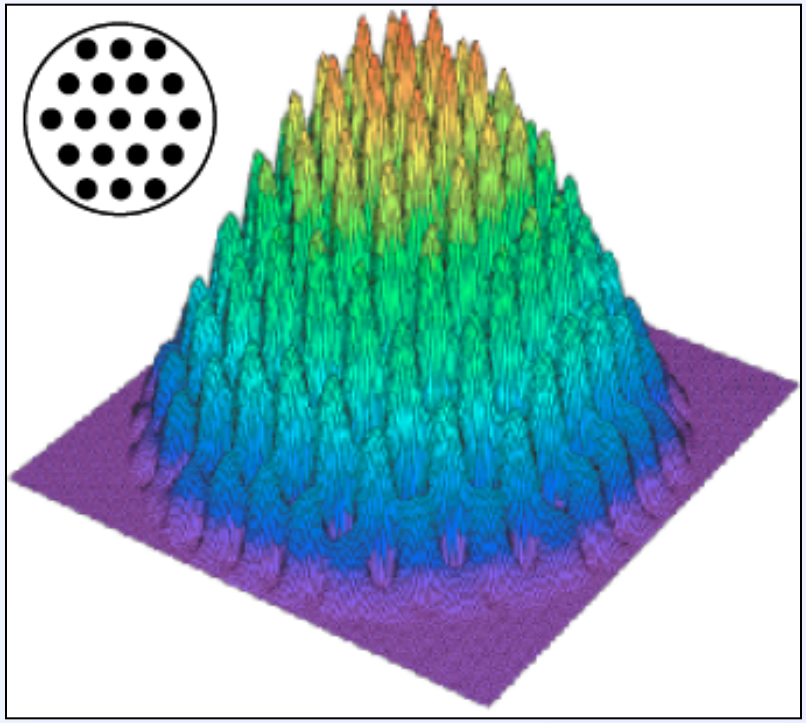
HMC Clinic– prototype multipost cavity systems

- Analog of photonic bandgap resonator
- Various posts can be translated as group to adjust frequency.
- Can maintain reasonably large volume and form factor

- Simulation of Electric field of the TM_{010} mode of a 96 metallic post array.
- Frequency 5 times empty cylinder
- Form Factor C ~ 0.5



Prototype multipost cavity



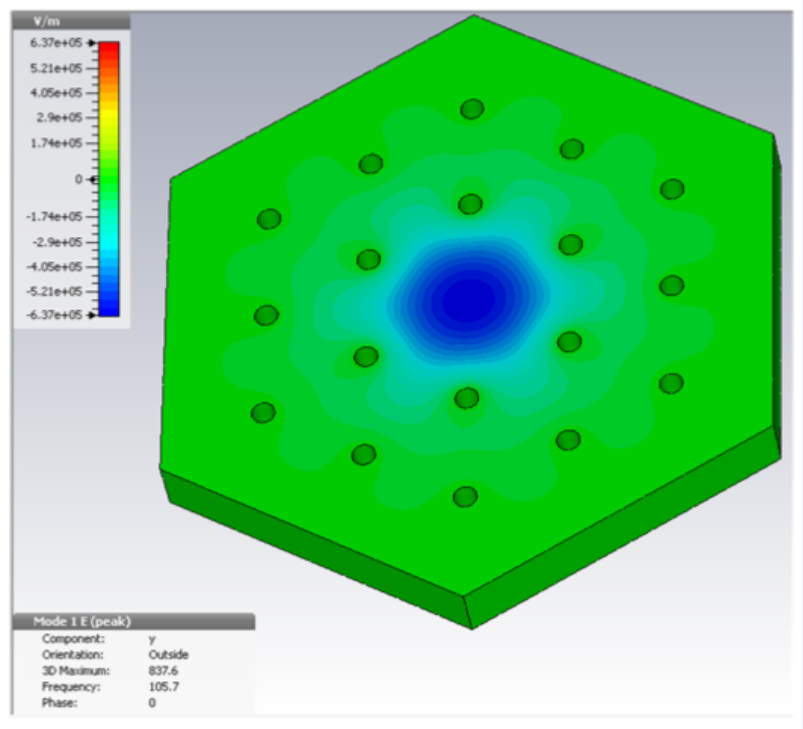
*C. Hagmann simulation

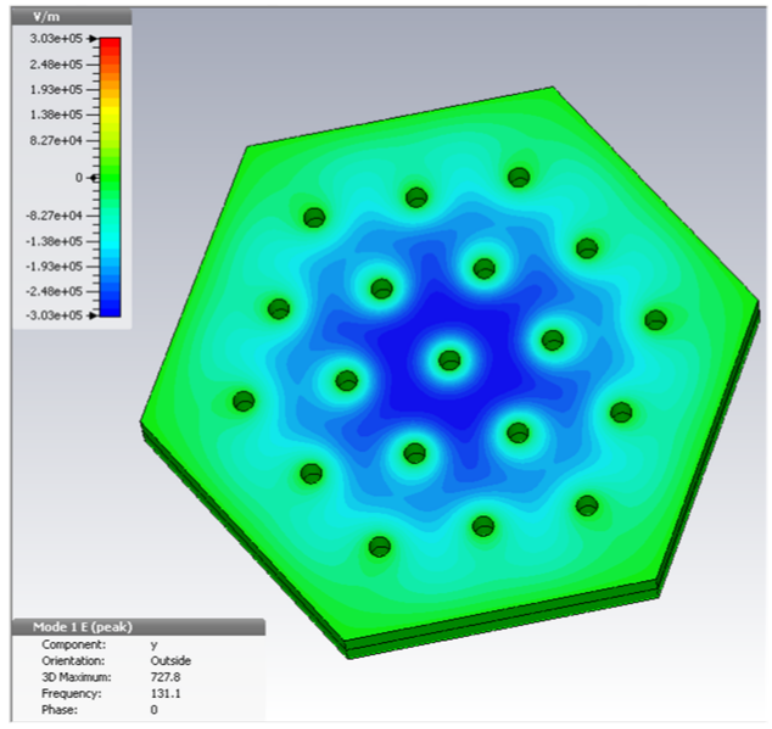
Multipost Cavity R&D

- Harvey Mudd College Clinic team: Team of 5 senior undergraduate Physics and Engineering students
- Work for fall/spring semesters on project for an external sponsor (LLNL in this case)
- Required for graduation (very well motivated).
- Currently have them working on looking at the design space and construction of a prototype

Initial phase comparing microwave simulation tools

CST Microwave Studio ← currently preferred for easy of use & accuracy
Comsol Multiphysics
Ansoft HFSS



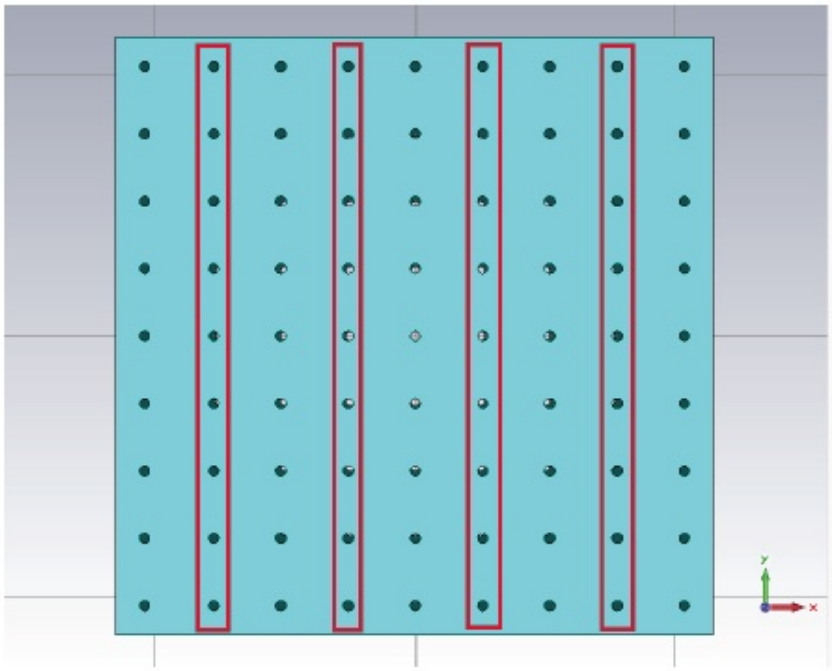


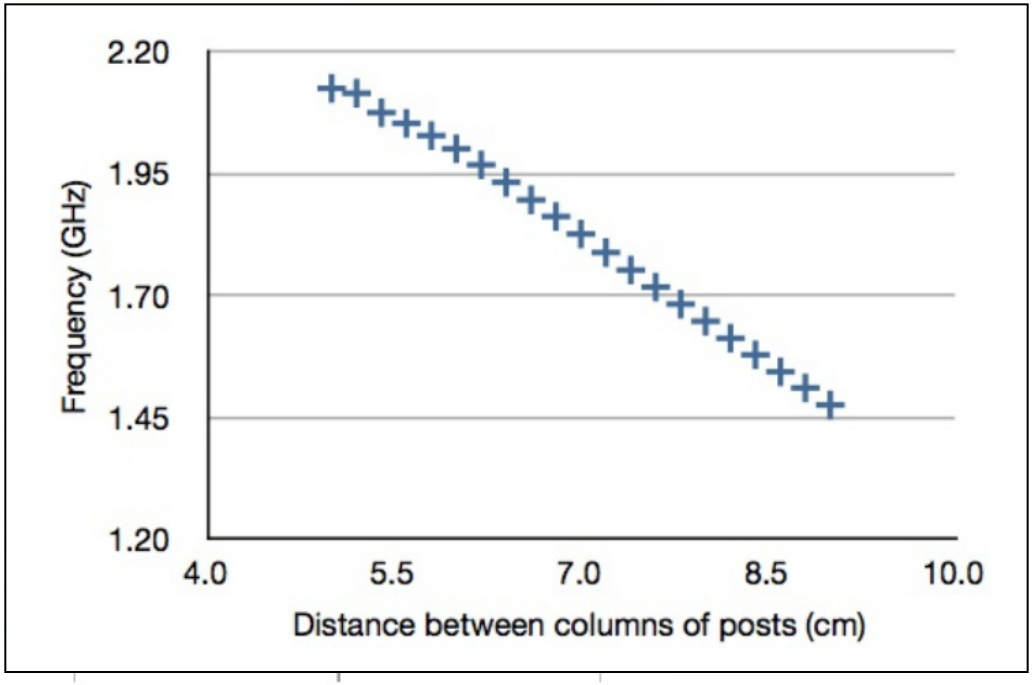
Large amount of Cavity Parameters to explore

Parameters	Variations
Cavity/Lattice Shape	Circle, hexagon, square
Post Radius	0.3, 0.4, 0.6, 0.8, 1, 1.25 cm
Post Spacing	3, 4, 5, 6, 7, 8 cm
Ellipses	None, inner ring
Major/Minor Axis Ratio	1.25, 1.5, 1.75, 2

Current HMC Clinic Status

- Settled on prototype design that would be relatively straightforward to construct and test.
- In construction now, looking to test in a week or two.

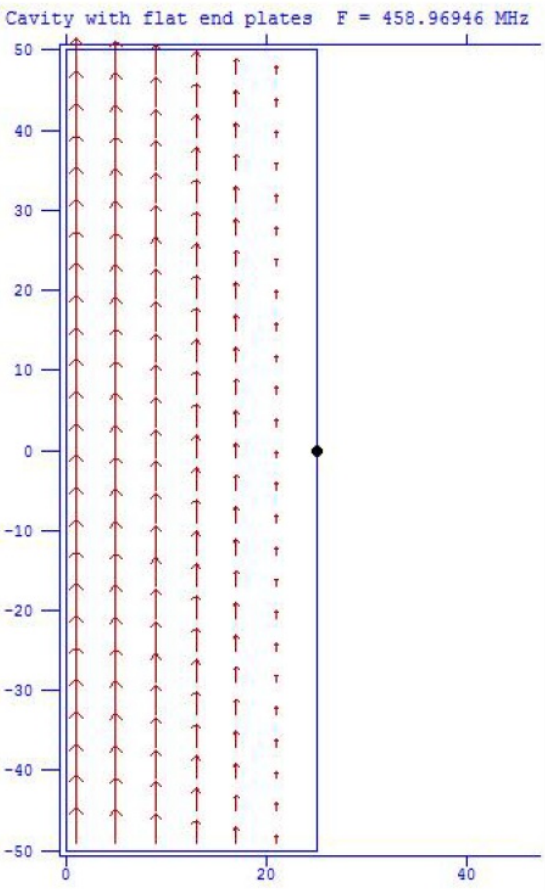


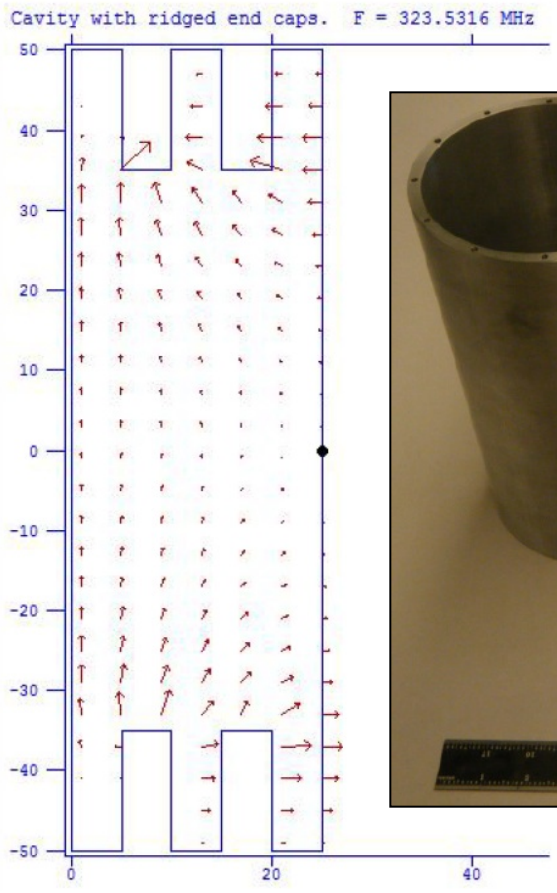


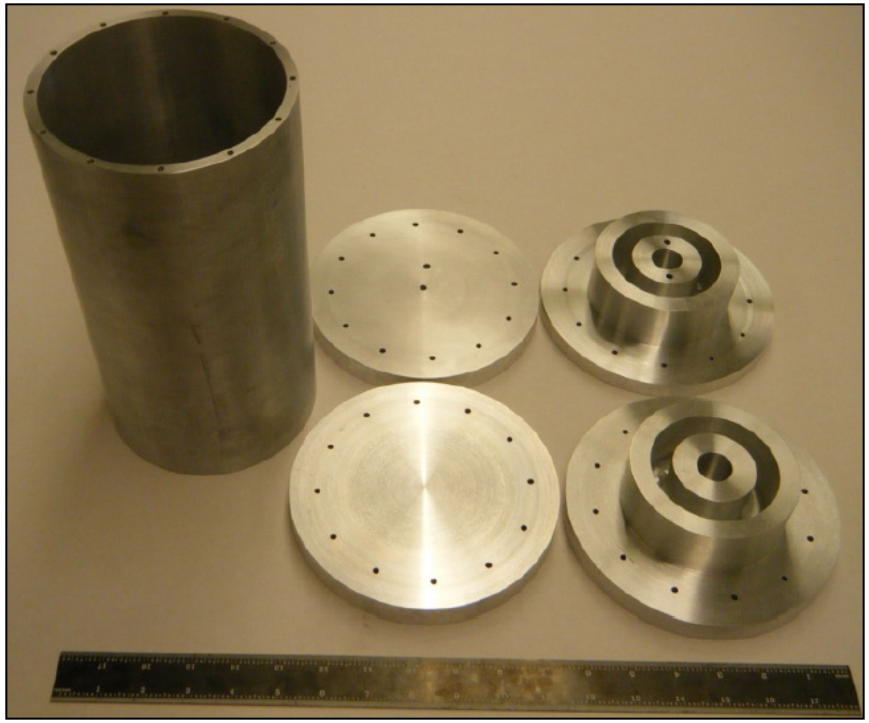
Simulation

“Slow-wave” cavity concept

- Possibility to lower the TM_{010} resonant frequency (without large amount of dielectric material).
- U. of Washington (L. J Rosenberg, H. Swan)

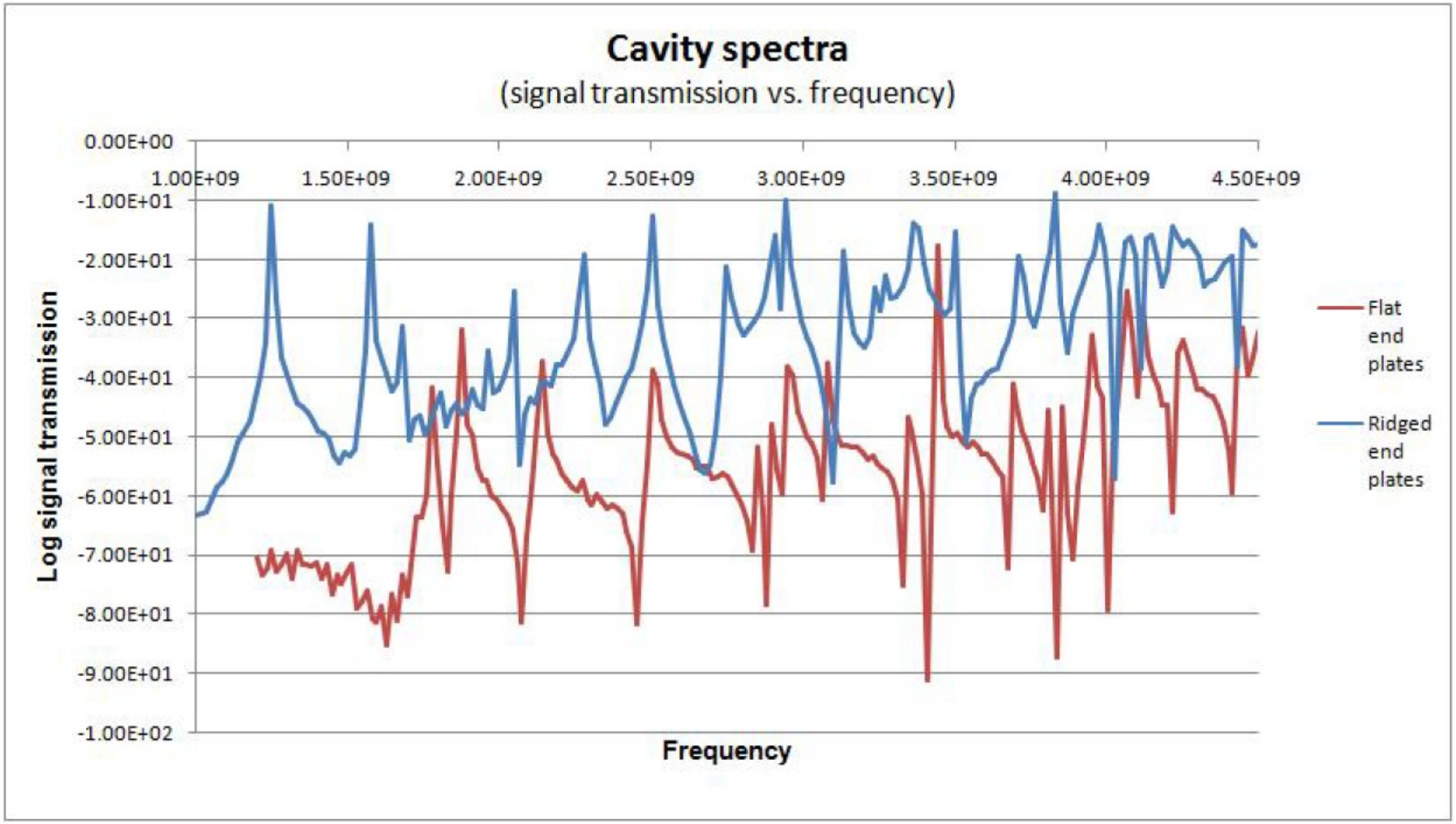






“Slow-wave” cavity concept

- Results lowered frequency by dramatically



The "Hybrid" superconducting cavity concept

What's the point?

$$P \propto g^2 \cdot B^2 V \cdot \min(Q_L, Q_a)$$

$$\frac{1}{f} \cdot \frac{df}{dt} \propto g^4 \cdot B^4 V^2 \cdot \min(Q_L, Q_a)$$

For copper cavities, $Q_a \sim 10^6$, whereas $Q_L \sim 50{,}000$

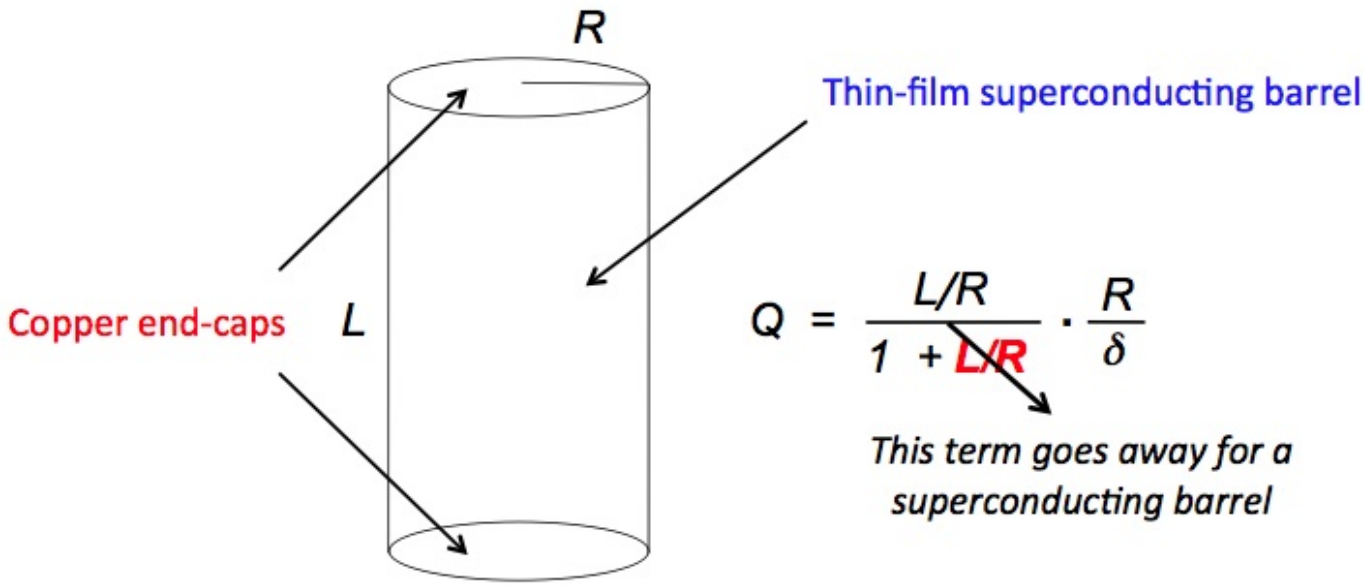
If you could increase Q_L by a factor of *e.g.* x10 :

- P would increase by x10
- df/dt would increase by x10 *(for constant g)*
- g would improve by ÷1.8 *(for constant scan speed)*

*slides from Karl van Bibber

The "Hybrid" superconducting cavity concept

The concept of a hybrid superconducting cavity:



$$Q_{hybrid} = (1 + L/R) \cdot Q_{cu}$$

For typical ADMX cavity, L/R = 5, enhancement factor = 6

*slides from Karl van Bibber

The “Hybrid” superconducting cavity concept

The science of thin-film superconductors is mature

PRL 105, 257006 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Far-Infrared Conductivity Measurements of Pair Breaking in Superconducting $Nb_{0.5}Ti_{0.5}N$ Thin Films Induced by an External Magnetic Field

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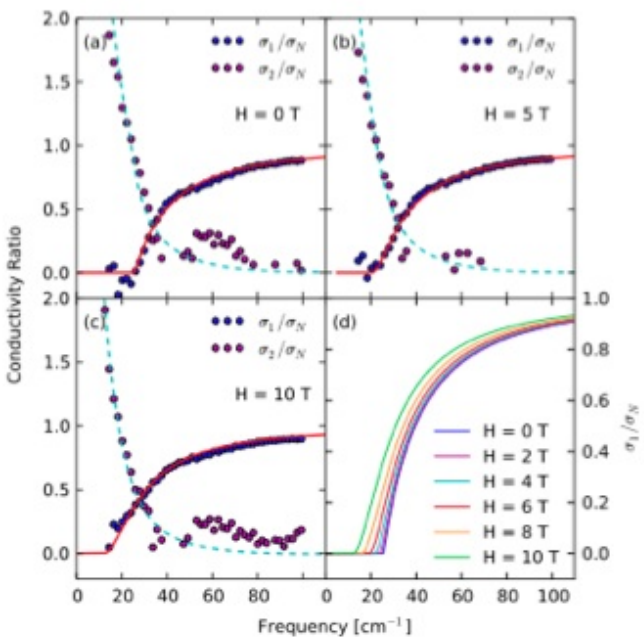
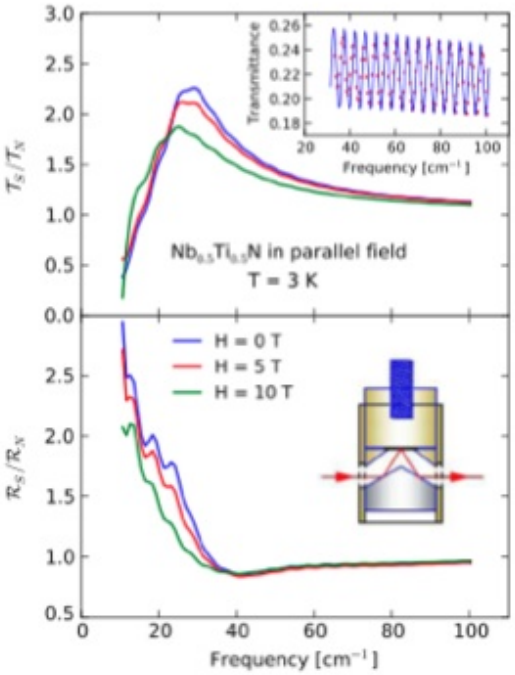
(Received 16 August 2010; published 16 December 2010)

We report the complex optical conductivity of a superconducting thin film of $Nb_{0.5}Ti_{0.5}N$ in an external magnetic field. The field was applied parallel to the film surface and the conductivity extracted from far-infrared transmission and reflection measurements. The real part shows the superconducting gap, which we observe to be suppressed by the applied magnetic field. We compare our results with the pair-breaking theory of Abrikosov and Gor'kov and confirm directly the theory's validity for the optical conductivity.

DOI: 10.1103/PhysRevLett.105.257006 PACS numbers: 74.78.−w, 74.25.Ha, 78.20.−e, 78.30.−j





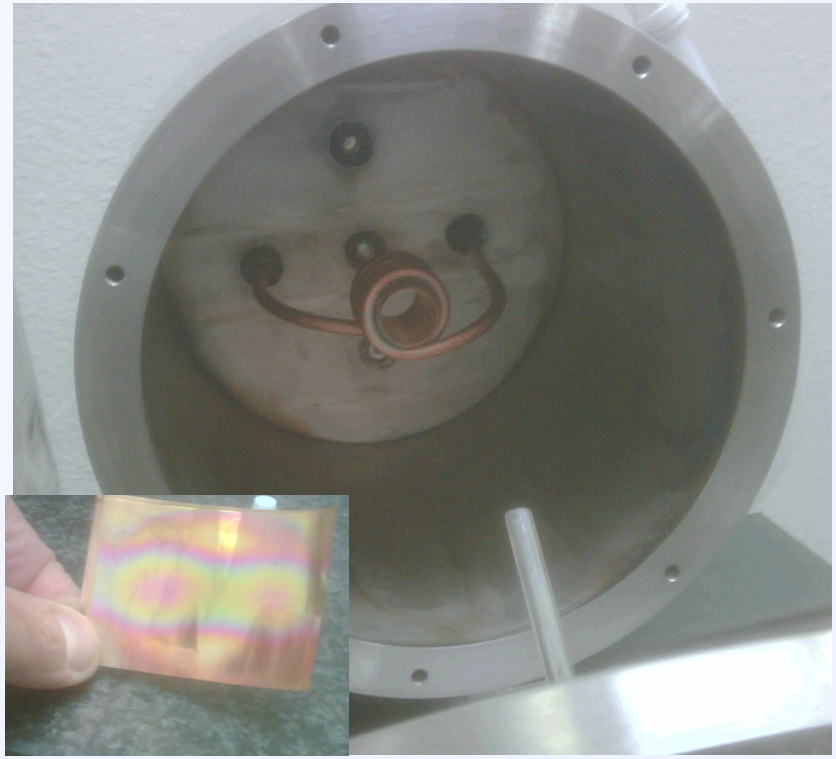
10 nm $Nb_{0.5}Ti_{0.5}N$ is perfect

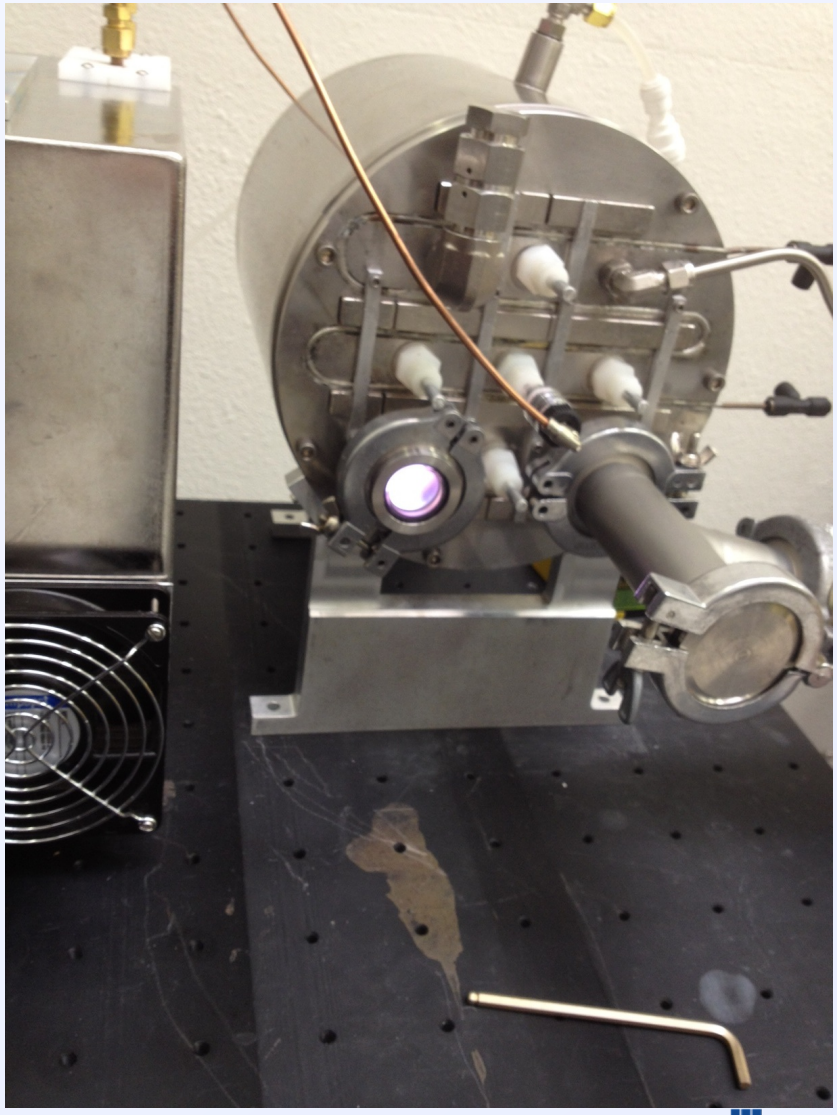
Supports $B_{||}$ up to 10 Tesla

*slides from Karl van Bibber

R&D has already begun on NbTiN superconducting coatings

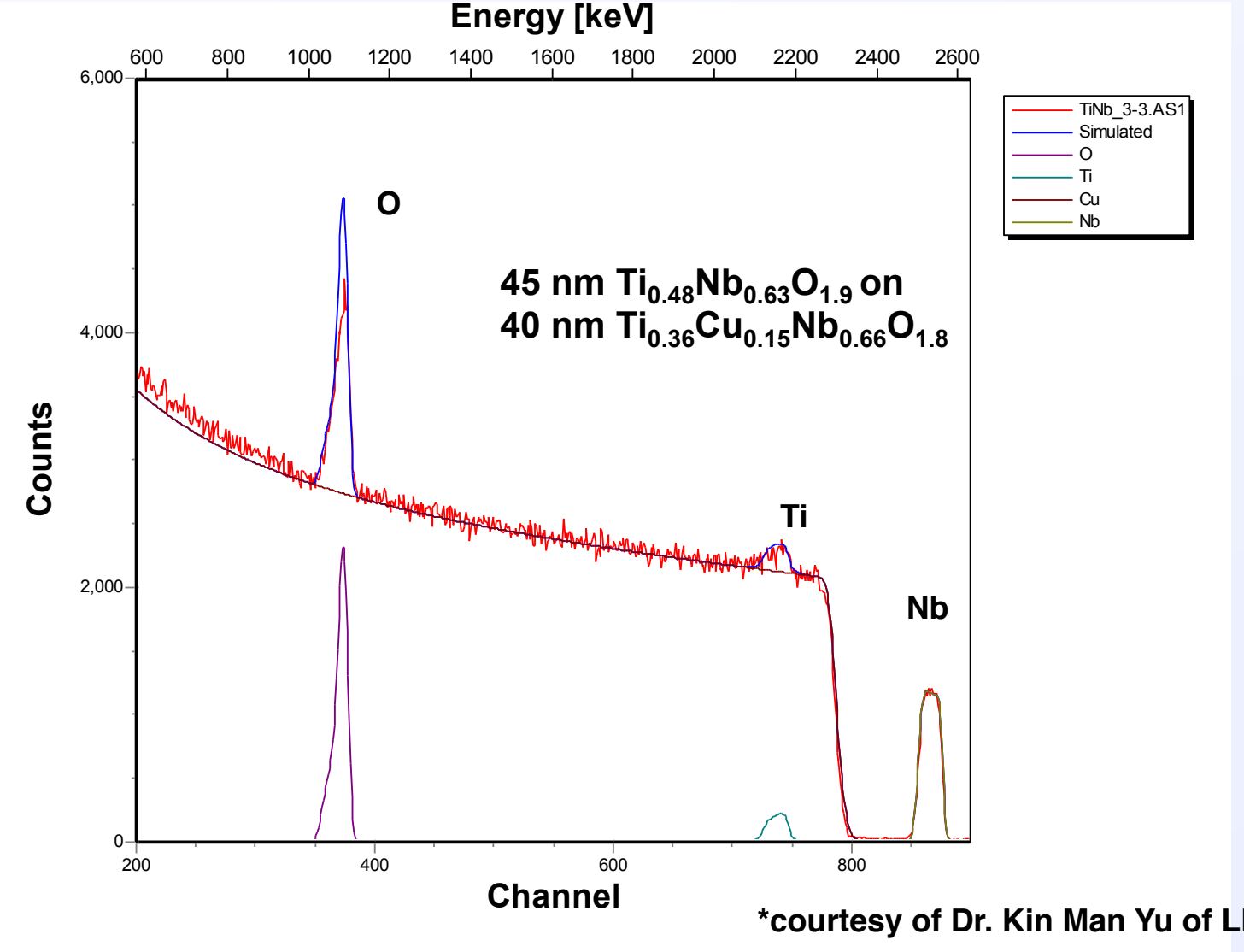
Using RF Sputtering Technique.
Co-sputtering Nb "beads" wrapped over axial Ti antenna.





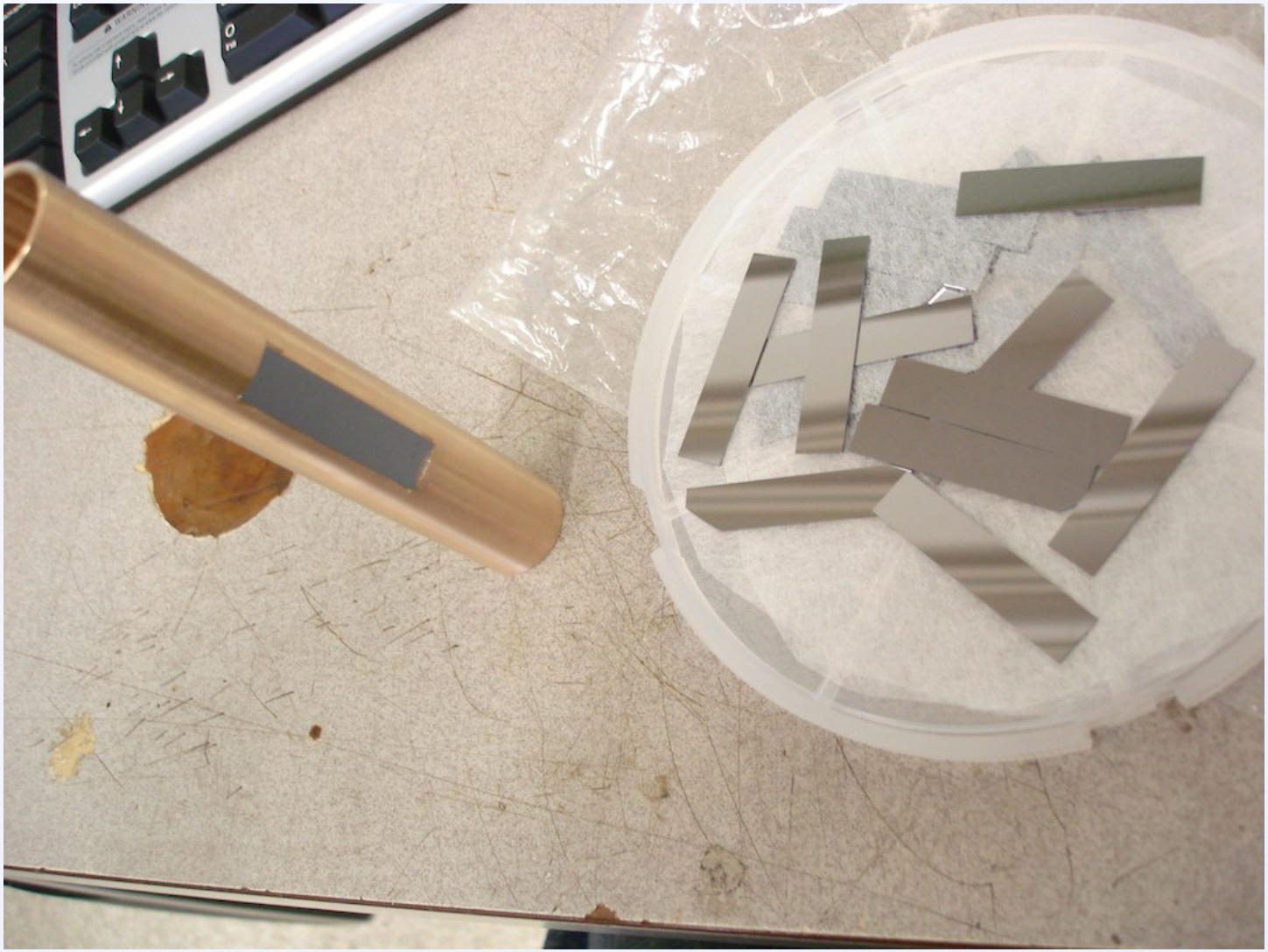
Initial system had a number of o-ring seals
Couldn't do better than few x 10^{-6} torr

Rutherford backscattering of 20 min NbTi deposition on copper foil



*courtesy of Dr. Kin Man Yu of LBNL

Testings: Deposit NbTiN on silicon wafers. RBS @ LBNL& LLNL.



Summary

TiNb

	Thickness (nm)	Ti:Nb:O
1	280	67:30:3
2	300	64:33:3
3	320	62:36:2
4	300	61:37:2
5	300	64:34:2

Ti only

	Thickness (nm)	[O]
1	200	3%
2	210	3%
3	220	3%
4	220	3%
5	210	3%

~0.2 nm of In at the interface

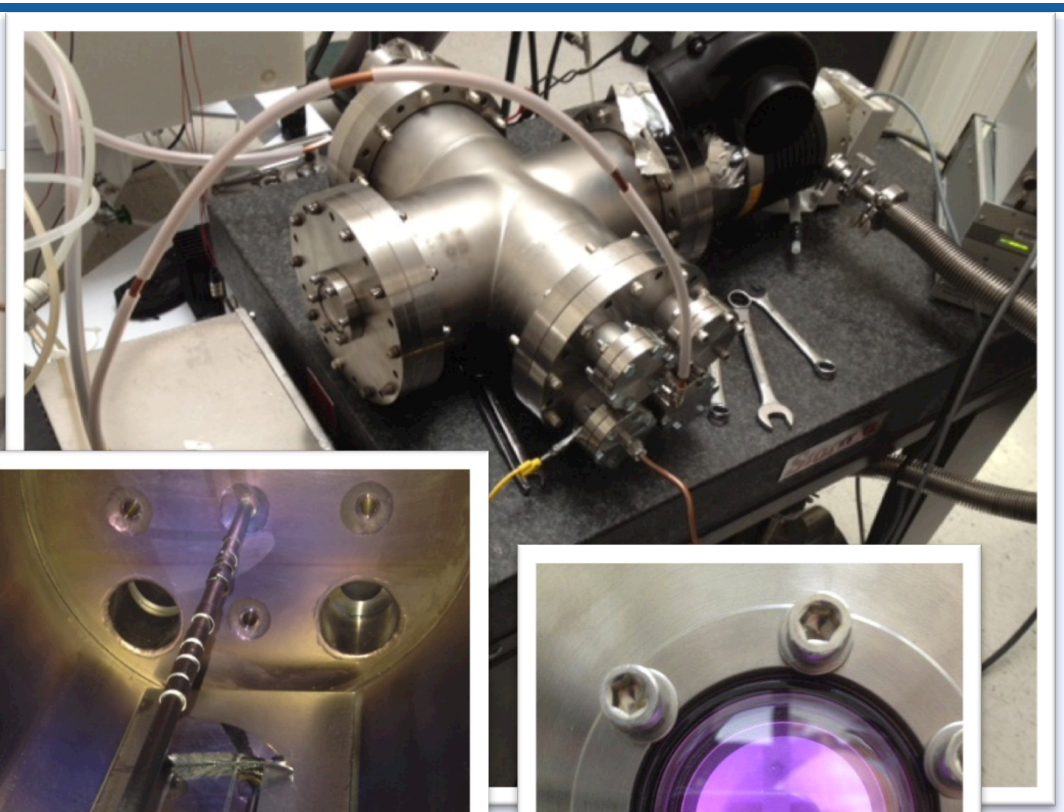
Yale glass slide

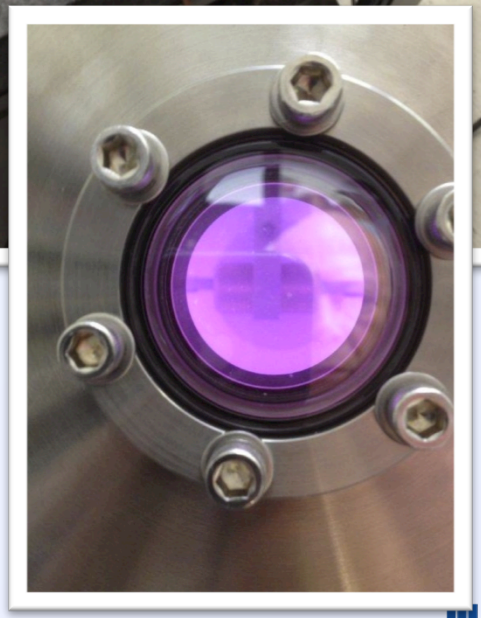
	Thickness (nm)	Ti:Nb:N:Ca
1	16	27:27:46:0
2	46	25:25:48:2
3	90	23:27:48:2
4	300	23:28:46:3

Each point 18 mm apart

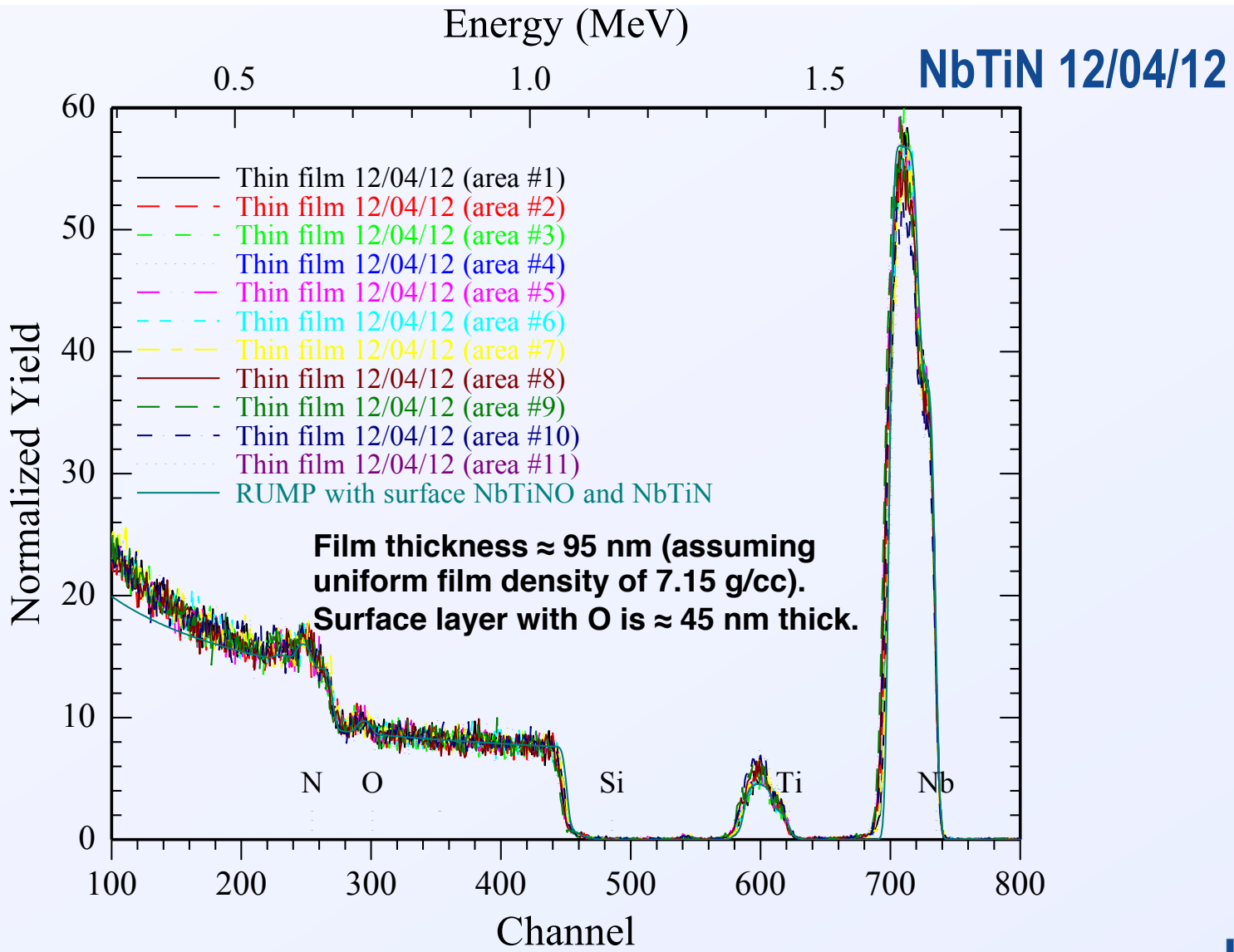
Current RF sputtering system (CF seals)

Now we can get much lower base pressure!

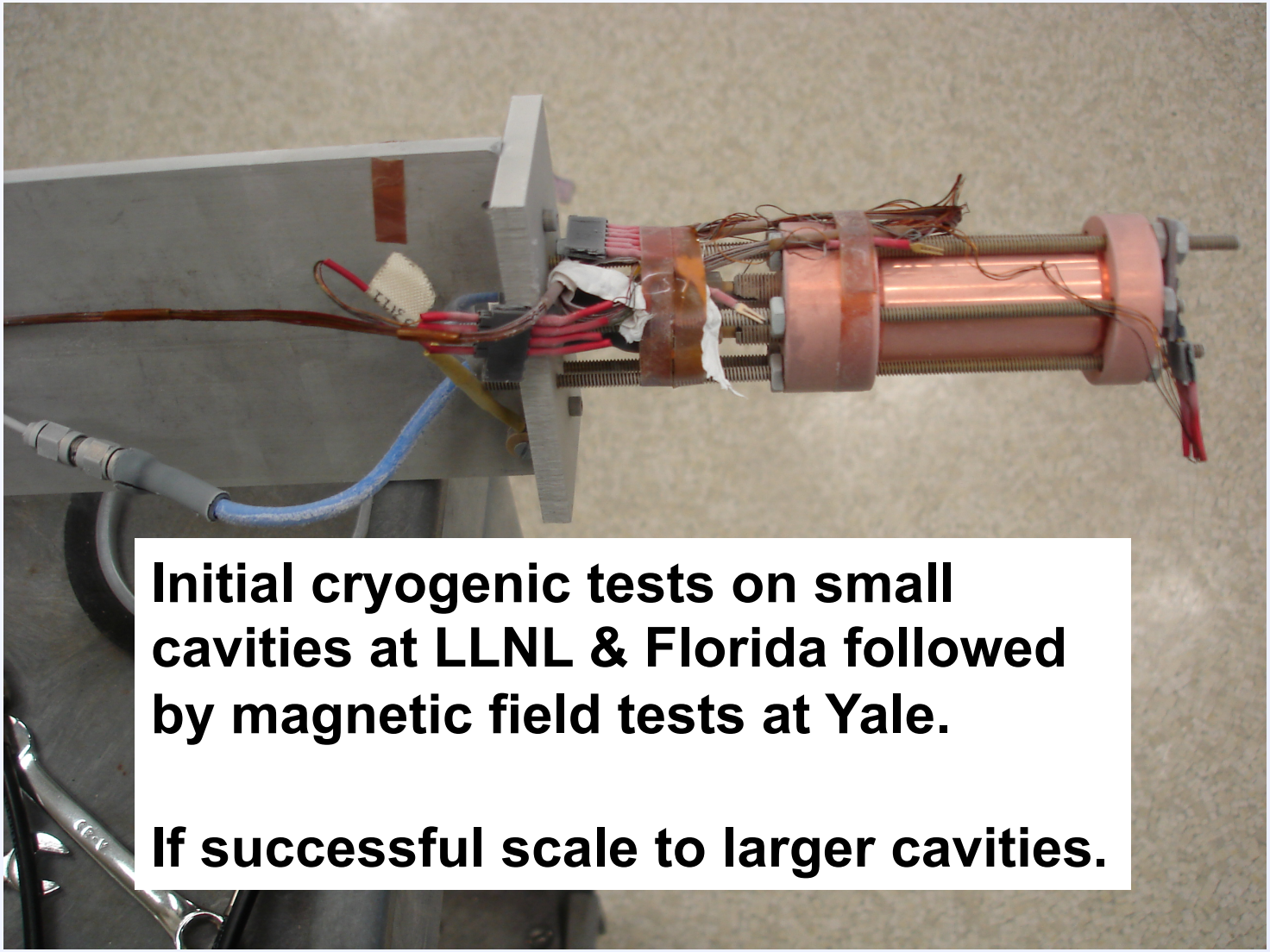




In addition there is a 4 MeV alpha beam at LLNL (local RBS)



Superconducting coatings will be placed on 1” cavity barrels



Initial cryogenic tests on small cavities at LLNL & Florida followed by magnetic field tests at Yale.

If successful scale to larger cavities.