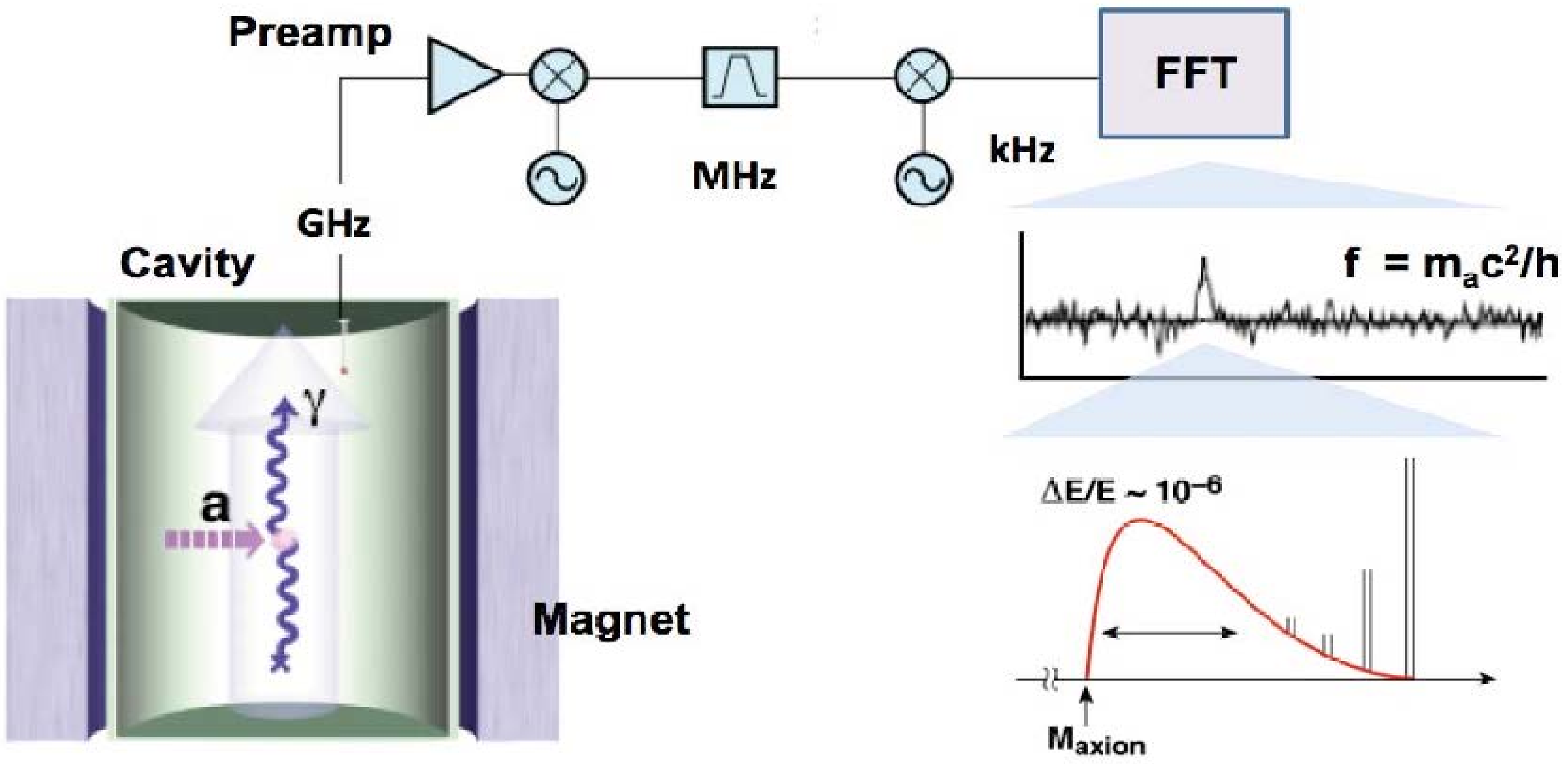
Hybrid and Superconducting Cavities

Presented by S.K. Lamoreaux

Yale University

ADMX-HF

Can Superconducting Coatings Help ADMX-type Experiments?



$$P_{sig} = g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B_0^2 V\, C\, Q$$

10^{-24} W is an interesting power level

How Much Q?

- Perhaps we want the cavity bandwidth to match the galactic axion effective bandwidth: “Maxwell-Boltzmann Distribution” and cavity interaction time both contribute to Q_a

$$Q_a = \frac{f}{\delta f} = 2 f \tau = 2 \frac{(11.5 GHz \cdot cm)}{R} \frac{2R}{3 \times 10^7 cm/s} \approx 1500$$

Neglects coherence length: approximately ½ de Broglie wavelength

$$Q_a = \frac{f}{\delta f} = 2 f \tau = 2 \frac{m_a c^2}{h} \frac{h/(2 m_a v)}{v} = v^{-2} c^2 = \beta^{-2} = 10^6$$

Which applies when the coherence length >> R

- $Q_L^{-1}=Q_w^{-1}+Q_o^{-1}$ is the “loaded Q”
- High Q *(low bandwidth)* limits maximum scan speed

Intrinsic cavity wall loss and output power coupling loss (optimum signal to noise when coupling is approximately equal to wall loss)

$$Q_L^{-1}=Q_w^{-1}+Q_o^{-1}$$

No real reason to not reduce Q_W^{-1} to near-zero
(some technical questions, e.g. amplifier stability).

We can make Q_L anything we want

$$\frac{s}{n} = \frac{P_{sig}}{kT_S}\sqrt{\frac{t}{\Delta\nu}}$$. Dicke Radiometer equation

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

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

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

Superconducting Films

- A bulk superconductor expels fields from the interior; for type II, a “normal” layer forms near the surface, separated by a thin transition layer (Abrikosov) between the regions
- For a thin film, the entire layer is in a mixed state, if the applied field is nearly perpendicular to the thin direction
- This thin film provides a superconducting boundary condition
- D. Tanner suggests that this can be used to improve cavity *Q* for ADMX experiments

The science of thin-film superconductors is mature

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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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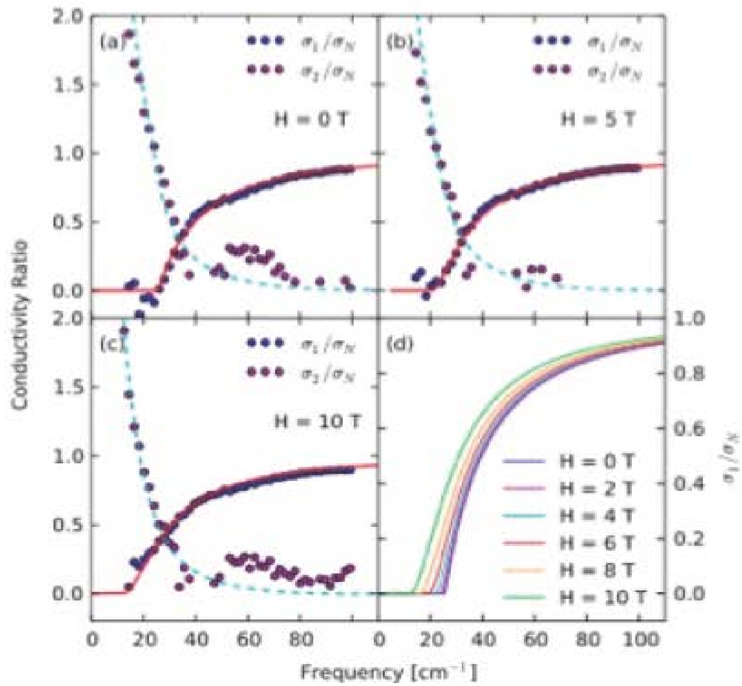
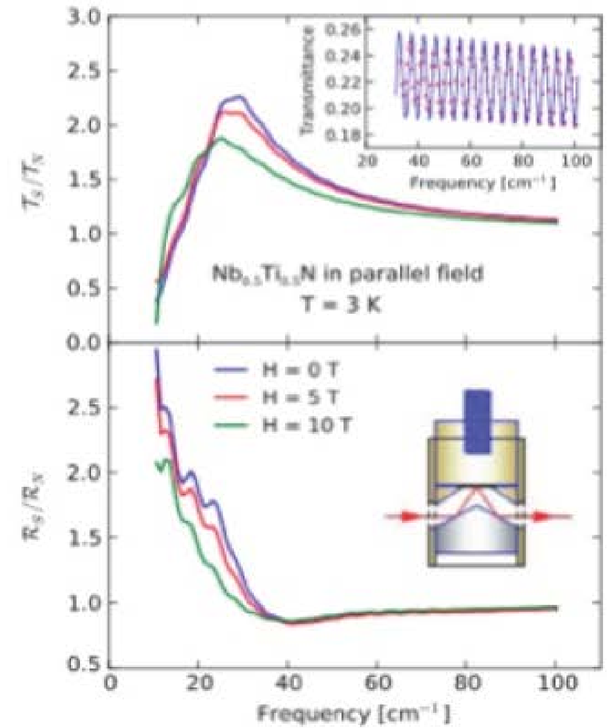
We report the complex optical conductivity of a superconducting thin film of $Nb_{0.5}Ti_{0.5}N$ in an external magnetic field. The field was applied parallel to the film surface and the conductivity extracted from far-infrared transmission and reflection measurements. The real part shows the superconducting 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





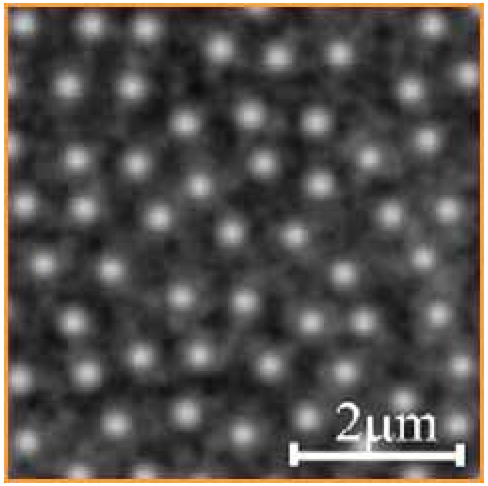
10 nm $Nb_{0.5}Ti_{0.5}N$ is perfect

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

*slides from Karl van Bibber

- **Magnetic-force microscopy of Vortex Lattice, 2002**
- Magnetic Force Microscopy
  Nb film, 40G, 4.3K

  A. Volodin et al.
  Katholieke Universiteit Leuven
  Europhys. Lett. 58, 582 (2002)

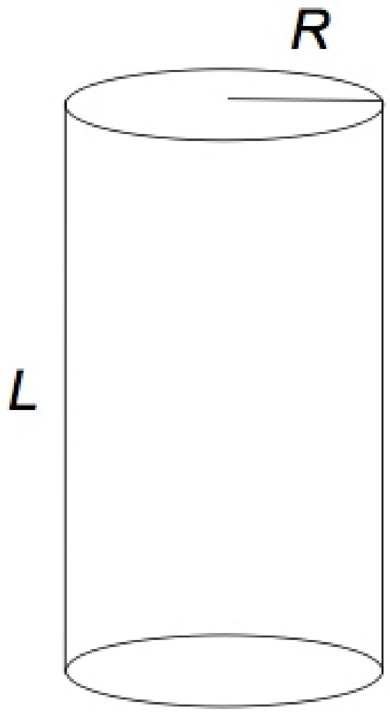


Requirements

- Strong field must be parallel to surface
- Perpendicular field forms vorticies in plane of film
- Require a very homogeneous magnet and precision alignment
- Main cylinder and tuning rods coatings can be effective; cylinder endcaps are perpendicular to field

The “Hybrid” superconducting cavity concept

Q of the TM_{010} mode for a conventional Cu cavity:



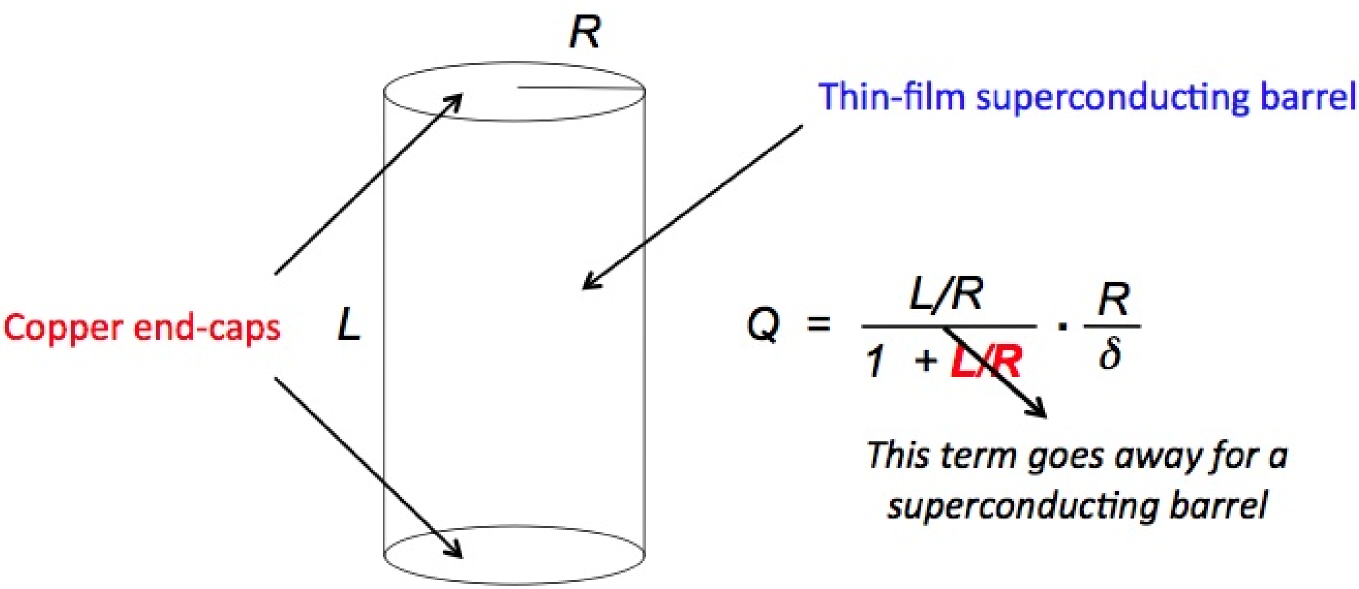
$$Q = \frac{L/R}{1 + L/R} \cdot \frac{R}{\delta}$$

Skin depth of Copper

*slides from Karl van Bibber

The “Hybrid” superconducting cavity concept

The concept of a hybrid superconducting cavity:



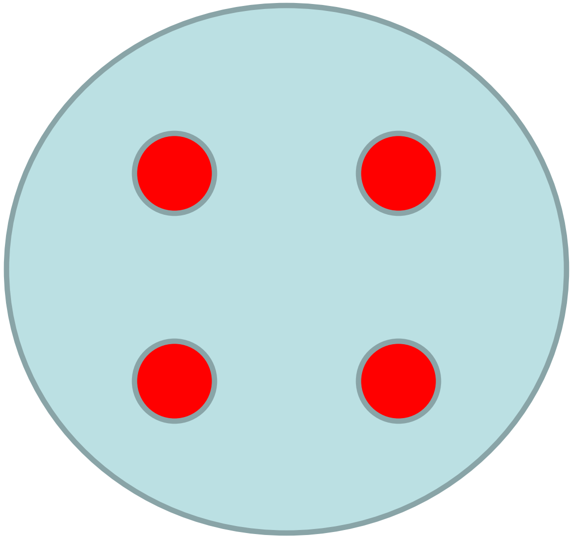
$$Q_{hybrid} = (1 + L/R) \cdot Q_{cu}$$

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

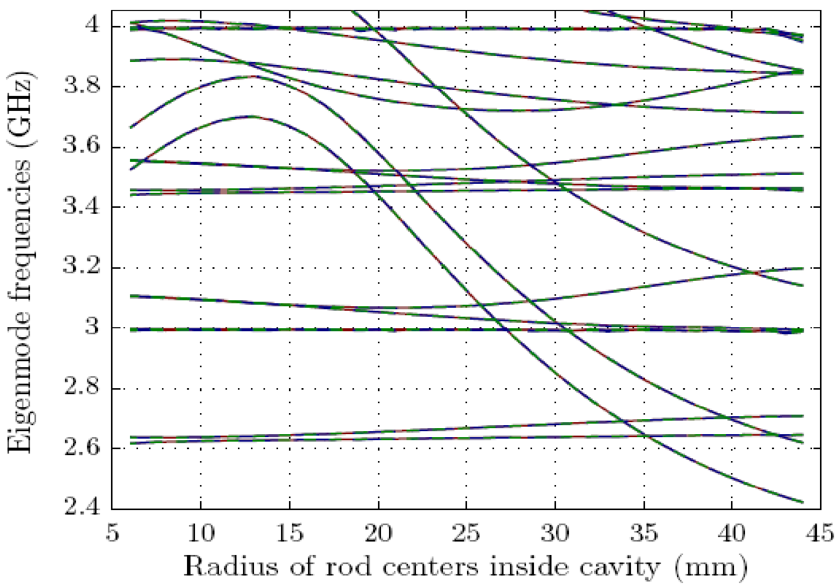
*slides from Karl van Bibber

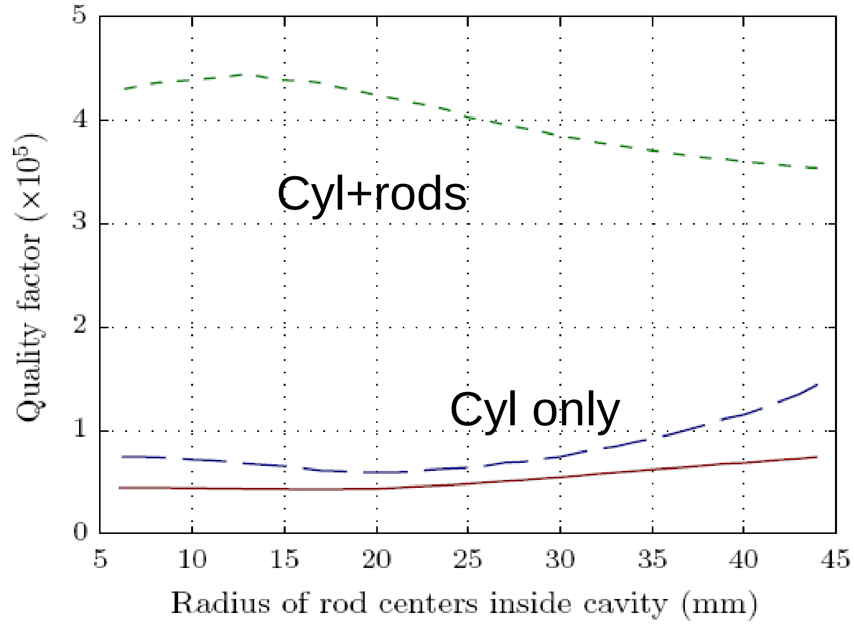
How Well Can We Do?

- Need to consider tuning rods
- Case study: 1 cm rods, Cu, 4 symmetrically placed



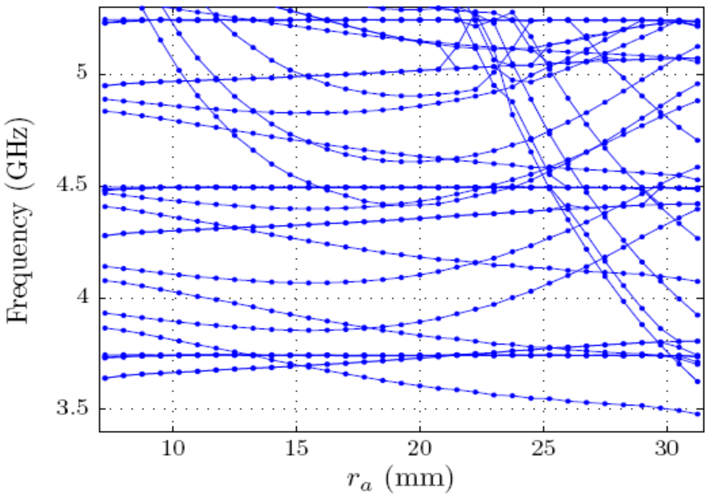
Comsol Results

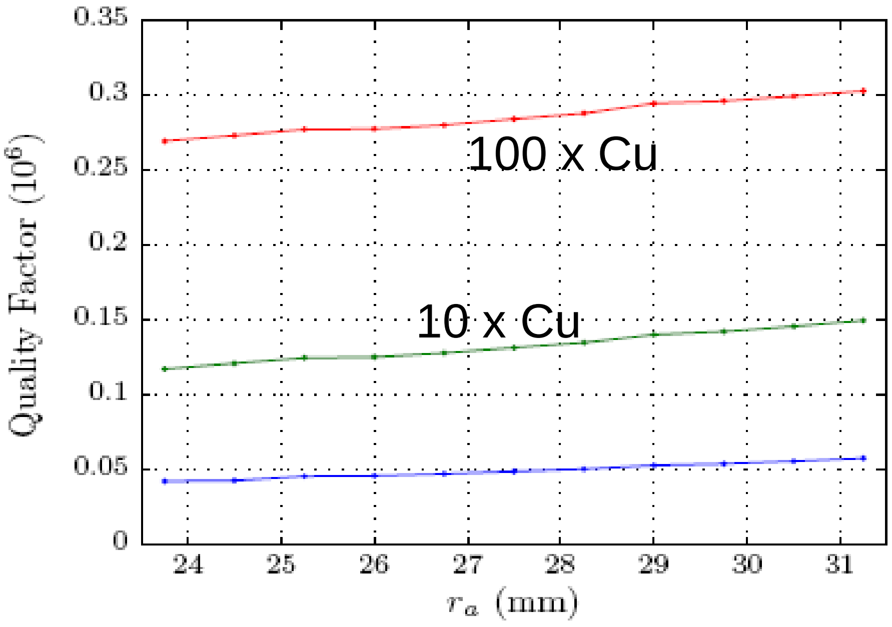




10 cm diameter, 15 cm long cavity; effect of coating only the cylinder and both cylinder/tuning rods with superconductor

20 cm long, 7.5 cm dia cavity, 4   1 cm rods



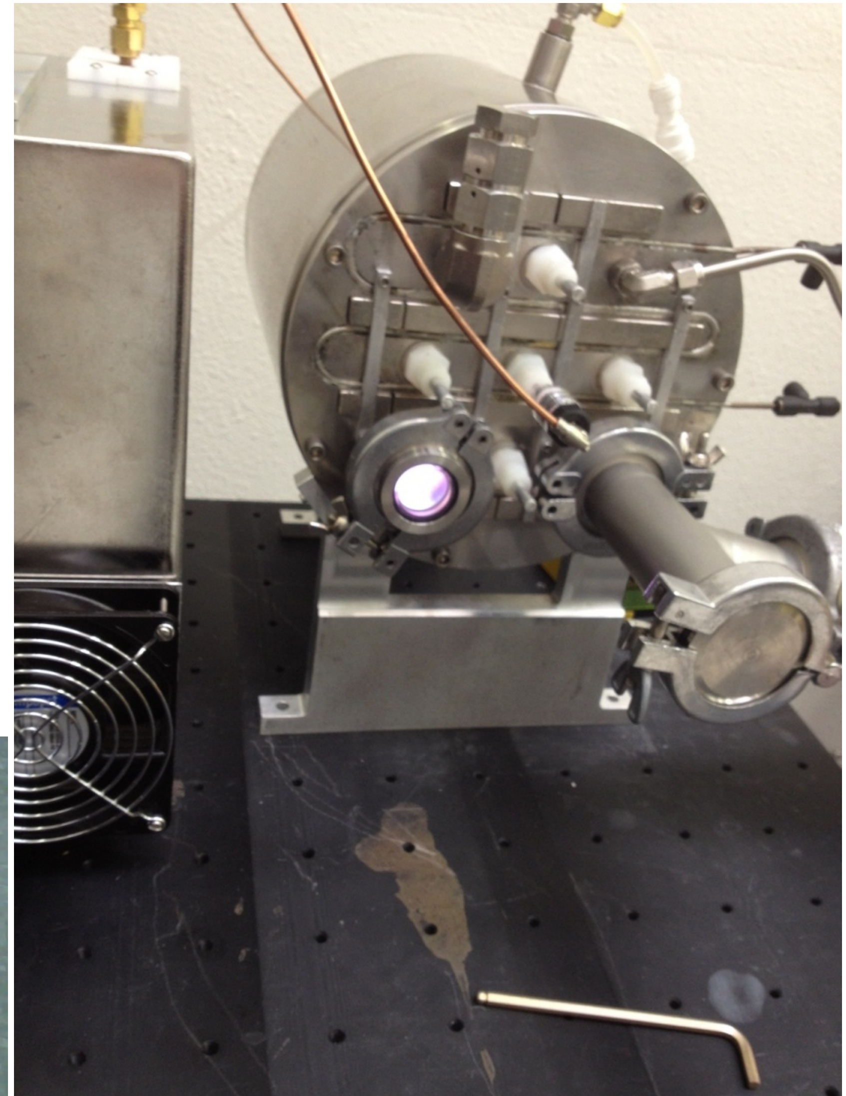


Requirements

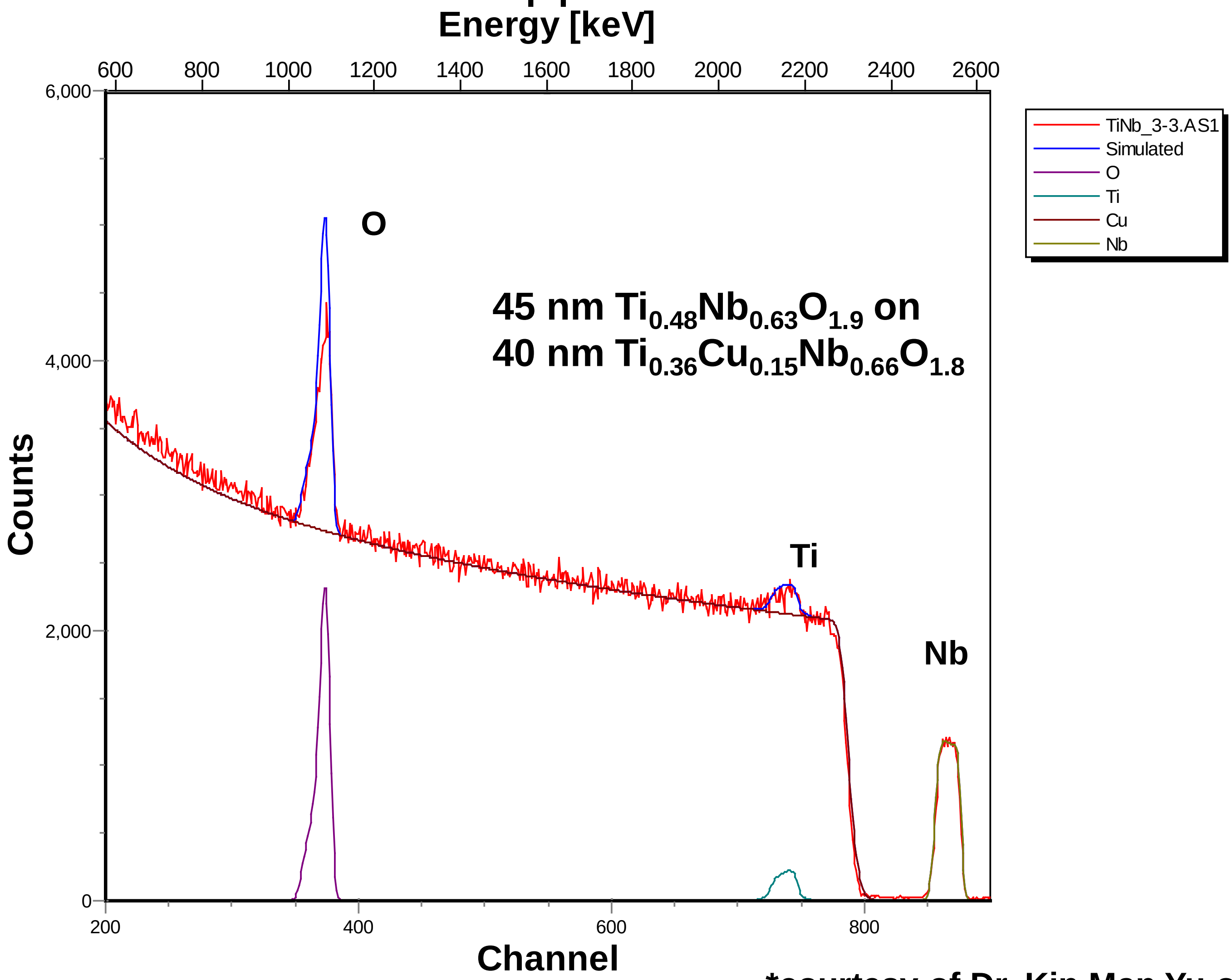
- Need 100 times better conductivity than Cu in the anomalous skin depth region
- At any frequency other than “0”, a superconductor presents a finite resistance
- Vortices increase this resistance, and the vortex density is proportional to the perpendicular field
- <100 G perpendicular field is required– need well-designed magnet, careful alignment (.01 T/10 T=.001 radians=.06 deg)
- Magnet has been designed for ADMX-HF, being built by Cryomagnetics, Oak Ridge

R&D has already begun on NbTiN superconducting coatings

Currently in the process of setting up RF vapor deposition on foils for

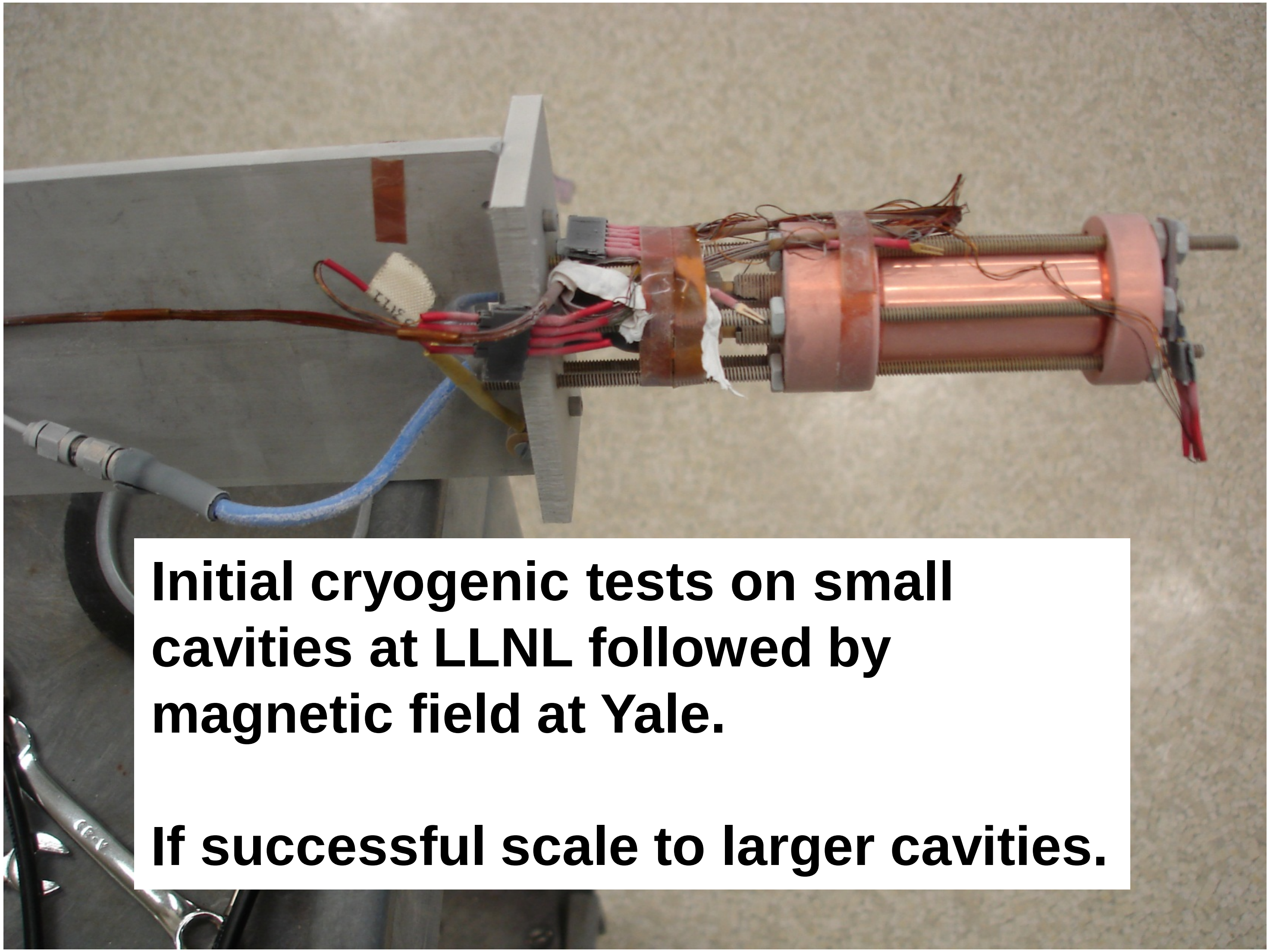


Rutherford backscattering of 20 min NbTi deposition on copper foil



***courtesy of Dr. Kin Man Yu of LBNL**

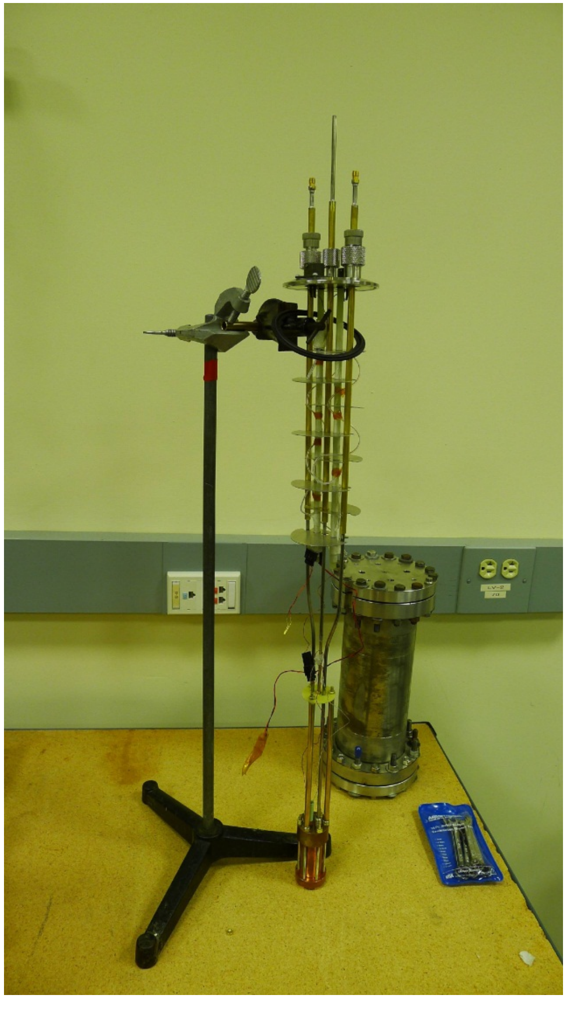
Superconducting coatings will be placed on 1” cavity barrels

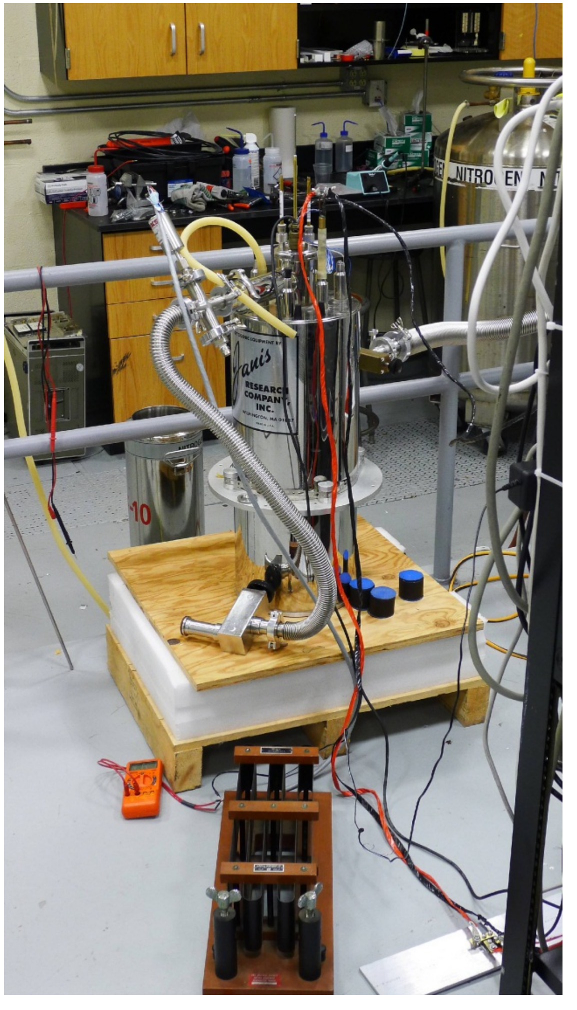


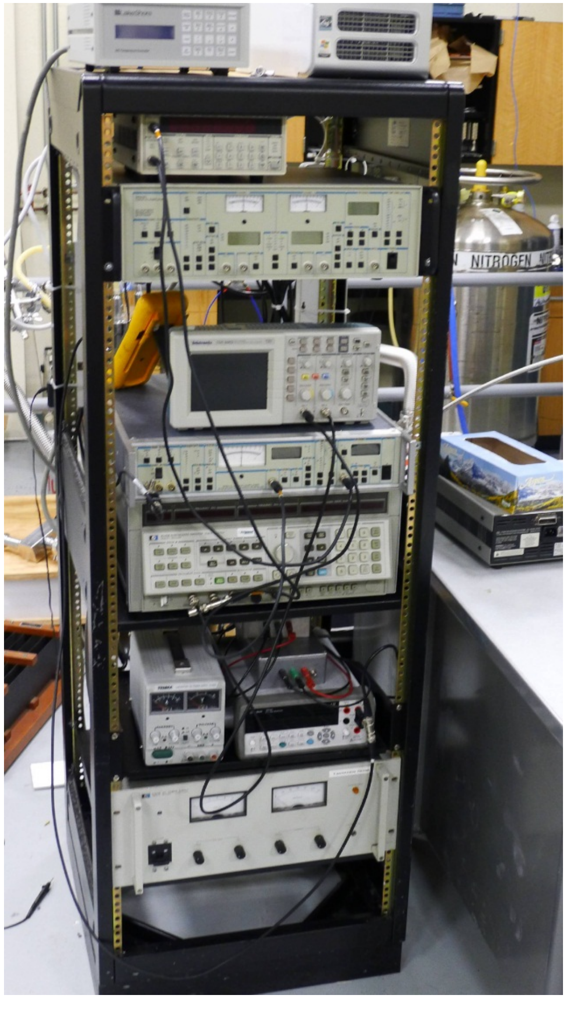
Initial cryogenic tests on small cavities at LLNL followed by magnetic field at Yale.

If successful scale to larger cavities.

Test Apparatus at Yale

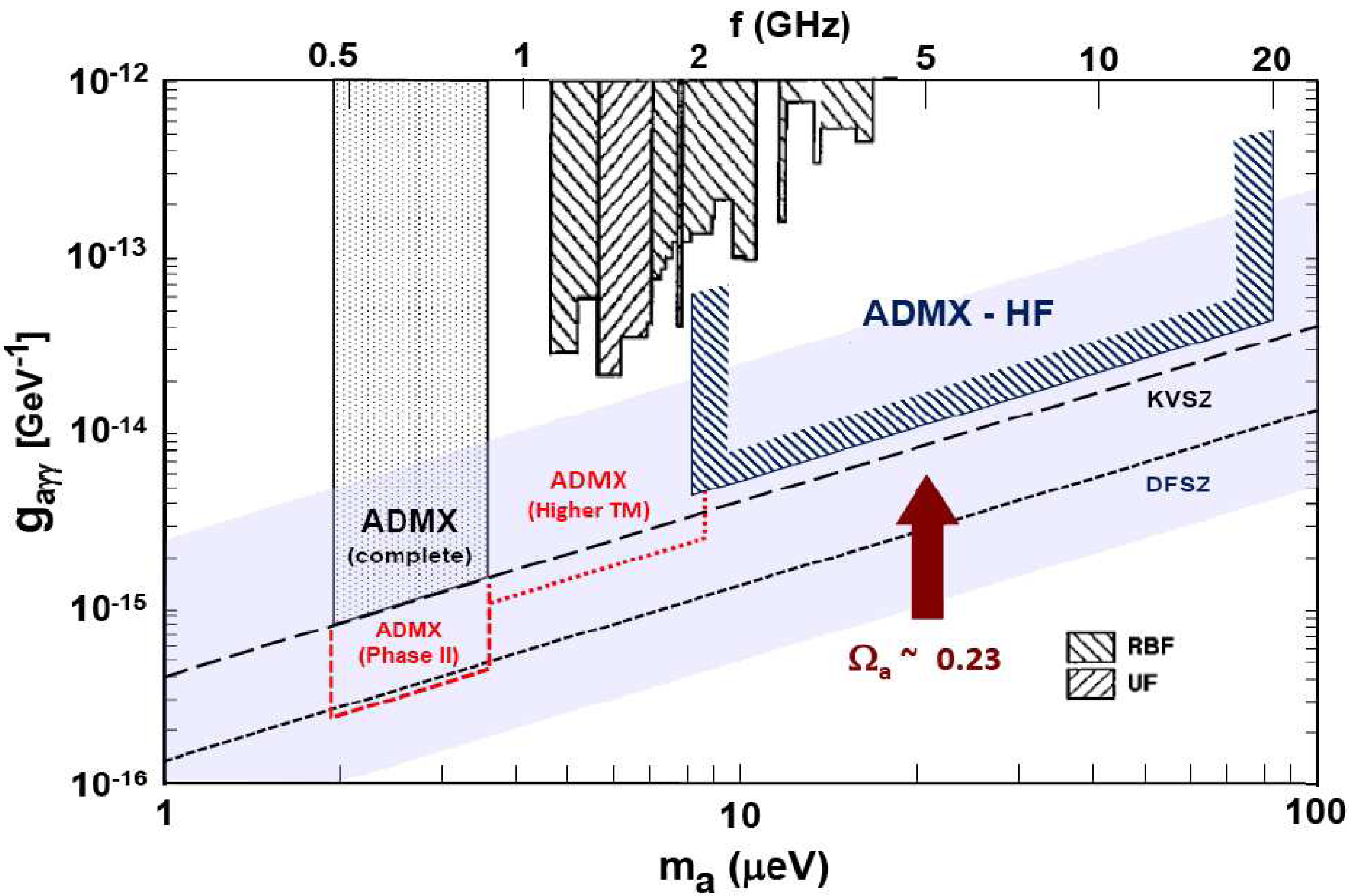






Conclusion

- Very much an R&D effort
- Other Coatings, e.g., Magnesium Diboride (H_{c2} of 40 T)
- The "cost" is small for a more than incremental gain in sensitivity



f (GHz)
0.5
1
2
5
10
20
10-12
10-13
10-14
10-15
10-16
$g_{a\gamma\gamma}$ [GeV-1]
1
10
100
m_a (μeV)
ADMX - HF
KVSZ
DFSZ
ADMX
(Higher TM)
ADMX
(complete)
ADMX
(Phase II)
Ω_a ~ 0.23
RBF
UF