Hybrid cavities for ADMX

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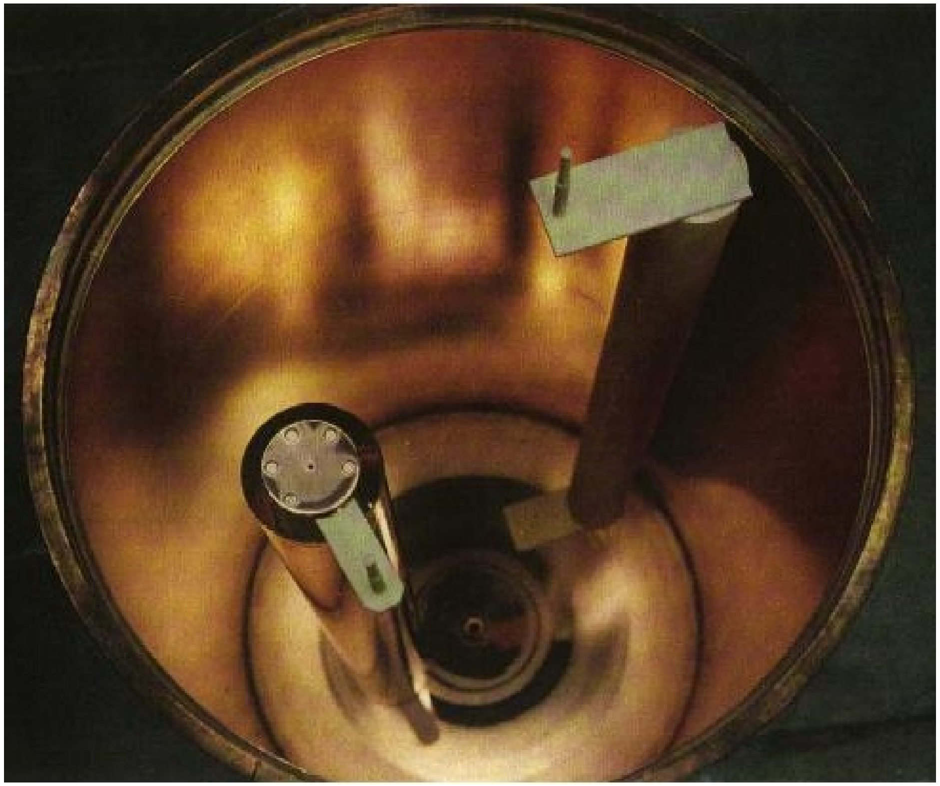

$$f = \frac{c}{2.61r}$$

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Our signals are very weak

- Power from the cavity is

$$P = 4 \cdot 10^{-22}\ \mathrm{W} \left(\frac{V}{200\ \ell}\right) \left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^2 C_{nl} \left(\frac{g_\gamma}{0.97}\right)^2 \cdot \left(\frac{\rho_\mathrm{a}}{0.5 \cdot 10^{-24}\ \mathrm{g/cm}^3}\right) \left(\frac{m_\mathrm{a}}{1\ \mathrm{GHz}}\right) \left(\frac{\min(Q_\mathrm{L}, Q_\mathrm{a})}{1 \times 10^5}\right)$$

- 1 GHz ⇔ 4 μeV ⇔ 50 mK
- Q_L ~ 0.5*140,000 (GHz/f)$^{2/3}$ (ASE) and Q_a ~10^6
- g_γ ~ 0.36 (DFSZ) or g_γ ~0.97 (KSVZ)
- C_{nl} is a form factor, overlap of $\vec{E} \cdot \vec{B}_0$ in the cavity.

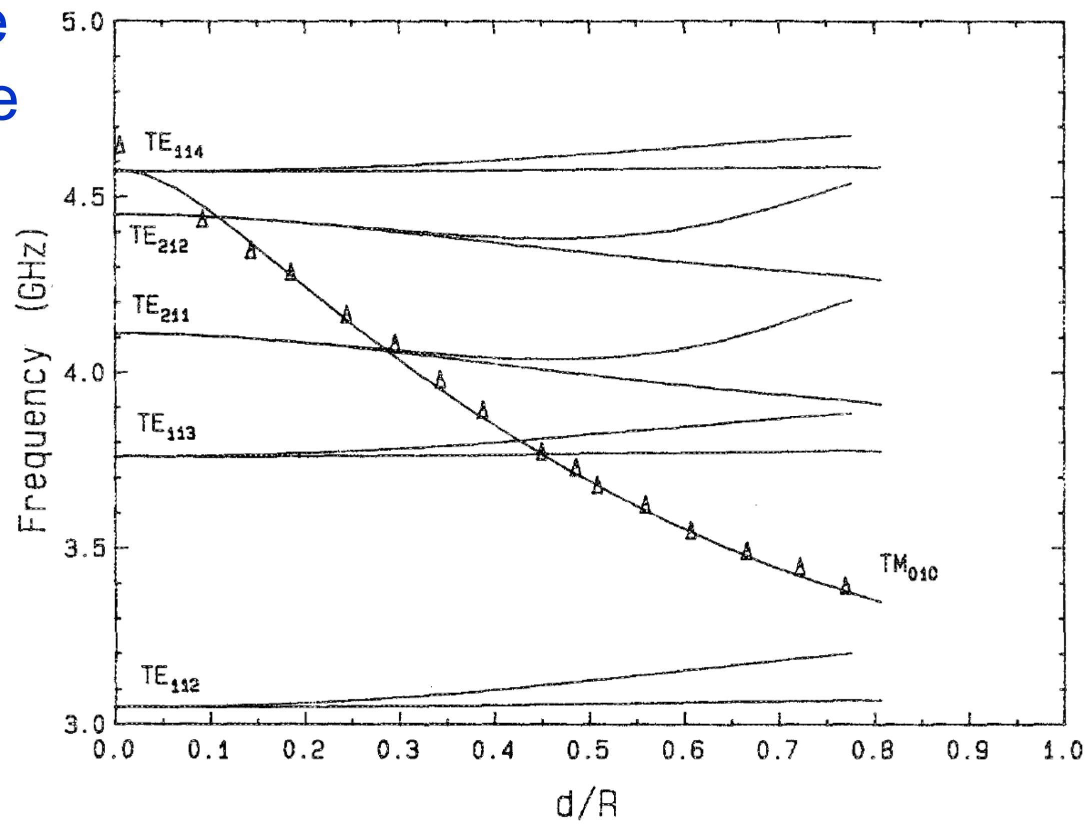
Length cannot get too long

- The longer the cavity, the more TE modes there are in the tuning range.
- With metal tuning rod, there are also TEM modes at

  ~ integer*$c/2L$

  $\sim$ 150 MHz for $L = 1$ m
- Typically:

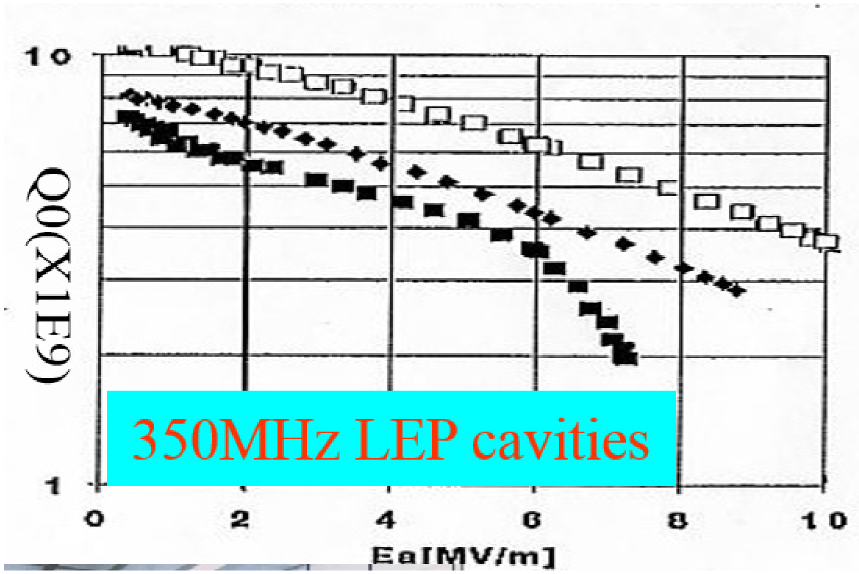
  $L \sim 4.4r$

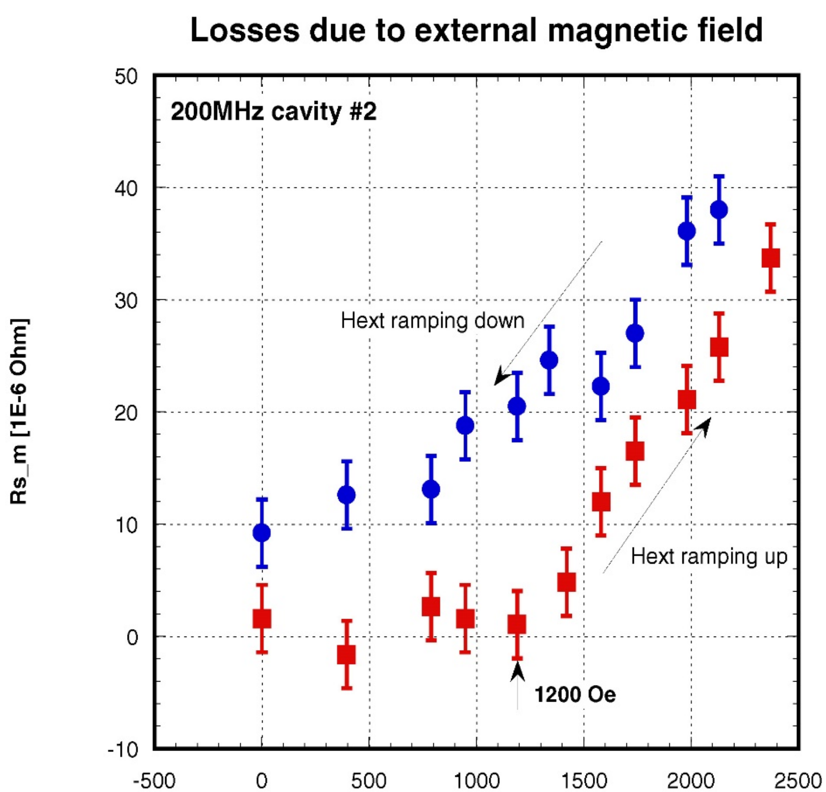


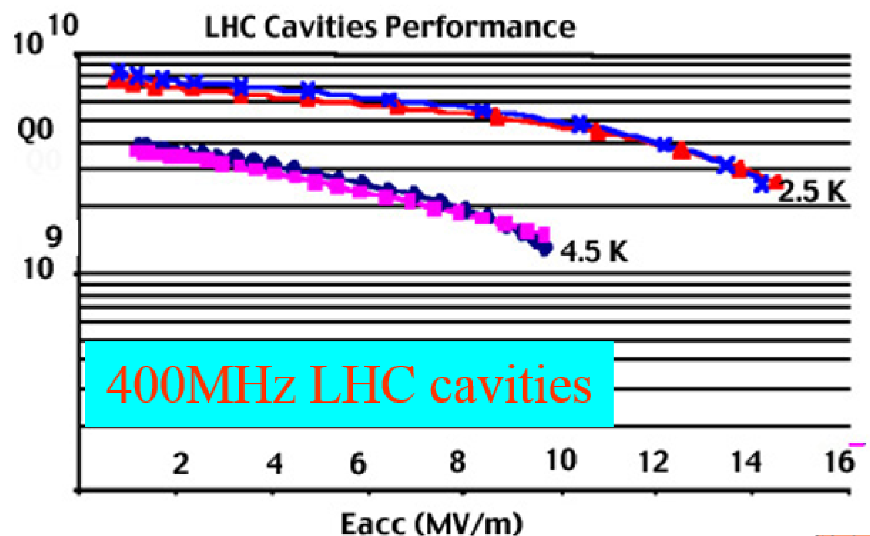
Modes for r = 3.6 cm, L = 15 cm cavity. d is the distance the metal rod is from the center.

Nb cavities have high Q

- Rong-Li Geng, LEPP, Cornell University
- Nb film (1-2 μm) magnetron sputtered on Cu







ADMX

Xi et al.

- PRL **105**, 257006 (2010).
- Thin film superconductor is ok in a magnetic field
- So long as the film was thinner than the spacing of fluxoids in the type-II superconductor
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- And if the field were applied parallel to the sample surface.
- The film thickness for 8 T fields would be about 100 ˚A.

Xi et al.

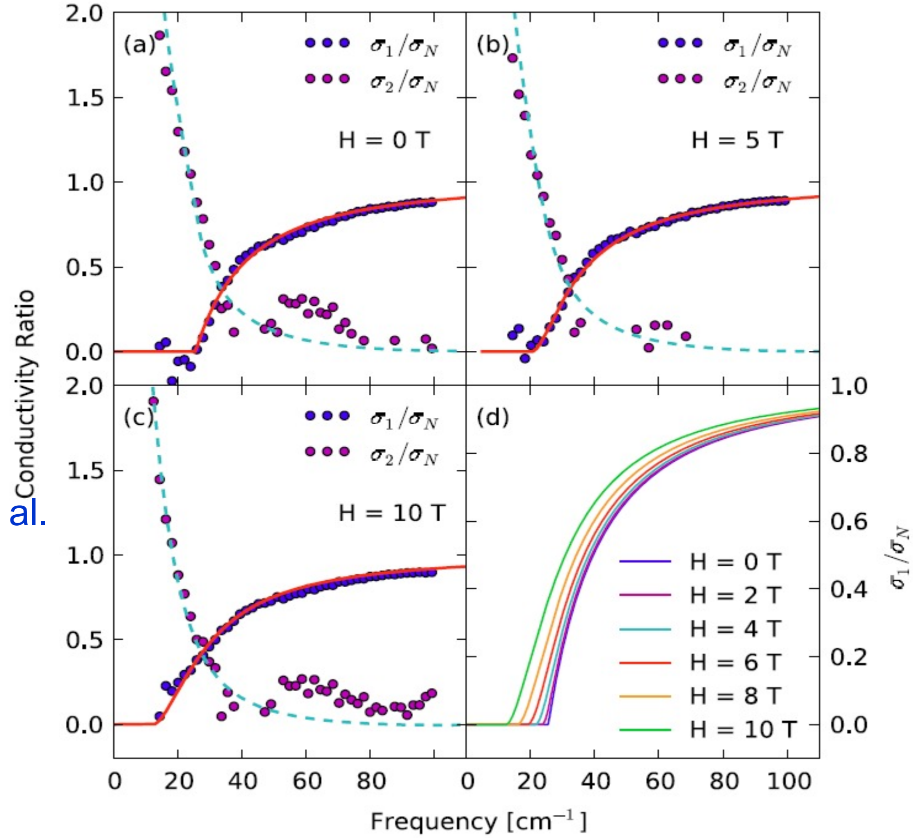
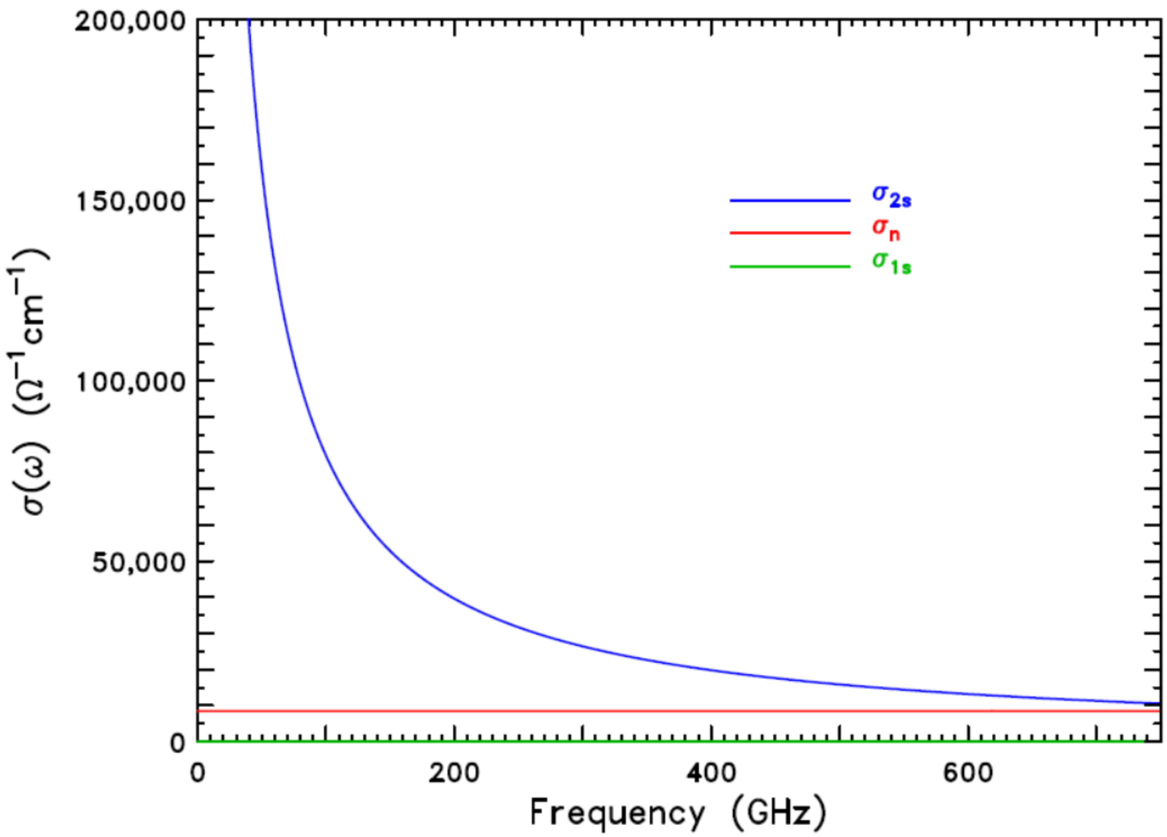


FIG. 2 (color online). (a)–(c) The real and imaginary parts of the $T = 3$ K superconducting state optical conductivity (normalized to the normal-state conductivity) at three different applied magnetic fields. The solid lines are fits to σ_1/σ_N using the pair-breaking theory. The dashed lines show the corresponding σ_2/σ_N as determined by a Kramers-Kronig transform of the real part. (d) The fitted σ_1/σ_N at six fields.

London model for superconducting electrodynamics

- 1 GHz « 450 GHz = 2Δ at 10T

$$\sigma_s(\omega) = \sigma_1 + i\sigma_2 = \frac{\pi n_s e^2}{2m}\delta(\omega) + i\frac{n_s e^2}{m\omega}$$



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Calculate the Q

- Unloaded (wall) Q for the TM_{010} mode (Jackson)

$$Q = \frac{H}{R+H} \cdot \frac{R}{\delta},$$

- H is cavity height and R cavity radius.
- R/δ occurs for all modes, the prefactor $H/(R+H)$ depends on the mode.
- For TM_{010} $f_0 = c/2.61R$, so, using λ_0, the vacuum wavelength

$$Q = 0.382 \cdot \frac{H}{R+H} \cdot \frac{\lambda_0}{\delta}.$$

- Low frequency reflectance: $\mathscr{R} = 1 - \sqrt{\frac{2\omega}{\pi\sigma_{dc}}}$; absorbance: $\mathscr{A} = 1 - \mathscr{R} = \sqrt{\frac{2\omega}{\pi\sigma_{dc}}}$
- Classical skin depth:

$$\delta = \sqrt{\frac{c^2}{2\pi\omega\sigma_{dc}}}.$$

- Algebra: $\mathscr{A} = 4\pi\delta/\lambda_0$
- Recast Q in terms of the absorbance of the wall:

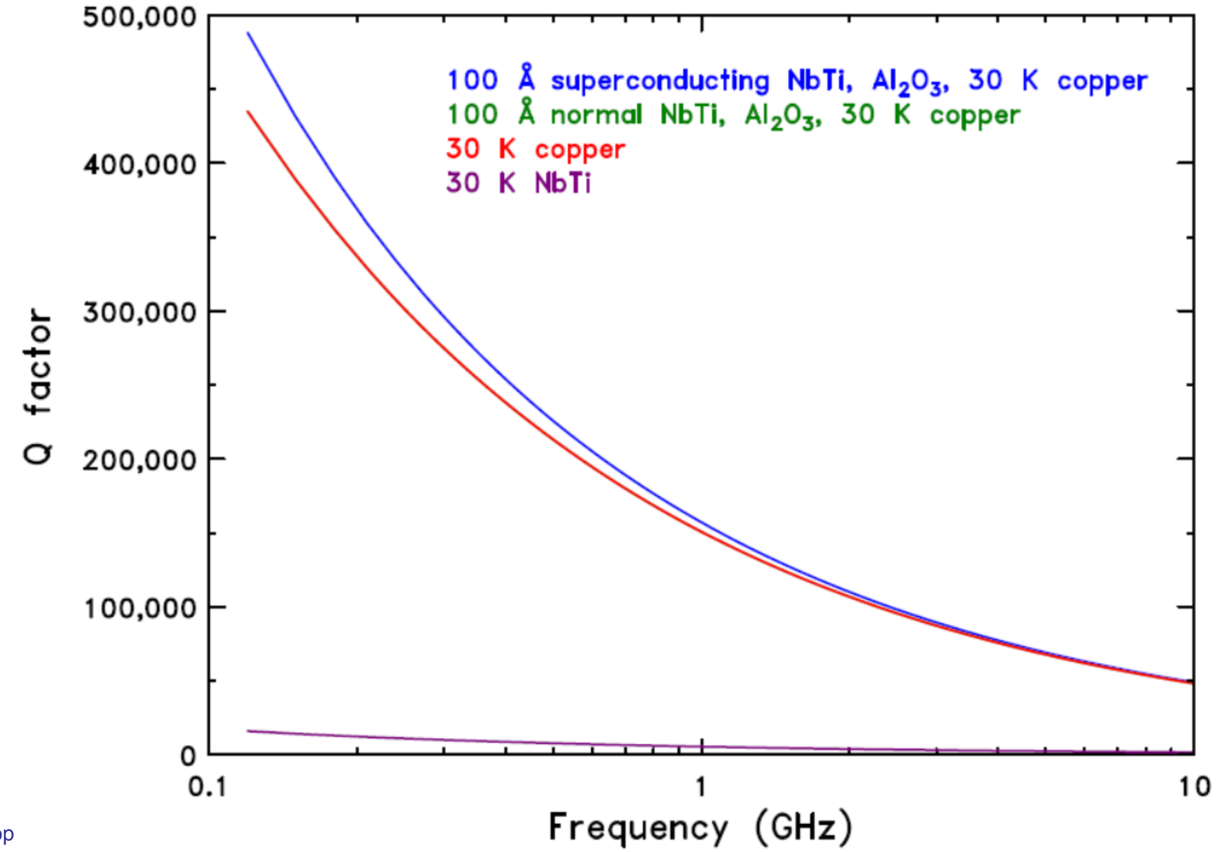
$$Q = 4.8 \cdot \frac{H}{R+H} \cdot \frac{1}{\mathscr{A}}.$$

Q for NbTi on copper

- Height = 1 m. Radius = 0.25 m.

$$Q = \frac{4}{\mathscr{A}}.$$

- Use this for both copper cavity and coated cavity.
- From the point of view of the loss of stored energy, there is no difference between a homogeneous wall and a layered wall.



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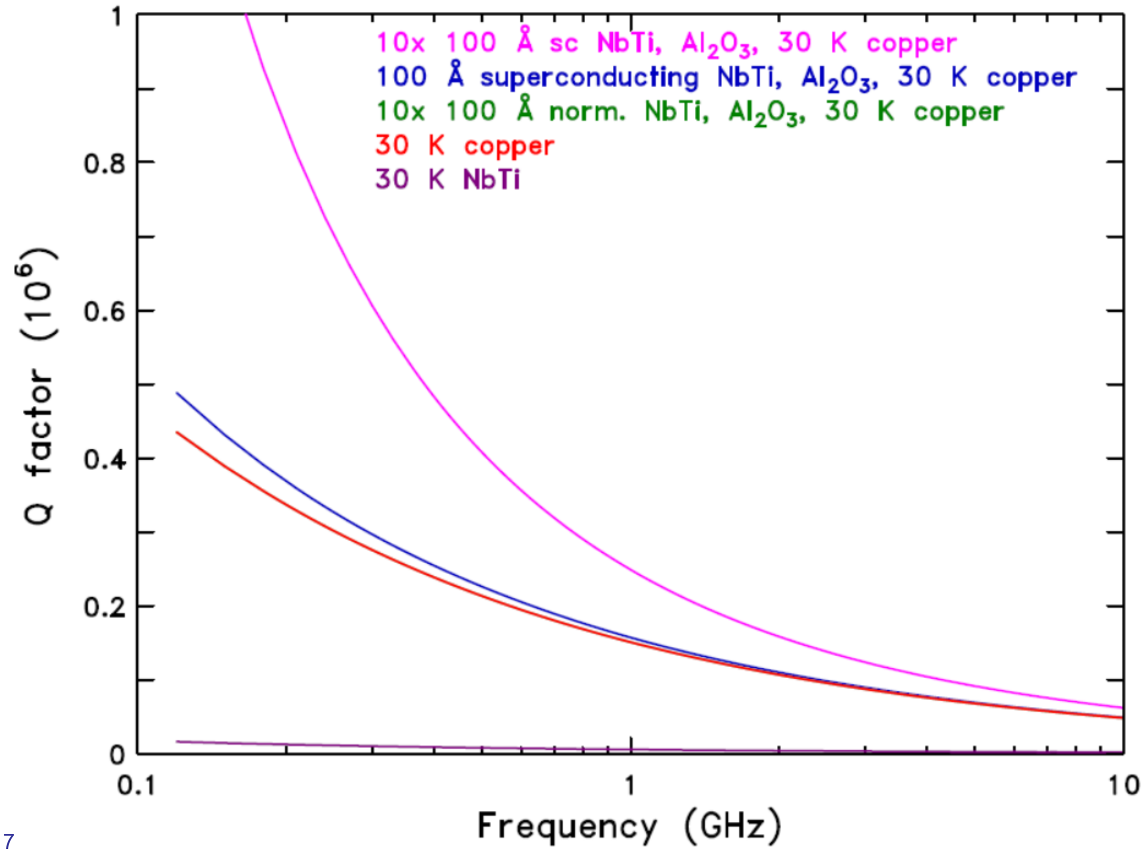
Q for multilayer NbTi on copper

- Height = 1 m. Radius = 0.25 m.

$$Q = \frac{4}{\mathscr{A}}.$$

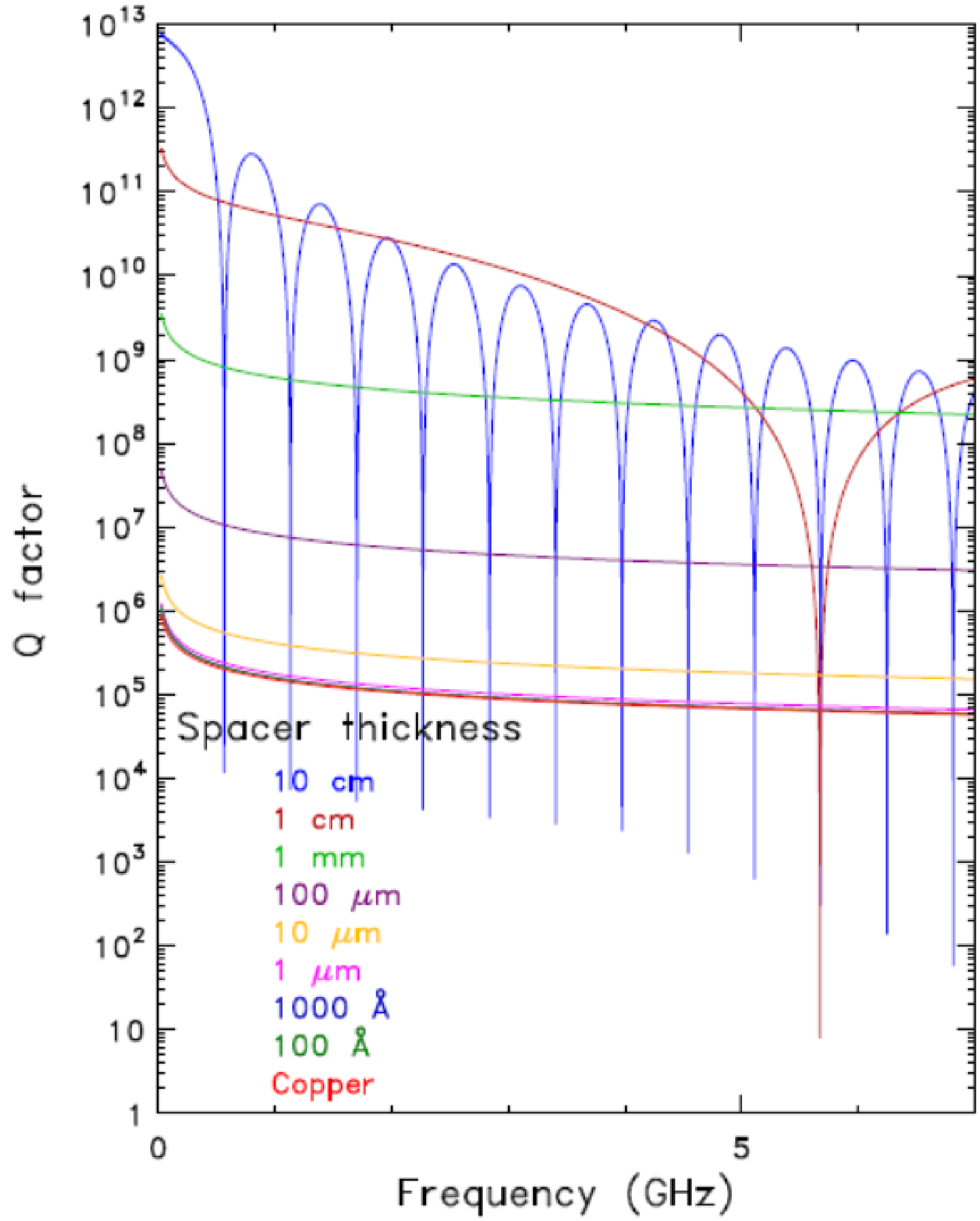
- Use this for both copper cavity and coated cavity.
- From the point of view of the loss of stored energy, there is no difference between a homogeneous wall and a layered wall.



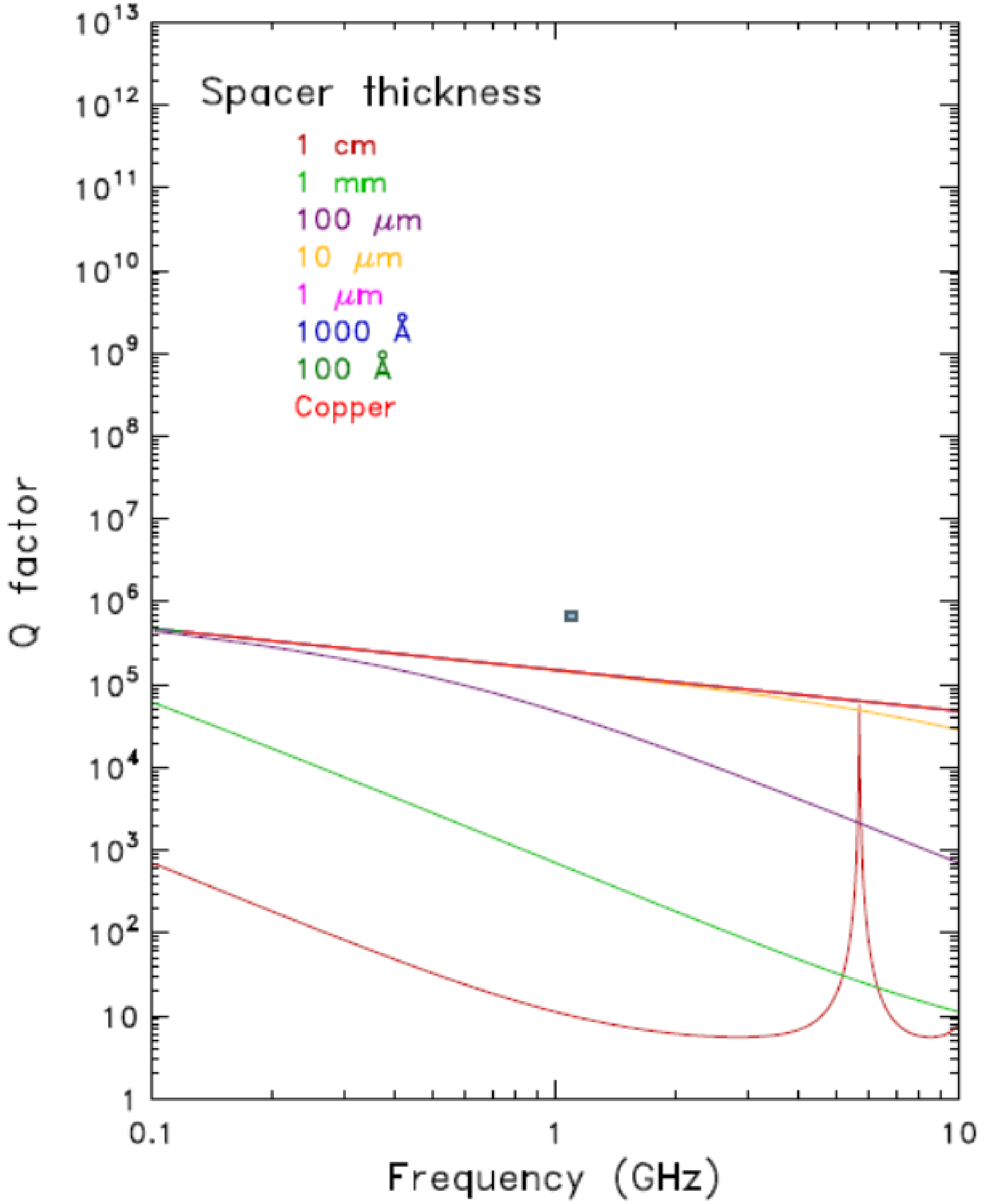
ADMX

Must make insulator *thick* ~ $\lambda/4n$

- *Single* NbTi layer
- Al_2O_3 spacer
- Dips when optical thickness of Al_2O_3 is $\lambda/2n$
  - n is the refractive index
- 1 mm is enough; $Q = 10^9$
  - 100 μm is probably OK, but who can fabricate a 50 cm diameter 1 m long cylinder with 100 μm walls?



Don't want NbTi to go normal!



ADMX

Now, the endcaps. Can't be NbTi!

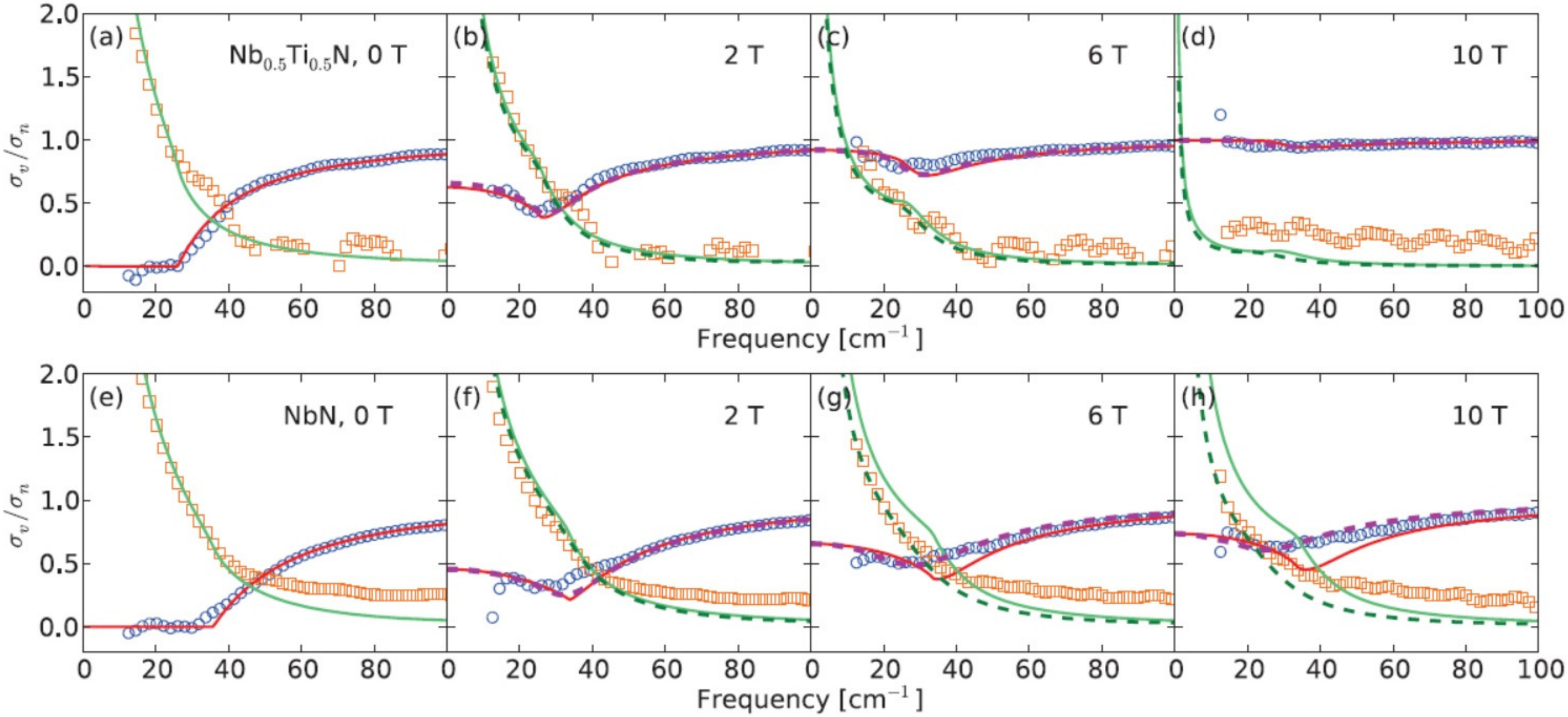


FIG. 2. (Color online) Real (circles) and imaginary (squares) part of the vortex-state optical conductivity σ_v for $Nb_{0.5}Ti_{0.5}N$ and NbN, normalized to the normal-state conductivity σ_n. The solid lines are MGT fits using Mattis-Bardeen theory for the superconducting host component and Drude theory for the normal cores (inclusions). The dashed lines are fits where the superconducting host component also includes pair-breaking effects.

- Xi et al. PRB 87, 184503 (2013).
- Superfluid (measured by σ_2) becomes small

End caps of copper

- Q of a cylindrical cavity (Jackson)

$$Q = \frac{V}{S\delta}(\text{Geometrical Factor}),$$

- Geometrical Factor is a mode independent number of order unity. It $= 2$ for TM_{010}
- $V = \pi R^2 H$. $S = 2\pi R^2$.

$$Q_e = \frac{H}{\delta}.$$

- $H = 4.4R$ to get

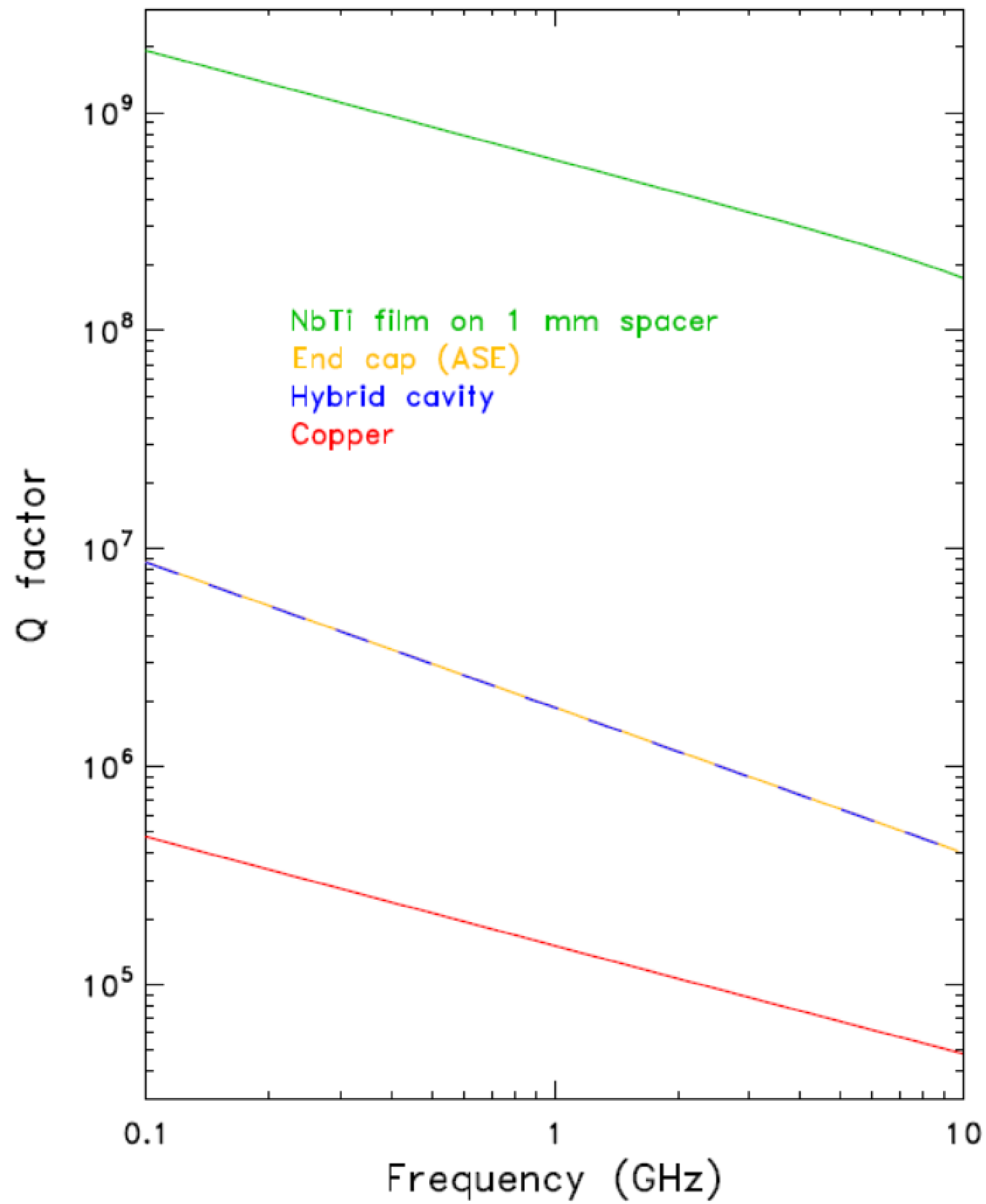
$$Q_e = \frac{21.2}{\mathscr{A}}.$$

For ASE $\delta \sim f^{-1/3}$ and $\mathscr{A} \sim f^{2/3}$. Then

$$Q_e = 1.9 \times 10^6 \left(\frac{f}{1\ \text{GHz}}\right)^{-2/3}.$$

Copper end cap, NbTi wall

- $1/Q = 1/Q_w + 1/Q_e$
- End caps are all (actually 99%)
- Factor of 10x in Q
- Factor of 10x in P
- Factor of 100x in scan rate



Requirements

- Superconducting thin film must have an upper critical field higher than the operating field of the detector.
  - NbTi or NbTiN the likely choices.
  - A-15 superconductors, such as V3Si and Nb3Sn ??
- Film must be thin, less than the spacing between vortices in the superconductor.
  - The areal density n of vortices is $n = B / \Phi_0$
  - Average spacing is of order $a = \sqrt{1/n}$ or ~ 16 nm in 8 T .
- Magnet must have the field lines are parallel to the cavity walls. \
- Superconductor must be coated on the inside of a mm-thick insulating cylinder
  - Fits inside thick copper or copper-plated cavity walls.
  - Must be a method to ensure that the normal-metal endcaps make good electrical contact to the copper outer wall and the superconducting coatings

Summary and conclusions

- Hybrid cavities are plausible.
- But not by coating the copper directly
- Need ~mm size spacer
- Exact spacer thickness not critical
- 10x increase in power available this way