Superconducting YBCO microwave cavity in a high magnetic field for axion dark matter search

Danho Ahn,[1,2] Ohjoon Kwon,[1] Sung Woo Youn,[1] Wonjun Jang,[3] Jhinhwan Lee,[4] Woohyun Chung,[1] Dojun Youm,[2] Yannis K. Semertzidis.[1,2]

[1]Center for Axion and Precision Physics, Institute of Basic Science, Daejeon 34141, Repulic of Korea

[2]Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea

[3]Center for Quantum Nanoscience, Institute of Basic Science, Seoul 33760, Republic of Korea

[4]Center for Artificial Low Dimensional Electronic Systems, Institute of Basic Science, Seoul 33760, Republic of Korea

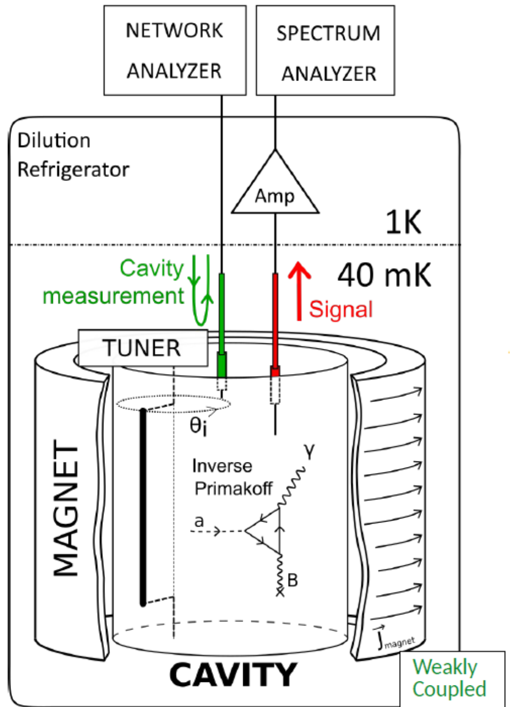
Outline

- Motivation and Goal
  - ✓ Axion Dark Matter Search with Tunable Resonant Cavity
  - ✓ Superconductivity in DC Magnetic Field

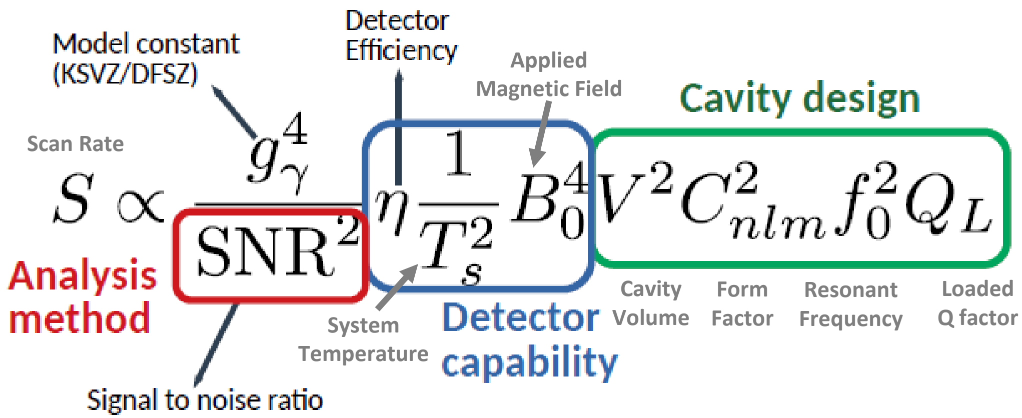
- High Temperature Superconducting (HTS) Cavity Prototype
  - ✓ Yttrium Barium Copper Oxide (YBCO)
  - ✓ 3 Dimensional HTS Cavity with YBCO Tape
  - ✓ Fabrication / Cavity Design
  - ✓ Measurement and Discussion

- Summary

Axion Search with Tunable Resonant Cavity



Simplified depiction of detection mechanism.



$$S \propto \frac{g_\gamma^4}{\mathrm{SNR}^2}\eta \frac{1}{T_s^2} B_0^4 V^2 C_{nlm}^2 f_0^2 Q_L$$

Caglar Kutlu *et al*, "First Results from CAPP-PACE" (2019).

Q factor: $$Q_0 = \omega \frac{U}{P_{loss}} \propto \frac{1}{R_s}$$

(U: Total Energy; P_{loss}: Dissipation; R_s: Surface Resistance)

Superconducting cavity can be a solution for high Q

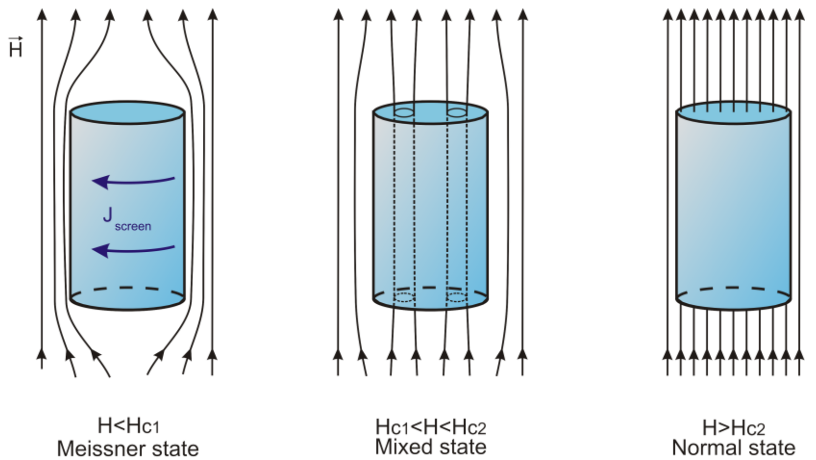
	CAPP (2018)	ADMX (2016)	HAYSTAC (2018)	Maximum
Q_L	3×10^4	$\sim 1 \times 10^5$	3×10^4	**1×10^6 (axion)**
B_0	8 Tesla	9 Tesla	9 Tesla	**> 25 Tesla**

P. W. Graham *et al*, "Experimental Searches for the Axion and Axion-like Particles," (2016).
B. M. Brubaker, "First Results from the HAYSTAC Axion Search," (2018).

Superconductivity in DC Magnetic Field

Three Phases of Type II Superconductor

https://www.cee.elektro.dtu.dk/news/nyhed?id=E6796539-A36B-4CA5-BC31-CBDBBCA335D8



Material	Crystal structure	Anisotropy	T_c (K)	H_{c2}
Nb47wt%Ti	Body-centred cubic	Negligible	9	12 T (4 K)
Nb_3Sn	A15 cubic	Negligible	18	27 T (4 K)
MgB_2	*P6/mmm* hexagonal	2–2.7	39	15 T (4 K)
YBCO	Orthorhombic layered perovskite	7	92	>100 T (4 K)
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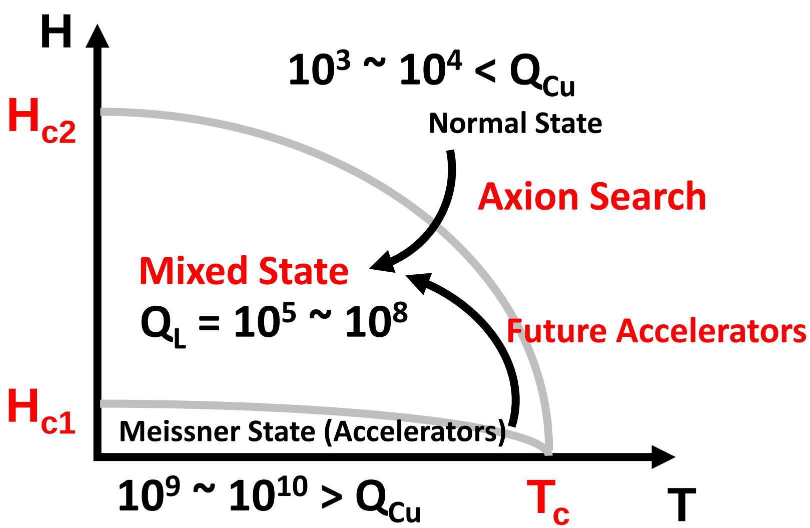
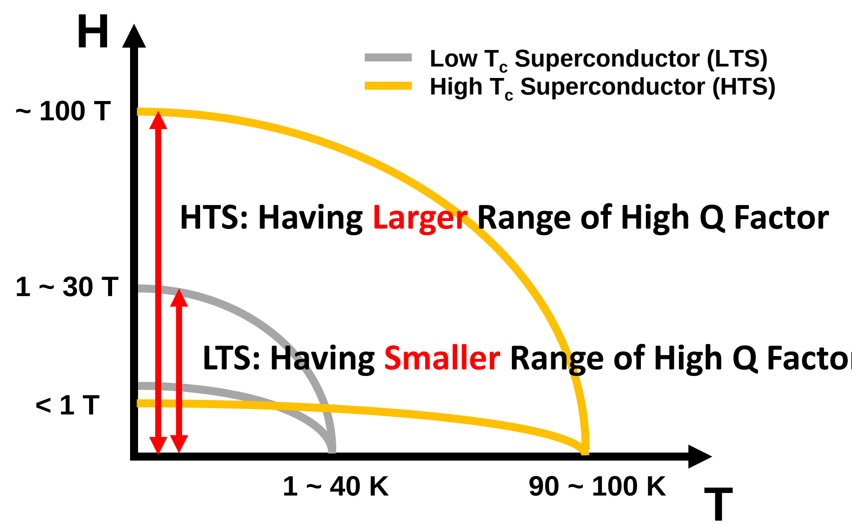
D. C. Larbalastier *et al*, "High-T_c superconducting materials for electric power applications," Nature (2001).





Superconductivity in DC Magnetic Field

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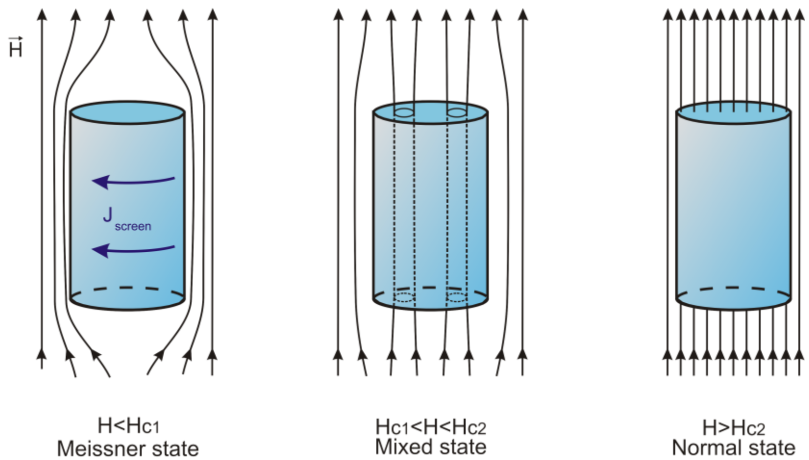

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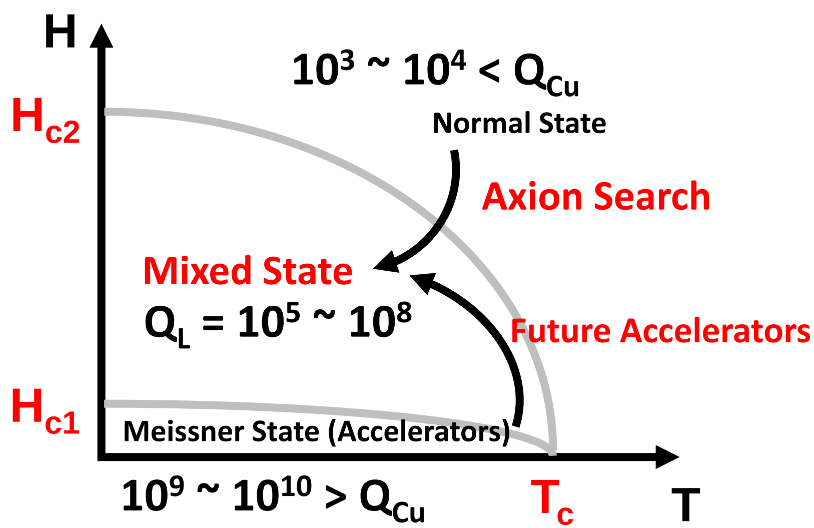
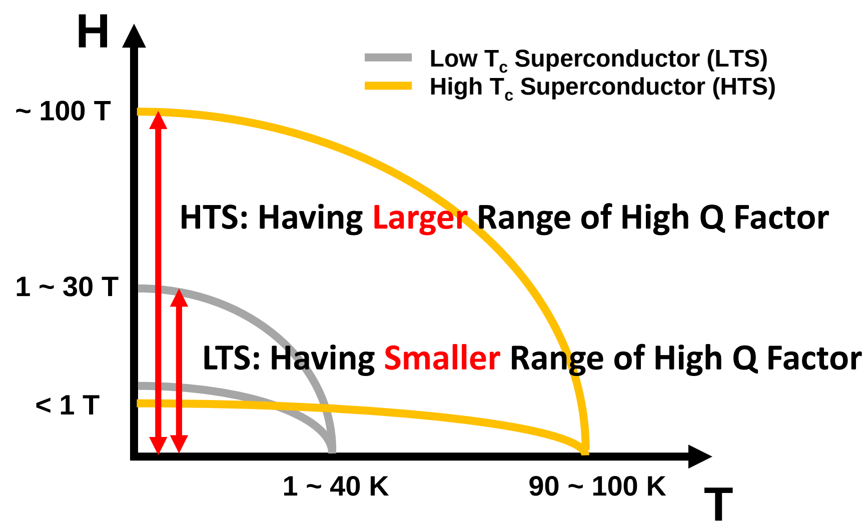
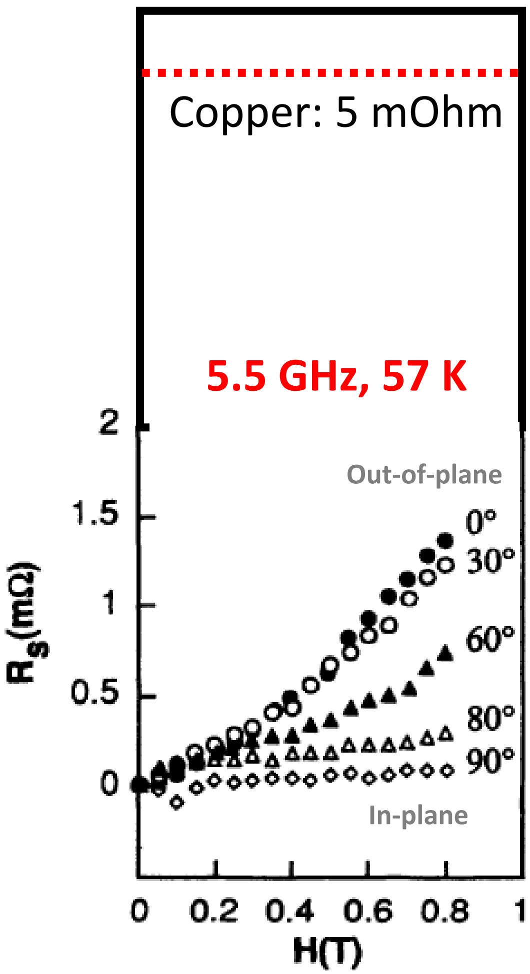




Let's evaluate well-studied YBCO film!

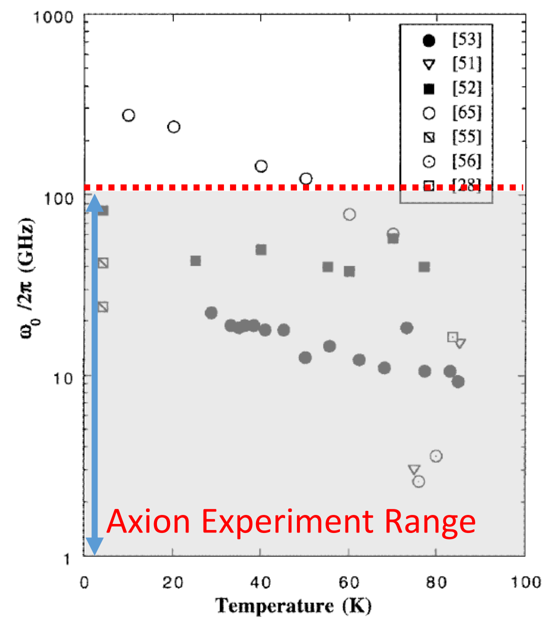
Are $YBa_2Cu_3O_{7-x}$ Films Good for Axion Search?

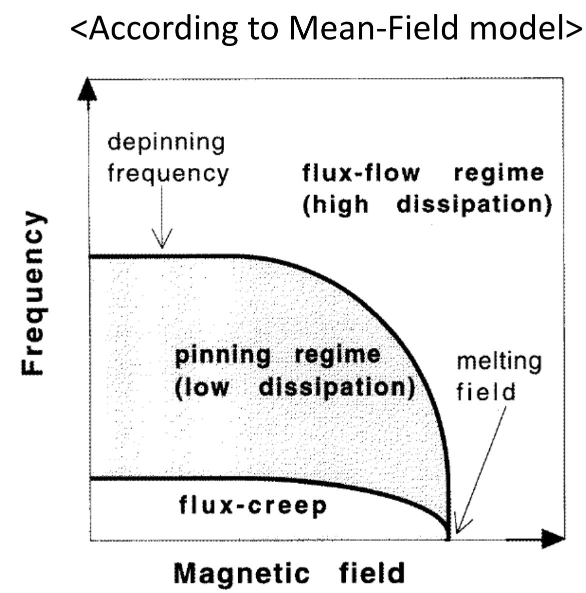
Surface Resistance (R_s)



M. Golosovsky *et al*, "Vortex depinning frequency in YBCO superconducting thin films," Phys. Rev. B (1994).

Depinning Frequency





M. Golosovsky *et al*, "High-frequency vortex dynamics in YBCO," Supercond. Sci. Technol. (1996).

The experiments say 'YES'

Why there is no practical YBCO microwave cavity?

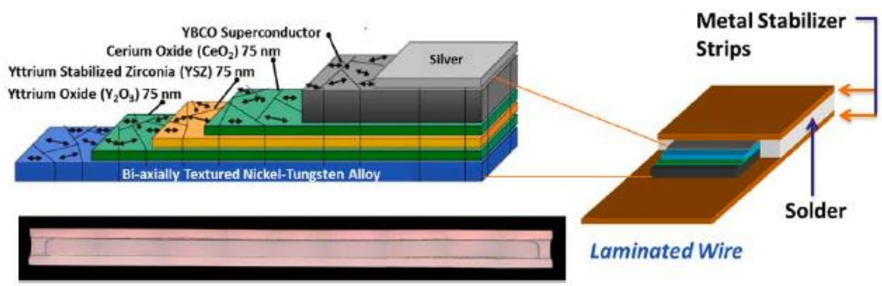
Impossibility of Biaxially Textured Cavity Surface

There is no method to implement biaxially textured film on the curved geometry.

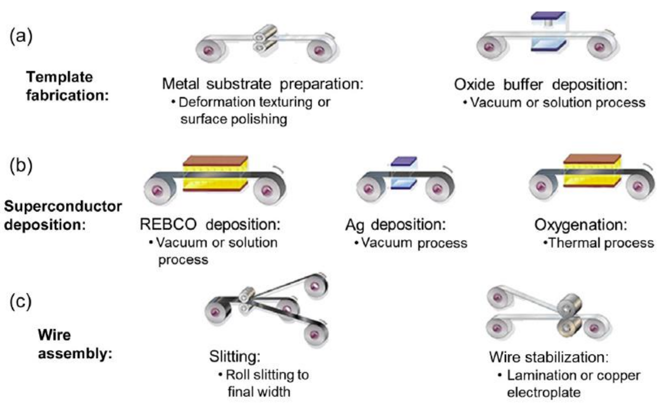
- Biaxially textured = Grains are aligned
  a, b crystal direction

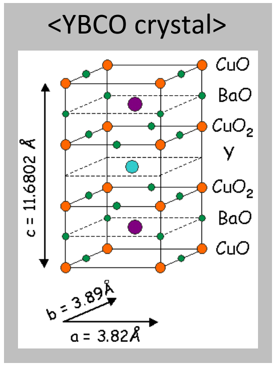
✓ RABiTs: YBCO, AMSC, 10mm width
✓ IBAD: ReBCO, Superpower

<Rolling-Assisted, Biaxially Textured Substrate (RABiTS) Method>



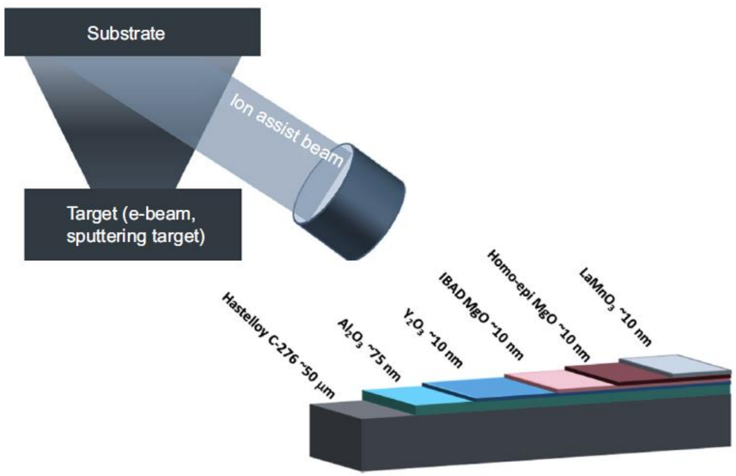
M. W. Rupich *et al*, "Second Generation Wire Development at AMSC," IEEE (2013).





C. Rey *et al*, "Superconductors in the Power Grid," Woodhead Publishing (2015).

<Ion Beam-Assisted Deposition (IBAD) Method>



C. Rey *et al*, "Superconductors in the Power Grid," Woodhead Publishing (2015).

How can we make 3D surface with planar objects?

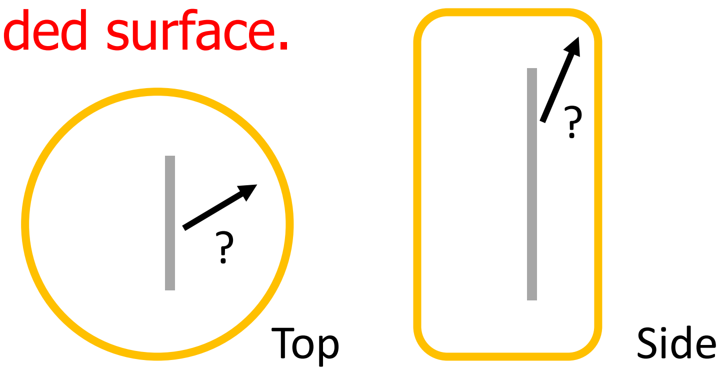
CAPP's Solution

- **Attaching HTS tape on the cavity inner surface.**

- Bulk HTS microwave cavity is not available.
  - ✓ Growing well-textured HTS film on 3D surface is not available.

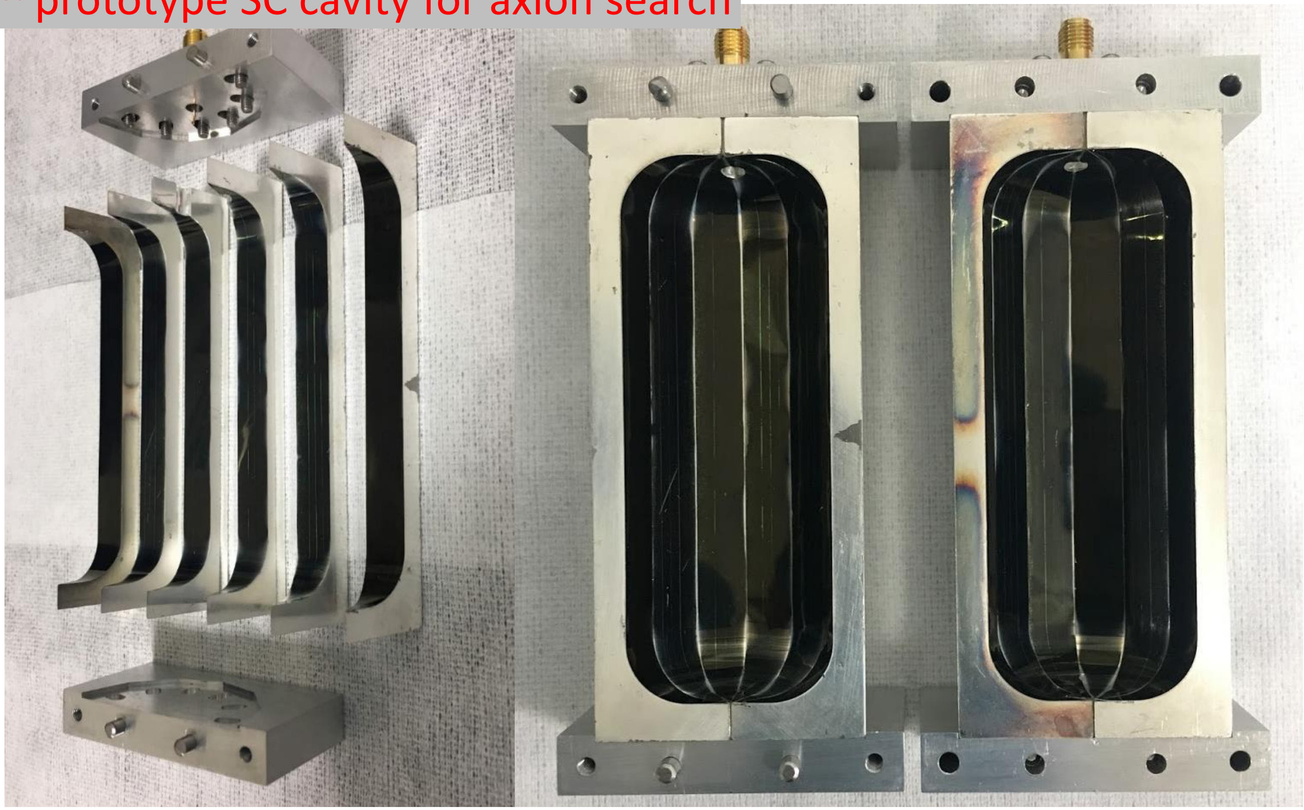
- Many HTS tapes available in market.
  - ✓ RABiTs: YBCO, AMSC, 10mm width
  - ✓ IBAD: ReBCO, Superpower

- How can we attach tape on the cavity inner surface?
  - ✓ Planar object does not fit to the rounded surface.



Prototype Cavity

1st prototype SC cavity for axion search



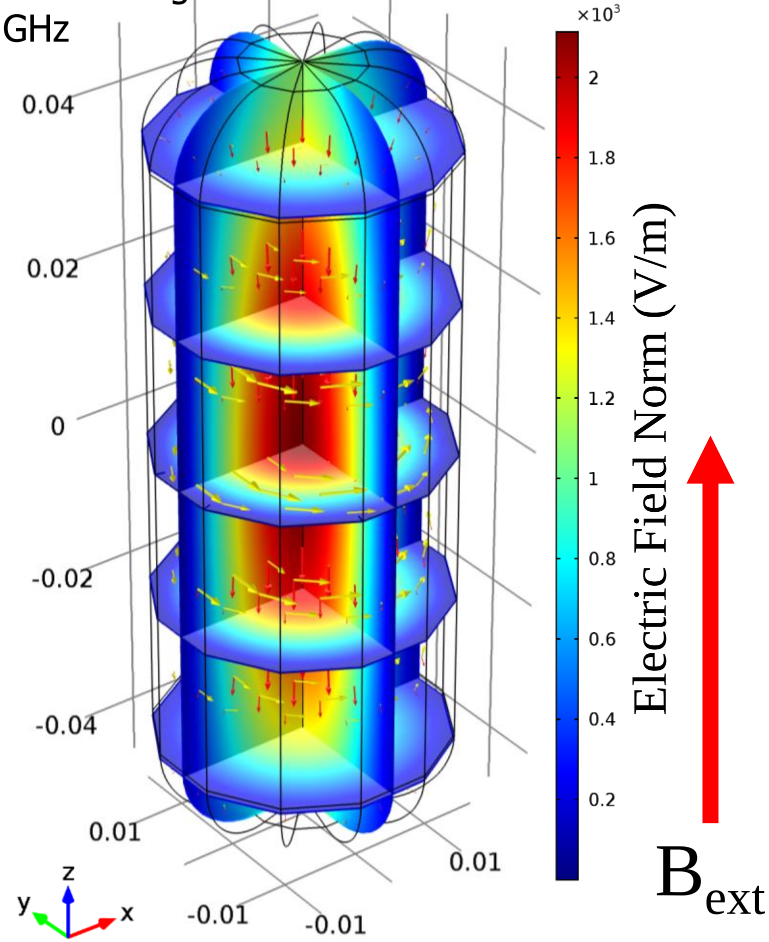
- Attach YBCO tape on the cavity inner surface with epoxy.
- Cut edges exposed on the sides and polish the sides.
- Remove the silver protective layer.
- Sputter silver on the side of the tape. (Ni-9W may cause large loss)

The Advantages of the Polygon Cavity

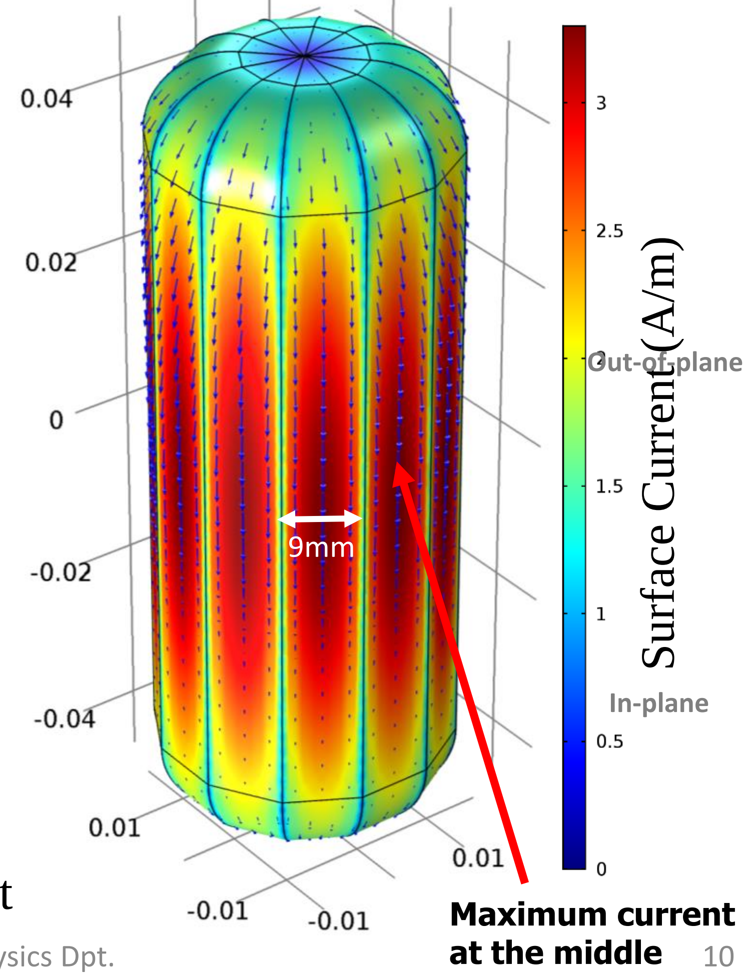
Polygon Shape: Planar surface
Vertical Cut: Avoiding Contact Problem

- ✓ Polygon cavity have been invented.
- ✓ COMSOL simulation confirms the cavity works fine with TM_{010} mode.

- ➢ Electric and Magnetic Field
- ➢ 6.85 GHz



- ➢ Surface Current



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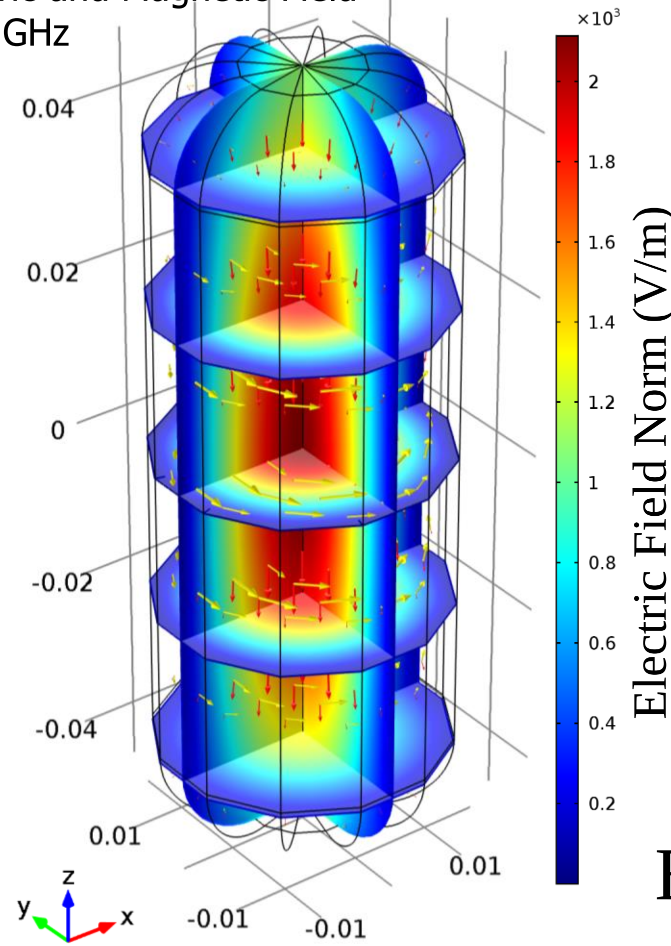

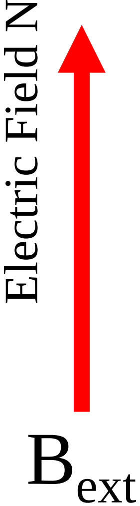

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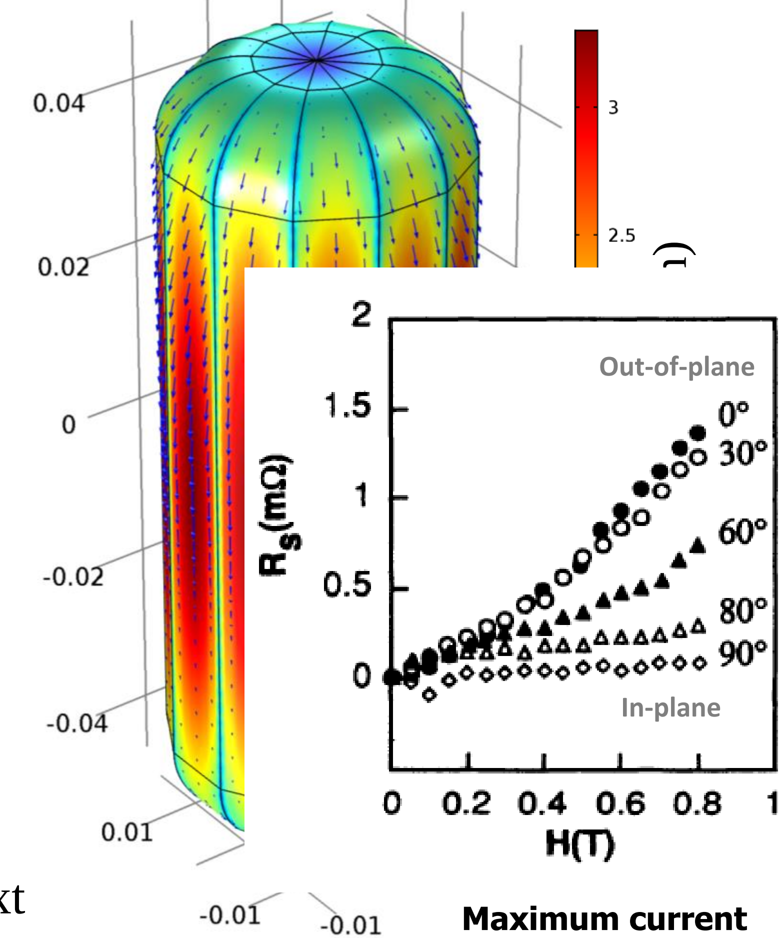
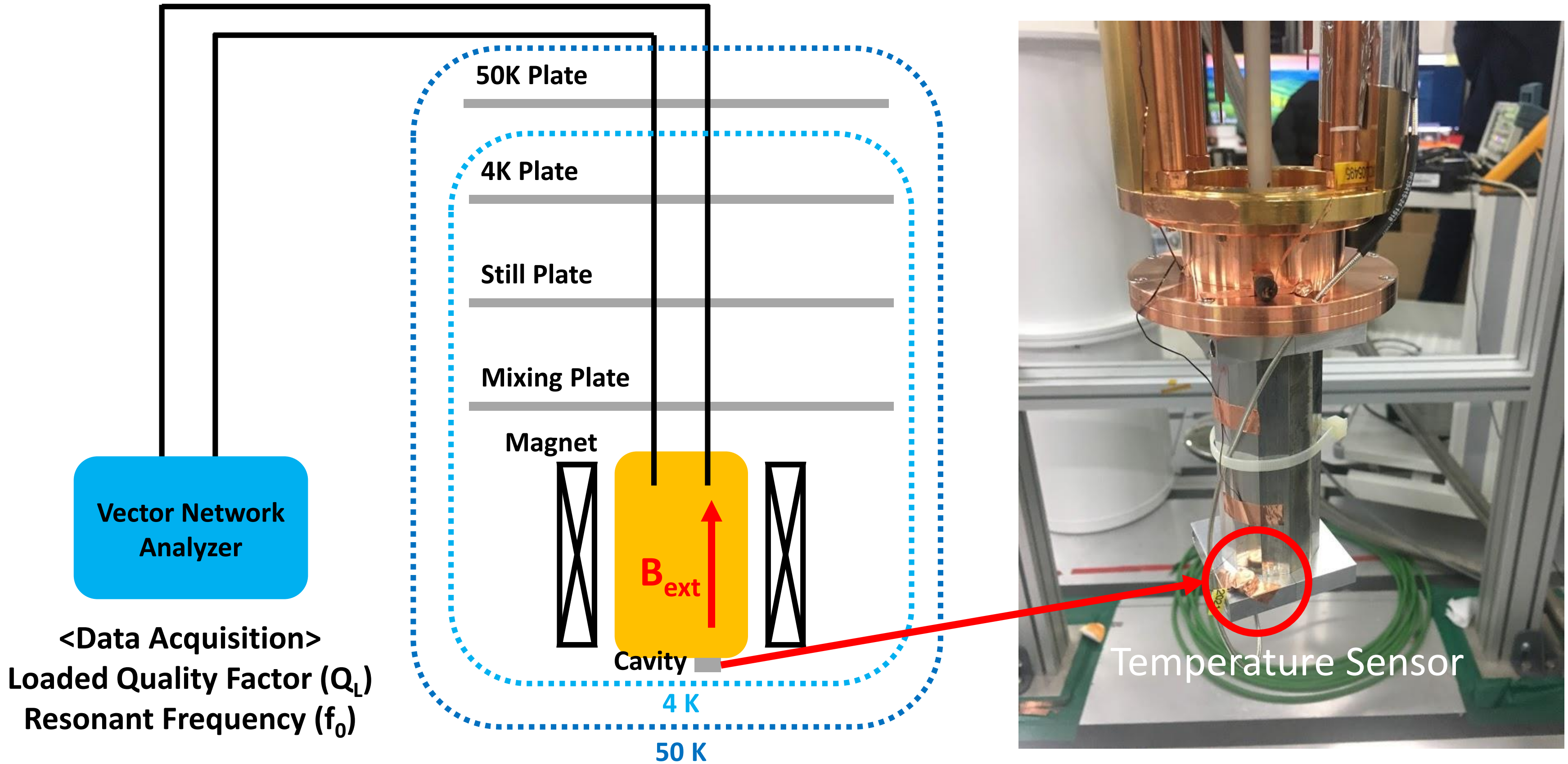


Maximum current at the middle

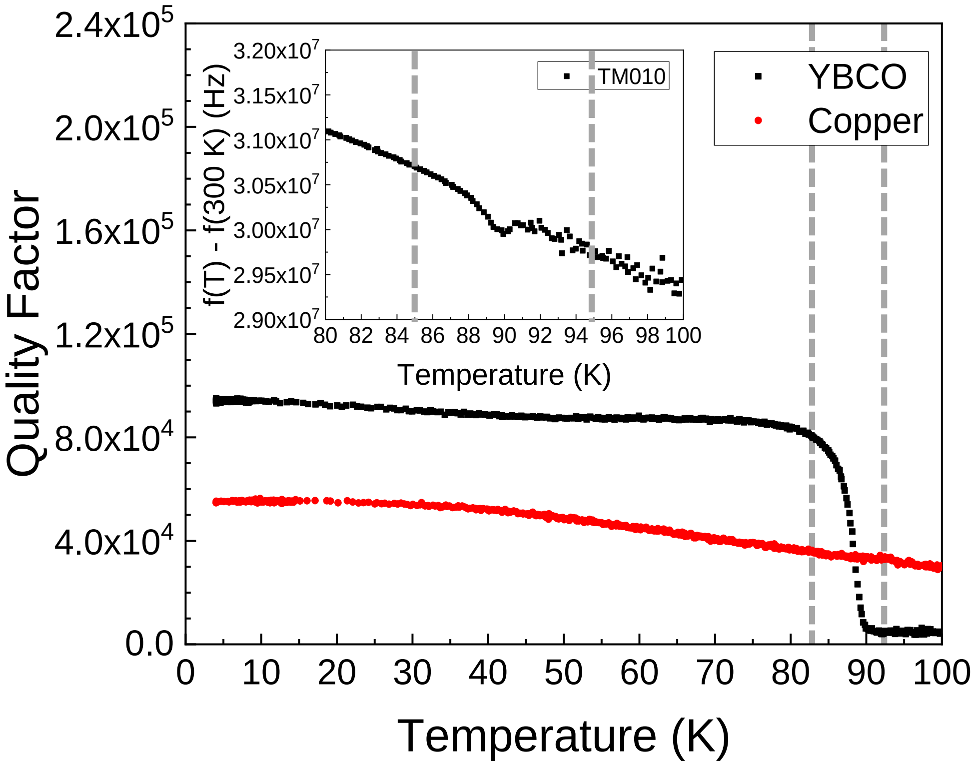
Measurement



- Weak coupling: $Q_L \sim Q_0$
- Temperature measurement: 300 - 4 K.
- Magnetic field measurement: 0 - 8 T (4 K)

Cavity Characterization (1): Temperature

D. Ahn *et al*, "Maintaining high Q-factor of superconducting YBa2Cu3O7−x microwave cavity in a high magnetic field," arXiv1904.05111 (2019).



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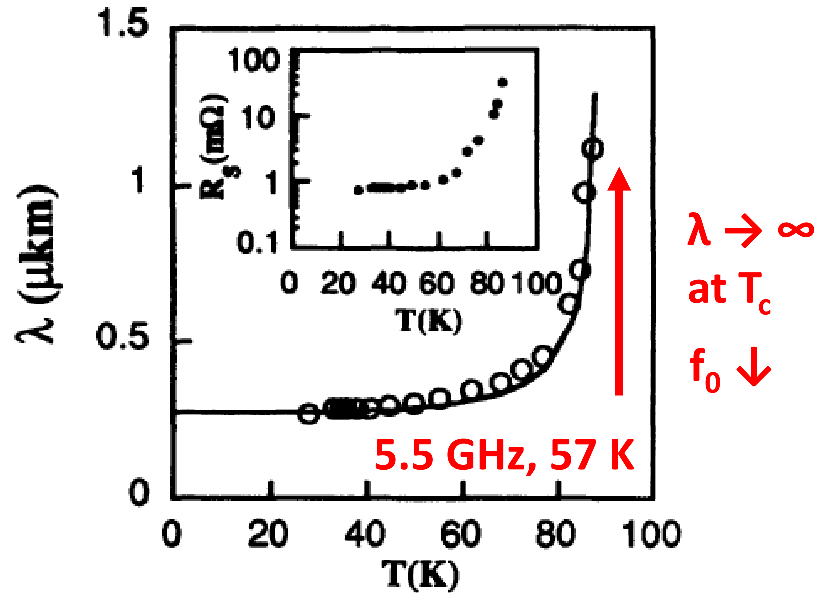
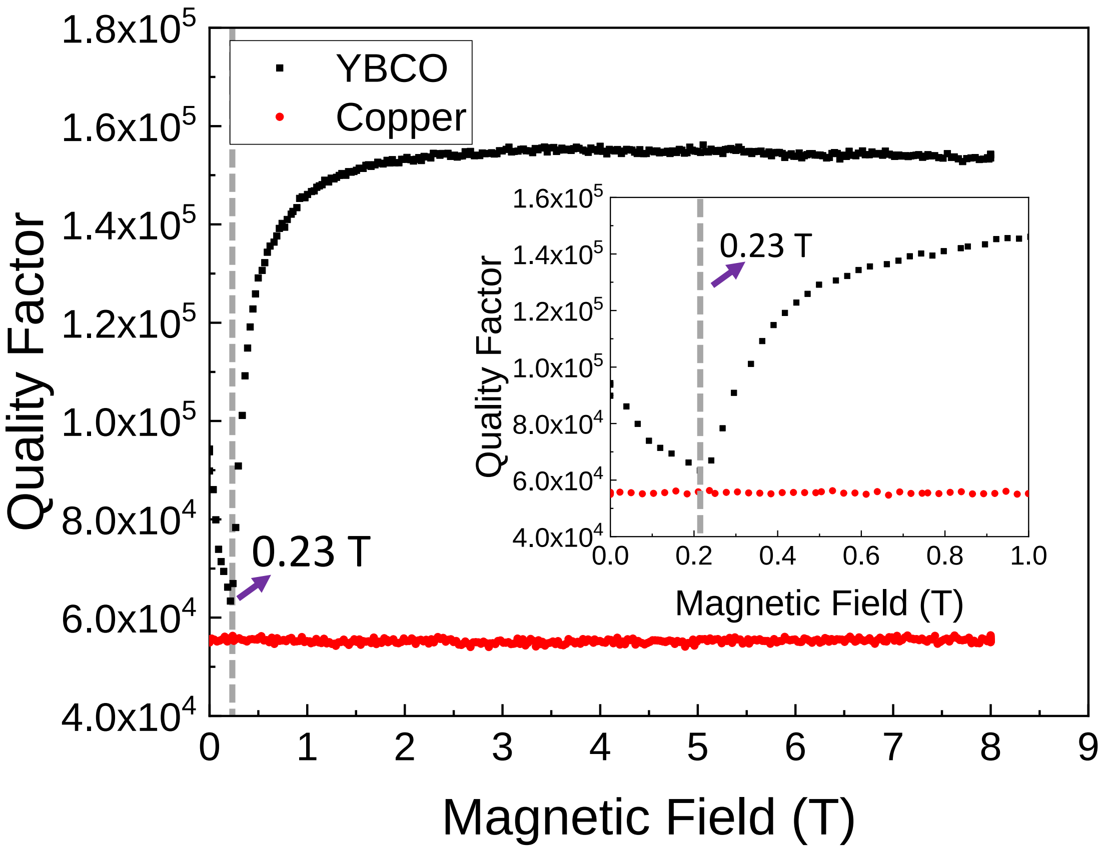


FIG. 2. Temperature dependence of the penetration depth λ of a pair of laser-ablated $YBa_2Cu_3O_{7-x}$ films at $f = 5.4$ GHz calculated from Eq. (6). The solid line is the two-fluid dependence $\lambda = \lambda_0[1-(T/T_c)^4]^{-1/2}$ with $T_c = 89$ K and $\lambda_0 = 0.27$ μkm. Inset shows temperature dependence of the surface resistance R_s.

- Transition temperature = 90 K
- Anomalous resonance frequency drop at 90 K
- Q factor of YBCO Cavity (4 K) = 95,000.
- Q factor of Copper Cavity (4 K) = 56,500.

Cavity Characterization (2): Magnetic Field



D. Ahn *et al*, "Maintaining high Q-factor of superconducting YBa2Cu3O7−x microwave cavity in a high magnetic field," arXiv1904.05111 (2019).

- Q factor at 0.23 T = 60,000
- Maximum Q at 3.5 T = 155,000
- $Q_{YBCO} \sim 3 \times Q_{cu}$

Why the quality factor increased suddenly?

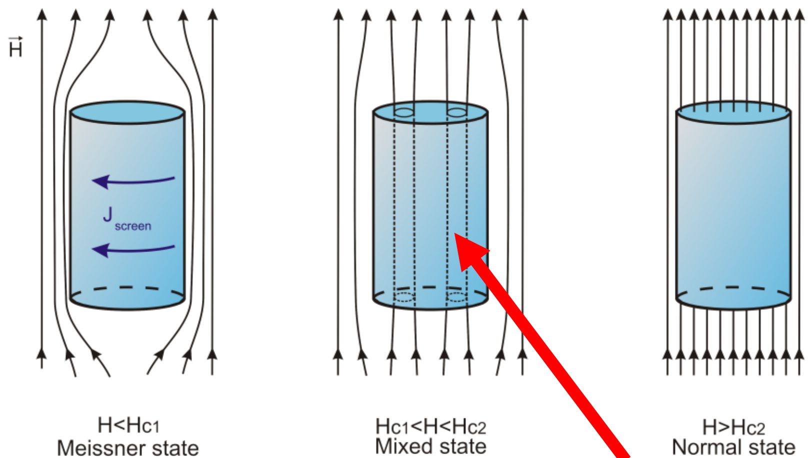
Main Loss?

$$\frac{1}{Q} = \frac{P_{YBCO\,film} + P_{etc}}{\omega U_{tot}}$$

Superconductivity in the DC Magnetic Field

Three Phases of Type II Superconductor

https://www.cee.elektro.dtu.dk/news/nyhed?id=E6796539-A36B-4CA5-BC31-CBDBBCA335D8



Vortex Vibration!

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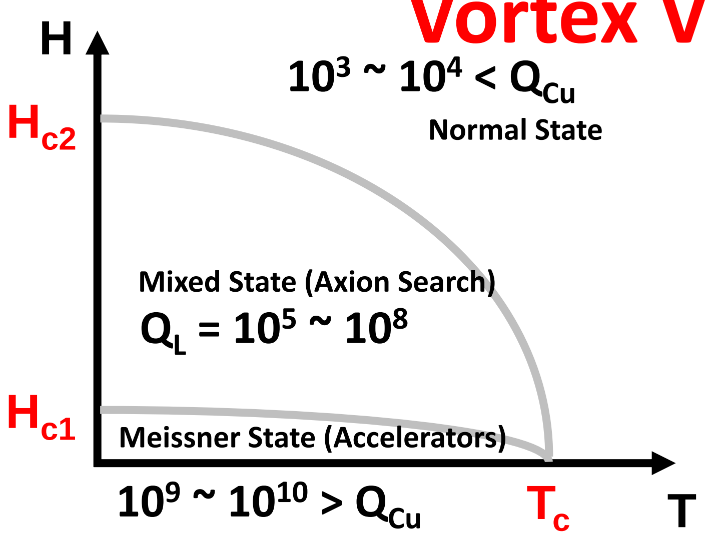
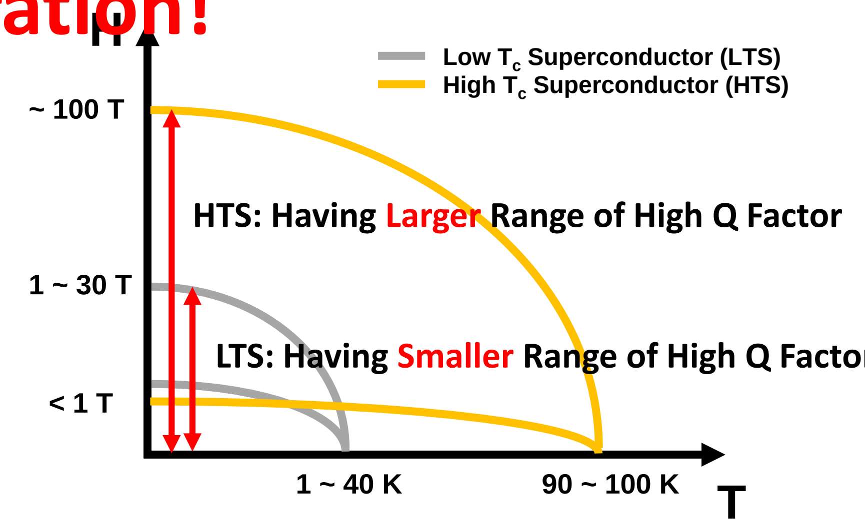
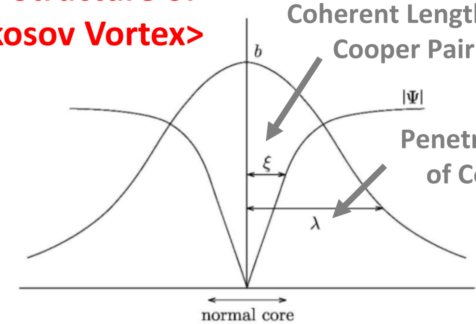




Vortex Vibration Makes Energy Loss

- In high magnetic field, vortices are the another source of the RF power dissipation.
  - ✓ Type II superconductors have mixed state which contain Magnetic Vortices.
  - ✓ Vortex vibration add another power loss which makes Q-factor degradation.
  - ✓ **Vortex pinning is essential** to prevent Q-factor reduction.

<The Structure of Abrikosov Vortex>



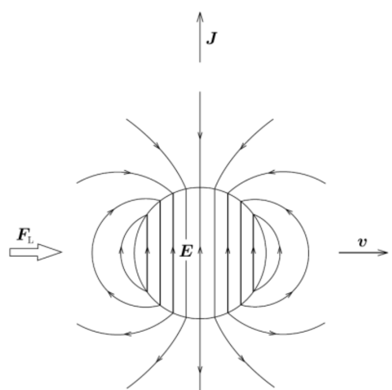
If κ ($\equiv \lambda/\xi$) is less than $1/\sqrt{2}$, the vortex cannot be formed.

In case of free vortices

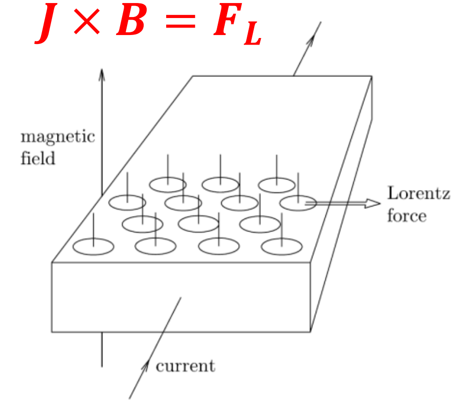
Resistivity from vortex vibration

$$\rho_f = \left[\frac{\dfrac{B}{\mu_0 H_{c2}}}{1+\dfrac{B}{\mu_0 H_{c2}}}\right]\boldsymbol{\rho_n}$$

Resistivity of Normal State **(Large)**



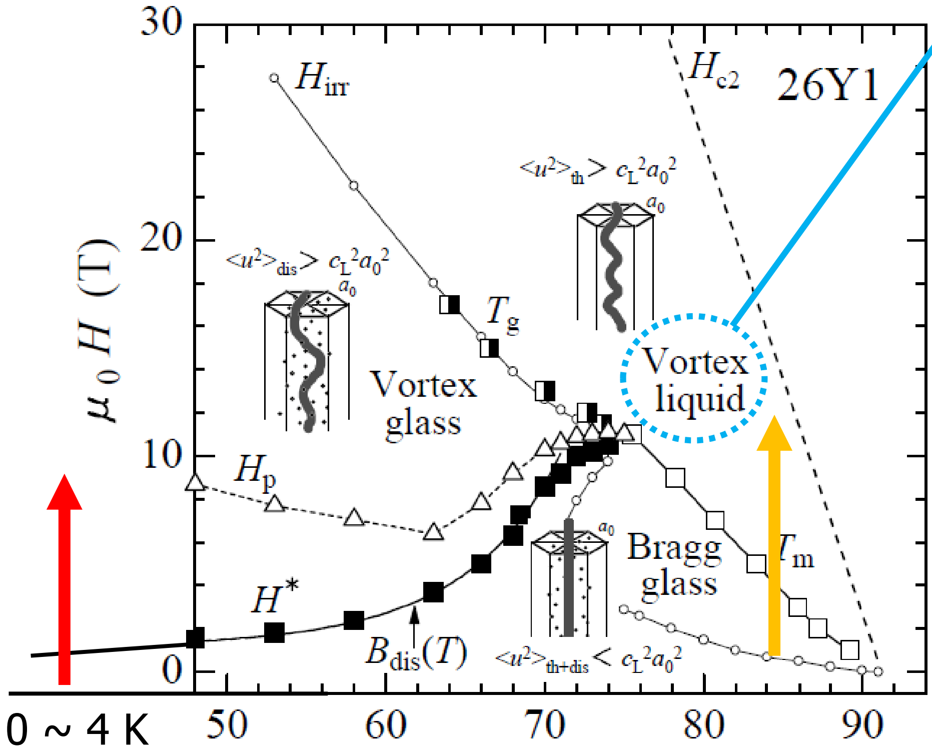
$$\boldsymbol{J \times B = F_L}$$



Teruo Matsushita, "Flux Pinning in Superconductors," Springer (2019).

Vortex Phase and Vortex Pinning

T. Nishizaki *et al*, “Vortex-matter phase diagram in YBa2Cu3Oy,” Supercond. Sci. Tehnol. (2000).



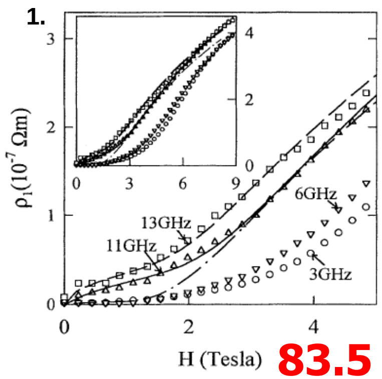
$H^*_{untwinned} > H^*_{heavy\text{-}twinned}$

Figure 7. The vortex-matter phase diagram in untwinned $YBa_2Cu_3O_y$. The transition lines $T_m(H)$, $T_g(H)$, and $H^*(T)$ terminate at the critical point and divide into three different phases of the vortex liquid, the vortex glass, and the Bragg glass. The full curve is a fit to the field-driven transition line $B_{dis}(T)$.

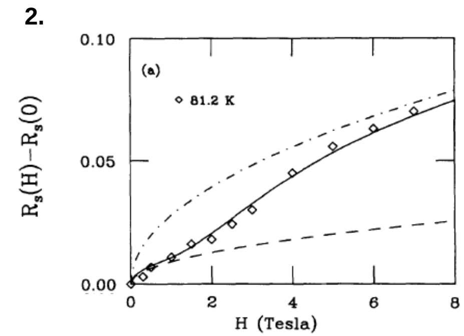
The mean-field model does not work in the vortex liquid

(Experiments)

1. J. Owaliaei *et al*, “Field-Dependent Crossover in the Vortex Response at Microwave Frequencies in YBa2Cu3O7-δ Films,” PRL (1992).
2. D. H. Wu *et al*, “Frequency and Field Variation of Vortex Dynamics in YBazCu3O7-δ,” PRL (1995).



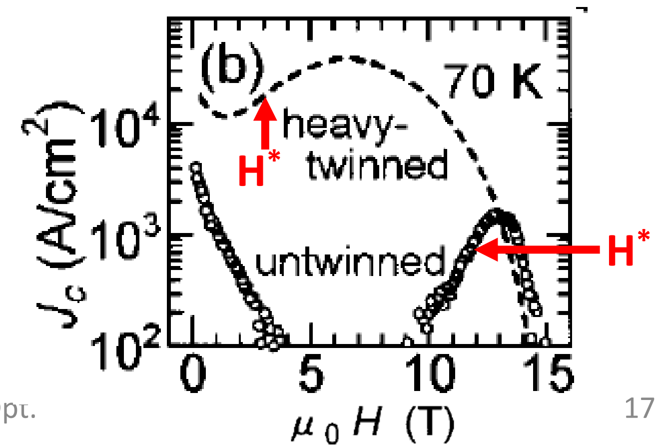
83.5 K



81.2 K

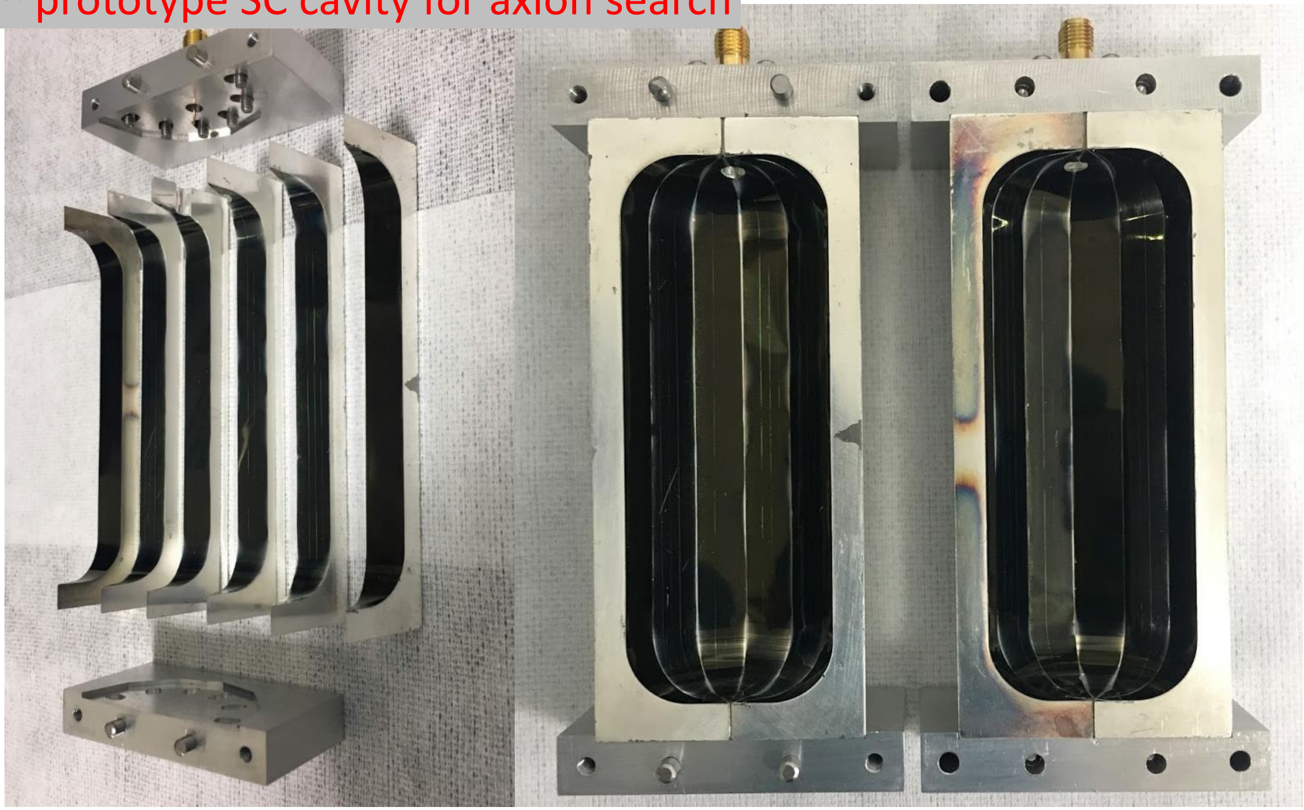
(Theoretical Works: Scaling Model)

1. D. S. Fisher *et al*, “Thermal fluctuations, quenched disorder, phase transitions, and transport in type-II superconductors,” PRB (1991).



The Other Possible Source of Energy Loss

1st prototype SC cavity for axion search



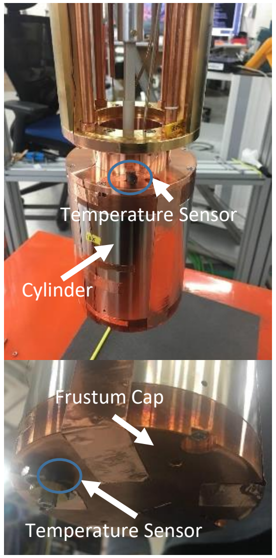
- Silver film was deposited on the cavity inner surface.
- The nickel-tungsten alloy was exposed.
- **We can improve the maximum quality factor in future**

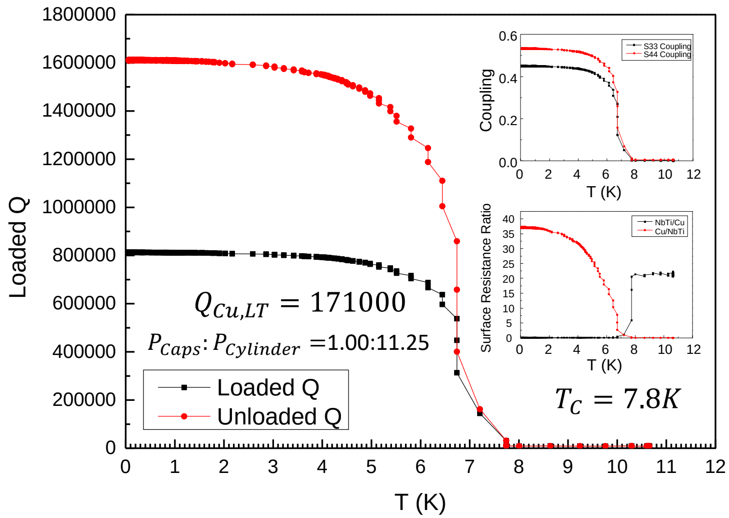
Summary

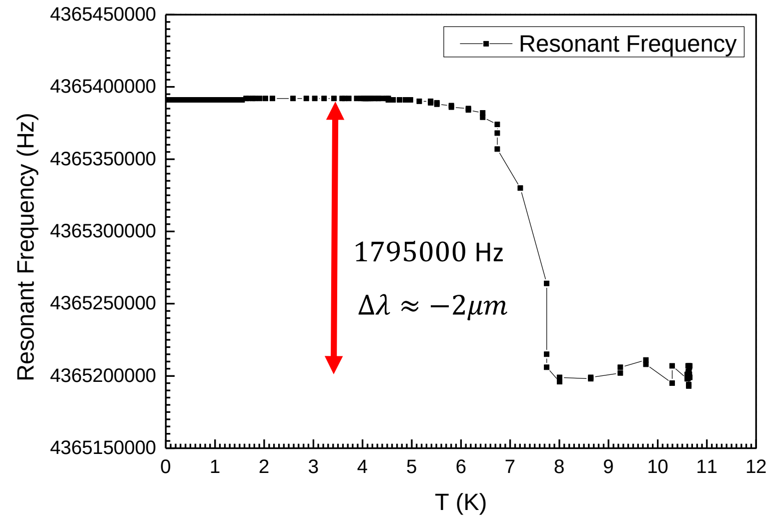
- In the axion search, making a high Q cavity in high magnetic fields is important technical issue.
- High-temperature superconductors are promising material for high Q cavities in high magnetic field.
- Yttrium Barium Copper Oxides (YBCO) satisfies the conditions which we need.
- To implement 3 dimensional structure of the YBCO, we designed the polygon cavity, and attached the tapes on the inner surface.
- The Q factor of YBCO cavity was characterized as **3 times higher** than the copper cavity at a high magnetic field.
- Furthermore we are going to enhance the maximum Q factor of the cavity, and uncover the mechanism of anomalous Q factor behavior at a high field. (>0.23 T)

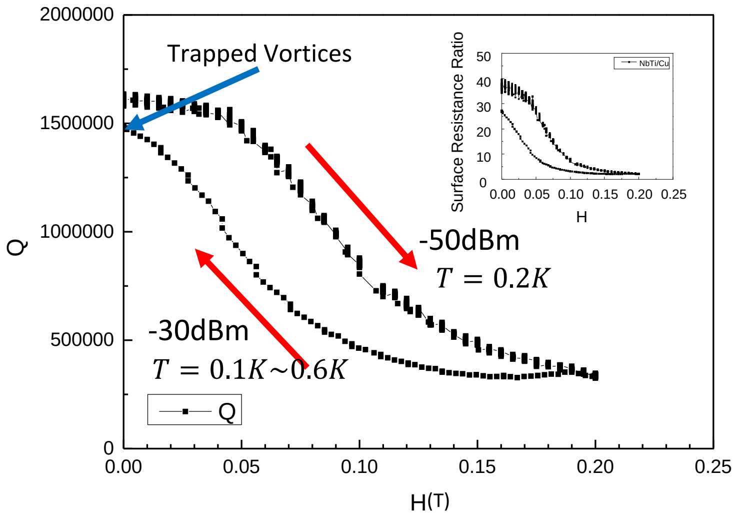
Thank you

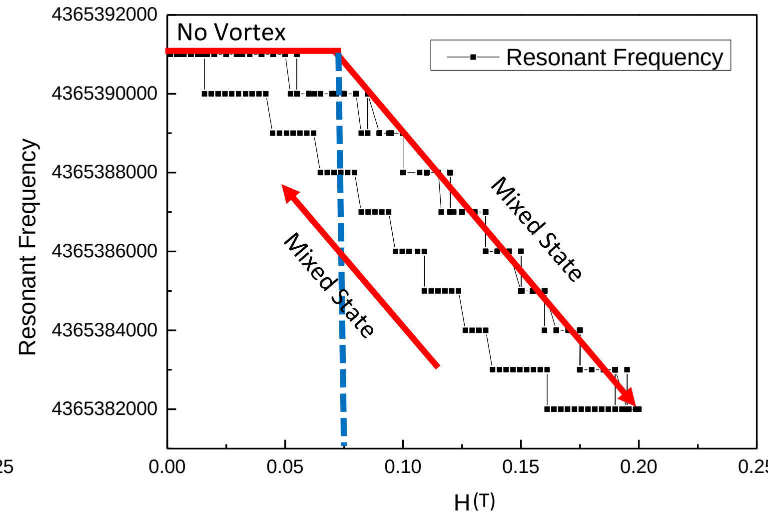
Niobium Titanium Film











Superconducting Radio-Frequency Cavity

SCIENTIFIC REPORTS

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Tunable Superconducting Cavity using Superconducting Quantum Interference Device Metamaterials

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Samuel Kim[1,2], David Shrekenhamer[1], Kyle McElroy[1], Andrew Strikwerda[1] & Jacob Alldredge[1]

Here we consider a tunable superconducting cavity that can be used either as a tunable coupler to a qubit inside the cavity or as a tunable low noise, low temperature, RF filter. Our design consists of an array of radio-frequency superconducting quantum interference devices (rf SQUIDs) inside a superconducting cavity. This forms a tunable metamaterial structure which couples to the cavity through its magnetic plasma frequency. By tuning the resonant frequency of the metamaterial through an applied magnetic flux, one can tune the cavity mode profile. This allows us to detune the cavity initially centered at 5.593 GHz by over 200 MHz. The maximum quality factor approaches that of the empty cavity, which is 4.5×10^6. The metamaterial electromagnetic response is controlled via a low-frequency or dc magnetic flux bias, and we present a control line architecture that is capable of applying sufficient magnetic flux bias with minimal parasitic coupling. Together this design allows for an *in-situ* tunable cavity which enables low-temperature quantum control applications.

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Topical Review

50 years of success for SRF accelerators—a review

Hasan Padamsee

Cornell University, Ithaca, NY 14850, United States of America

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CrossMark

Abstract
The past five decades have seen many successes in superconducting radio-frequency (SRF) enabling a variety of accelerators. These successes are the result of steady progress in understanding the science behind the performance limitations, and in developing effective countermeasures to advance key performance aspects. SRF technology has developed in parallel to bring major accelerators to reality for a wide variety of fields from high energy physics, nuclear physics, and nuclear astro-physics to materials science.

Keywords: accelerators, niobium, gradients, quality-factor

(Some figures may appear in colour only in the online journal)

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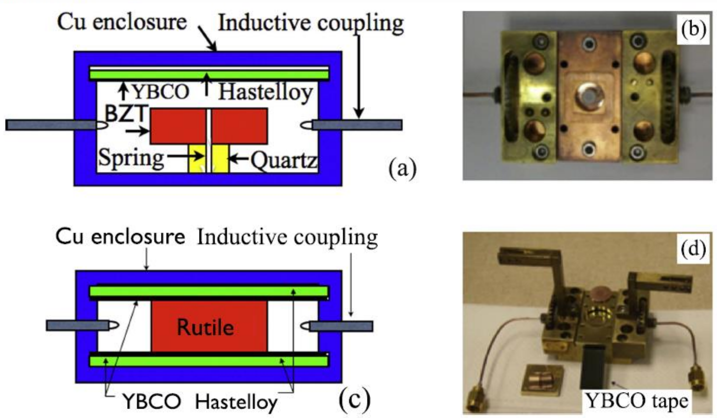


Figure 2. Schematic representation of (a) $TE_{01\delta}$ mode 13 GHz BZT SiPDR and (b) TE_{011} mode 9.4 GHz rutile RDR, designed to accommodate 12 mm wide tapes, are shown. SiPDR and RDR pictures are presented in (c) and (d), respectively.

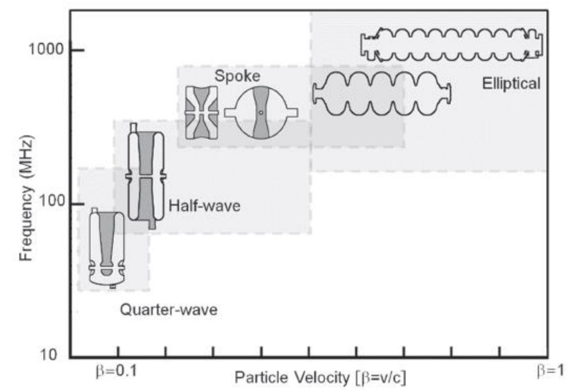


Figure 1. Superconducting cavities spanning the full range of β [9]. Reproduced with permission from [12]. Copyright © 2013, CCC Republication.

SRF in High Magnetic Field

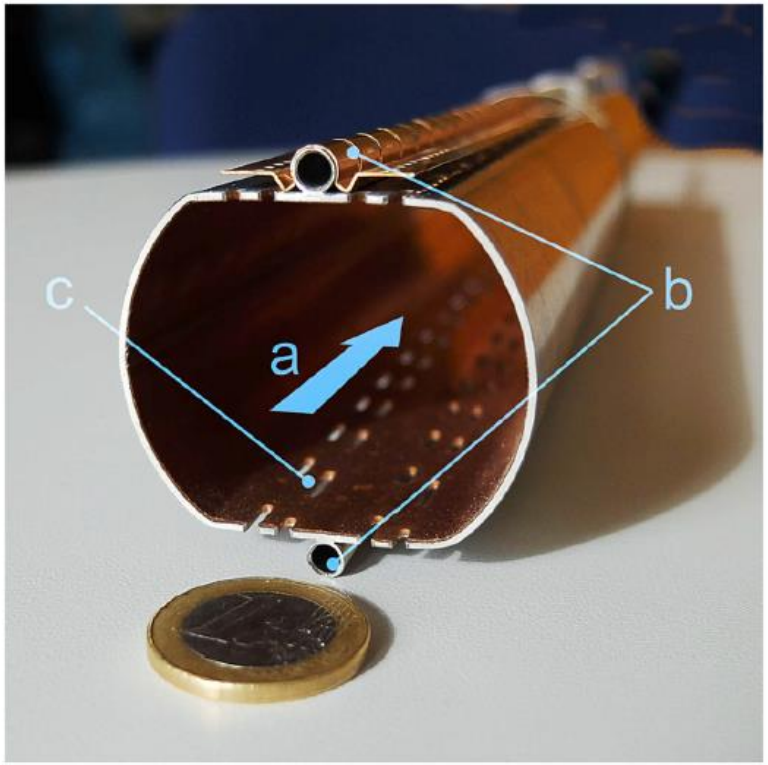
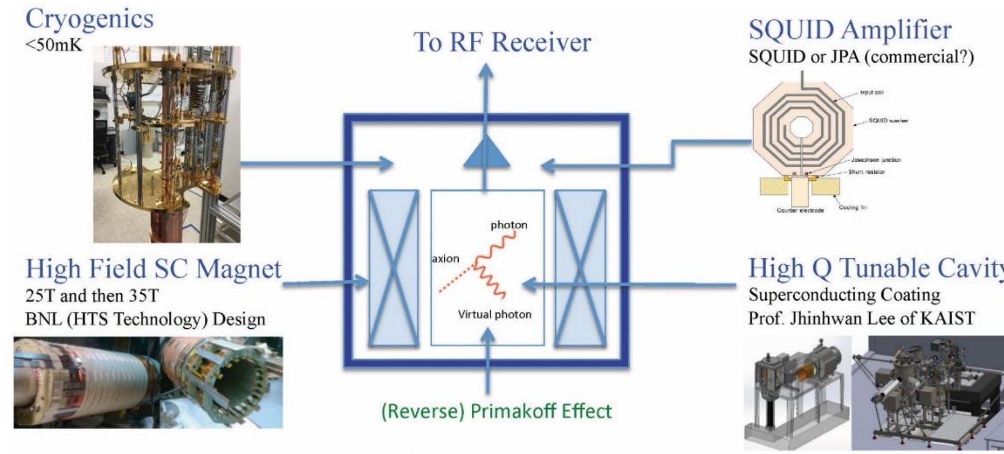


Figure 1. Photograph of the LHC beam screen. The proton beam moves along the axis indicated by the arrow (a). The tubes on top and at the bottom (b) are cooling channels for gaseous helium, and the slots (c) allow any desorbed gases to escape and to be cryopumped onto the surface of the cold bore of the surrounding magnet.

S. Calatroni *et al*, *Supercond. Sci. Technol.* **30** 075002 (2017).



$$P_{\alpha\to\gamma\gamma} = g^2{}_{\alpha\gamma\gamma}\frac{\rho_a}{m_a}B^2 V C_{mnp} min(Q_L, Q_a)$$

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{P_{\alpha\to\gamma\gamma}}{k_B T_{sys}}\sqrt{\frac{t_{int}}{\Delta f_a}}$$

$$\frac{df}{dt} \propto \frac{B^4 V^2 C^2 min(Q_L, Q_A)}{T_{sys}{}^2}$$