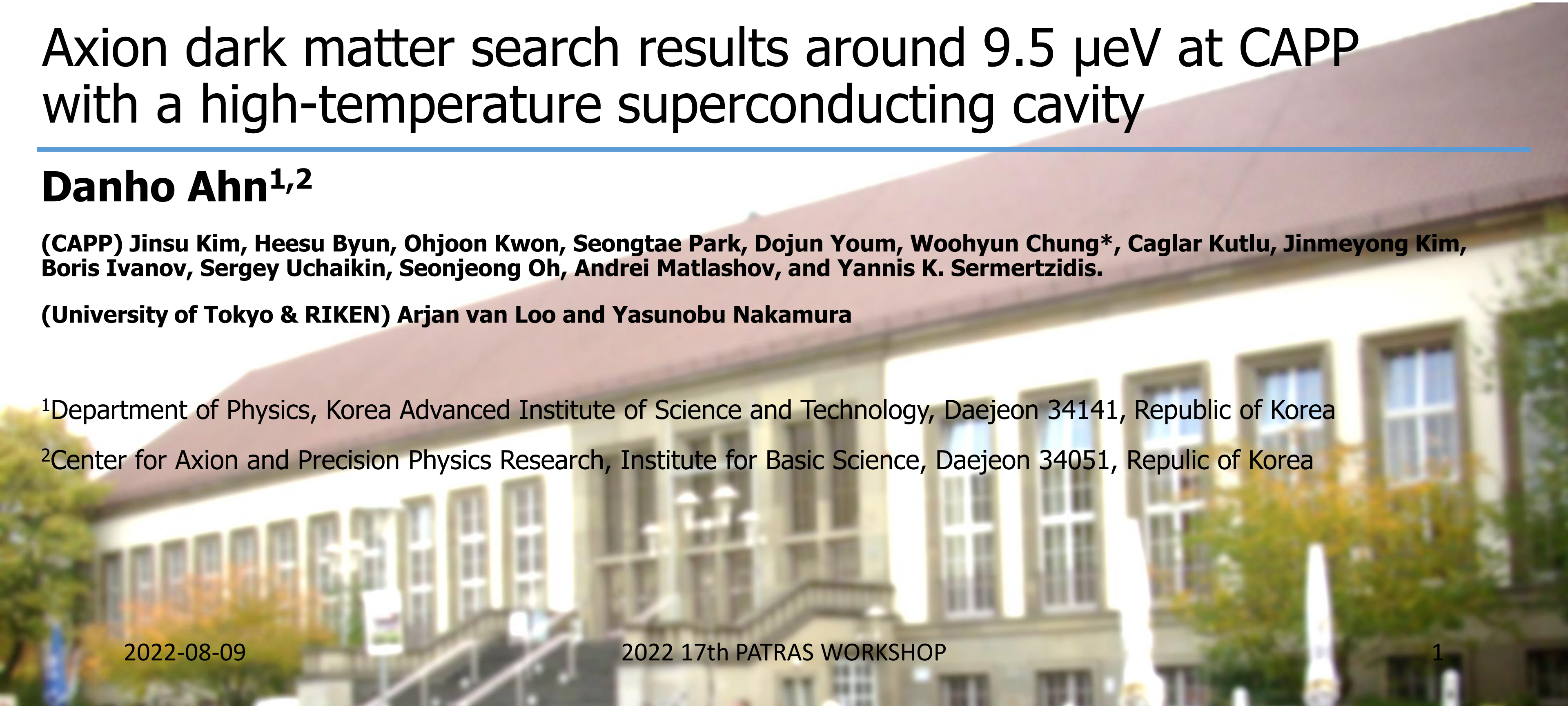


Axion dark matter search results around 9.5 μeV at CAPP with a high-temperature superconducting cavity

Danho Ahn[1,2]

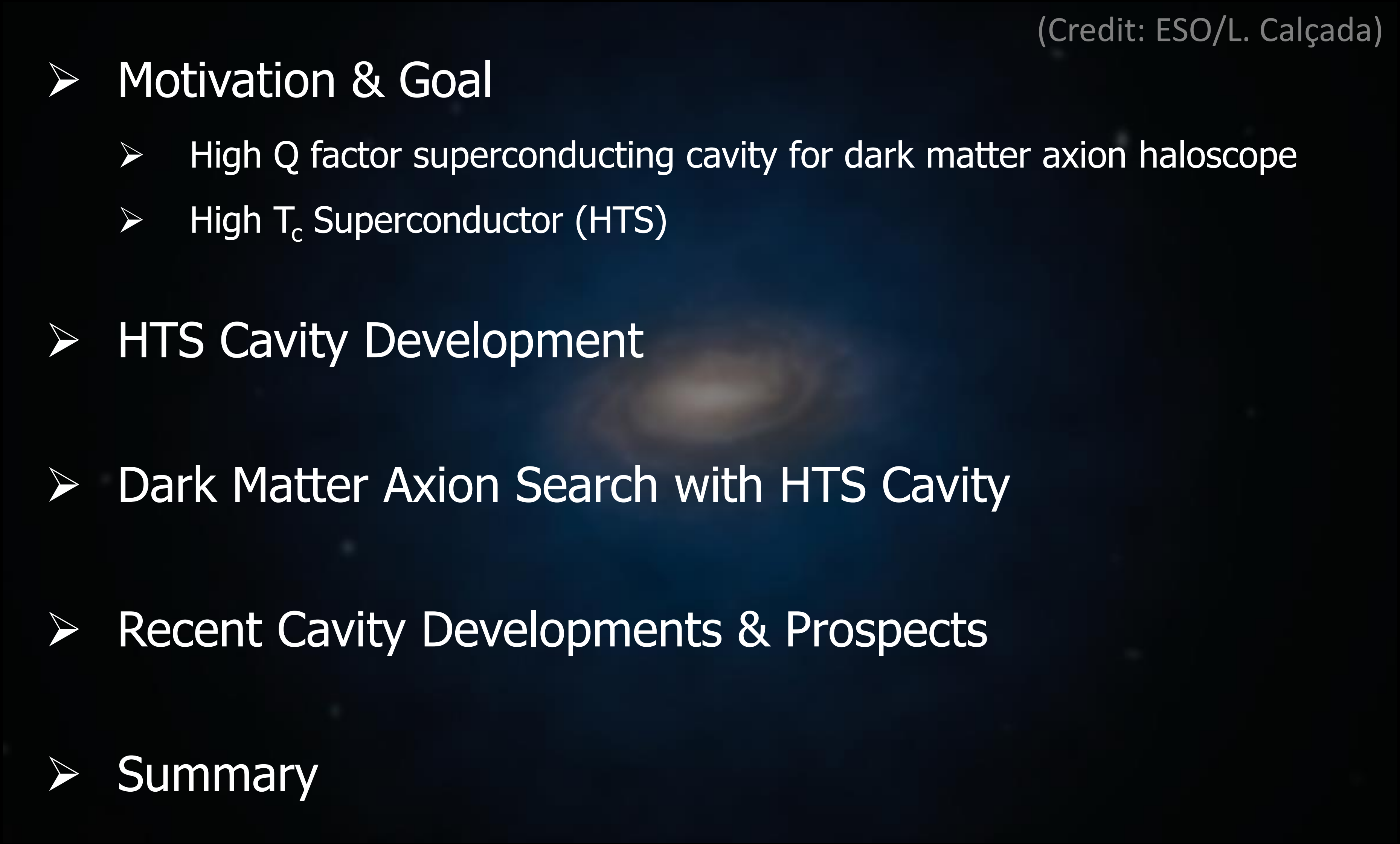
(CAPP) Jinsu Kim, Heesu Byun, Ohjoon Kwon, Seongtae Park, Dojun Youm, Woohyun Chung*, Caglar Kutlu, Jinmeyong Kim, Boris Ivanov, Sergey Uchaikin, Seonjeong Oh, Andrei Matlashov, and Yannis K. Semertzidis.

(University of Tokyo & RIKEN) Arjan van Loo and Yasunobu Nakamura

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

[2]Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Repulic of Korea

Outline

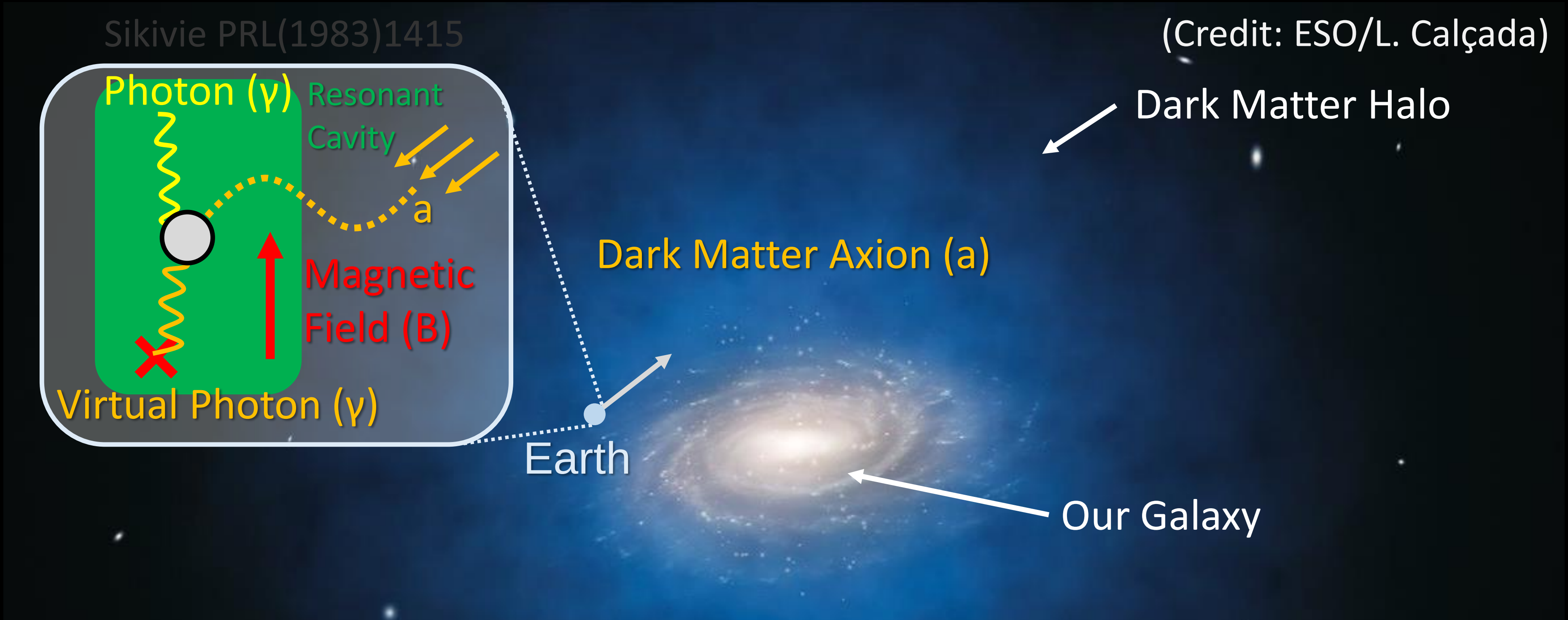

(Credit: ESO/L. Calçada)

- Motivation & Goal
  - High Q factor superconducting cavity for dark matter axion haloscope
  - High T_c Superconductor (HTS)
- HTS Cavity Development
- Dark Matter Axion Search with HTS Cavity
- Recent Cavity Developments & Prospects
- Summary

Cavity Quality Factor in Axion Haloscope

Sikivie PRL(1983)1415

(Credit: ESO/L. Calçada)



Conversion Power

Coupling Constant

Dark Matter Axion Density

Resonant Frequency

$$P_{a\gamma\to\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} B^2 V \omega_0 C \frac{Q_a Q_c}{Q_a + Q_c}$$

Axion Mass

Axion Quality Factor

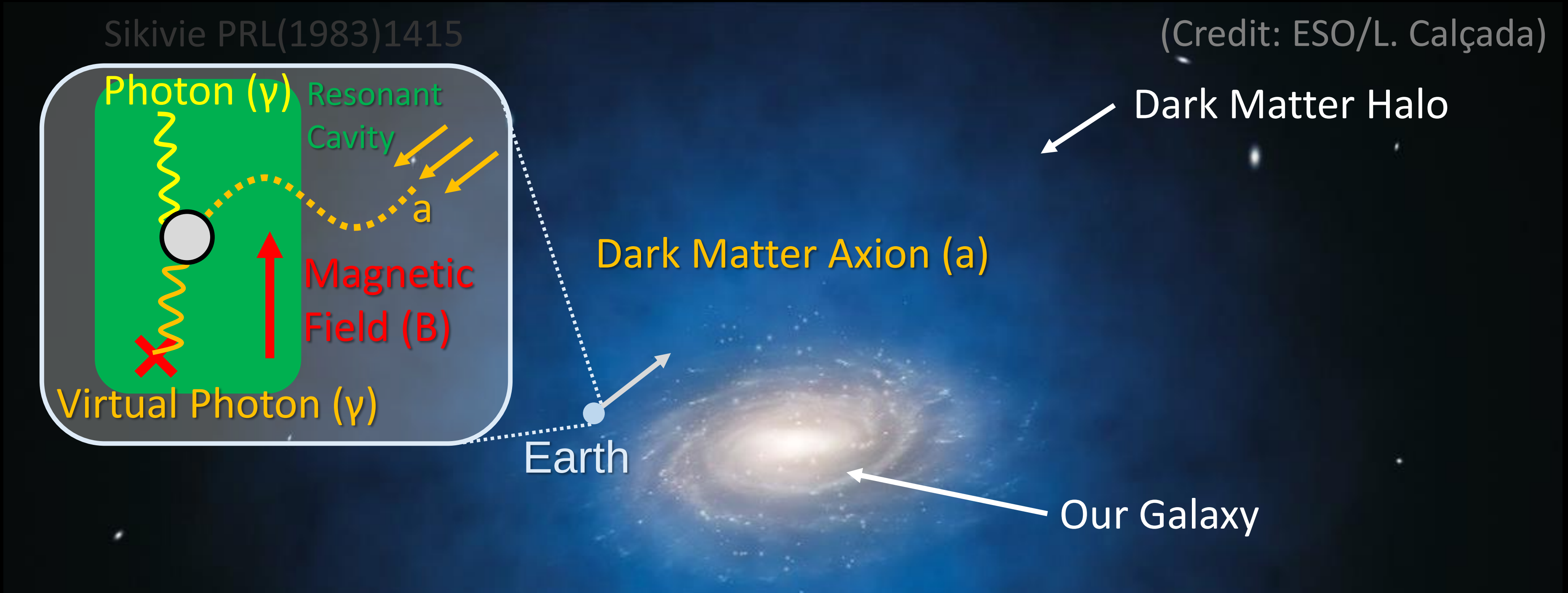
Cavity Quality Factor

Kim *et al*. JCAP03(2020)066

Cavity Quality Factor in Axion Haloscope

Sikivie PRL(1983)1415

(Credit: ESO/L. Calçada)



Scan Rate

Loaded Quality Factor

$$\frac{df}{dt} \propto \frac{B^4 V^2 C^2}{k_B^2 T_{sys}^2} \boldsymbol{Q_l} Q_a \left(\frac{1}{1+Q_l/Q_a}\right)$$

System Noise

Axion Quality Factor (10^6)

if $Q_l > Q_a \approx 10Q_{Cu}$

: 10 years → 1 year

Cavity Quality Factor

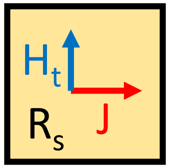
Kim *et al*. JCAP03(2020)066

Quality Factor of Superconducting Cavities

- Origin of Energy Loss $P_{surf} \propto R_s$

Low Surface Resistance
→ Superconductor (SC)

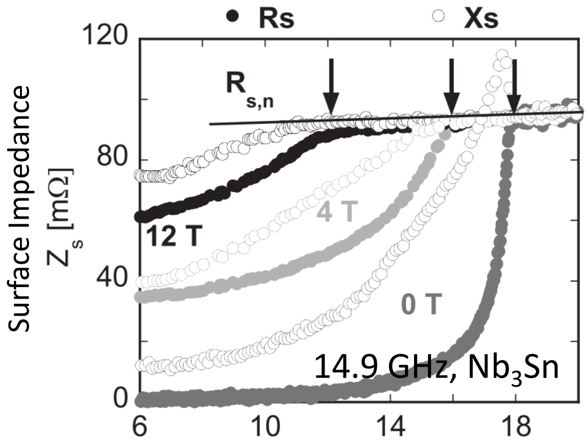
$$\frac{1}{Q} = \frac{P_{loss}}{\omega_0 U} = \frac{1}{\omega_0 U} P_{surf}$$



Surface Current Loss

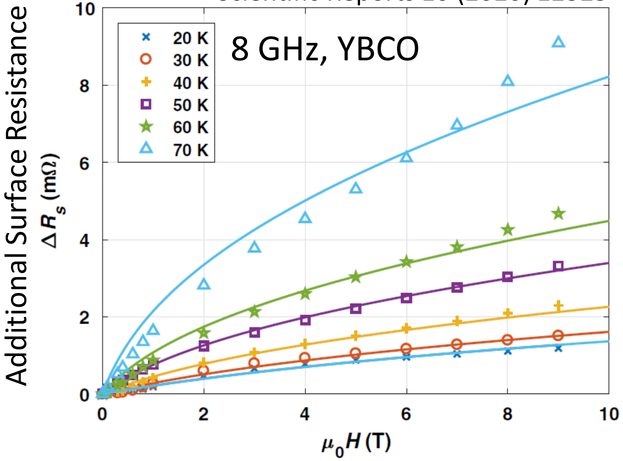
High Q

- Surface Resistance Increase in a High Magnetic Field



Posen *et al* SUST(2017)30

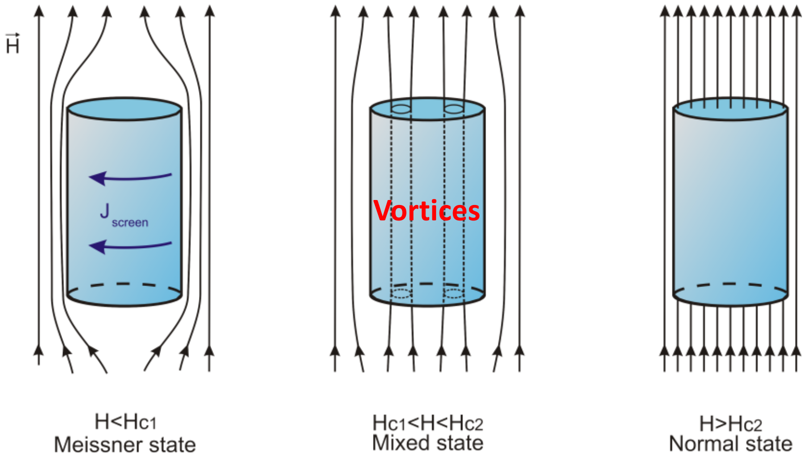
Scientific Reports 10 (2020) 12325

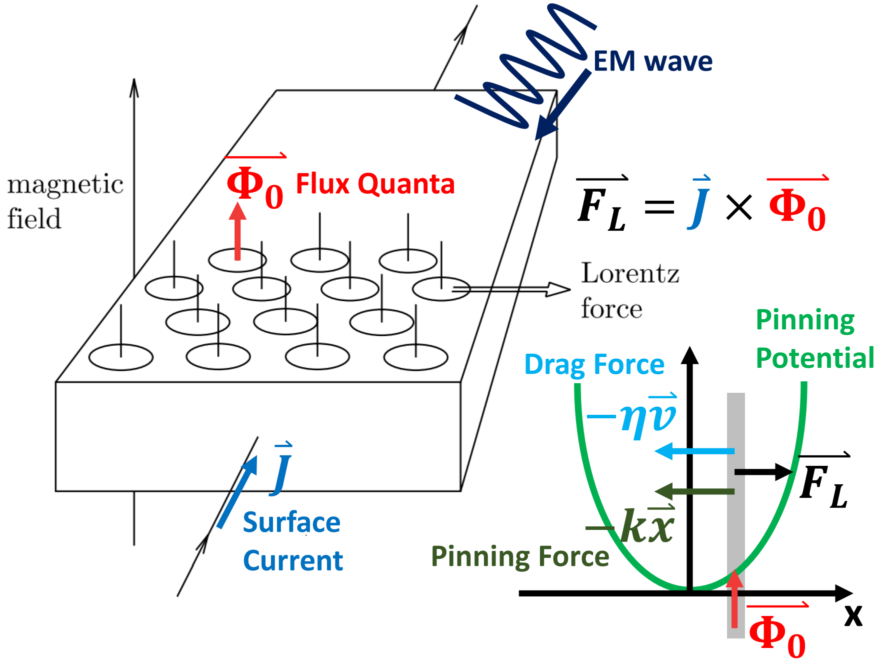


Superconductor in a High Magnetic Field

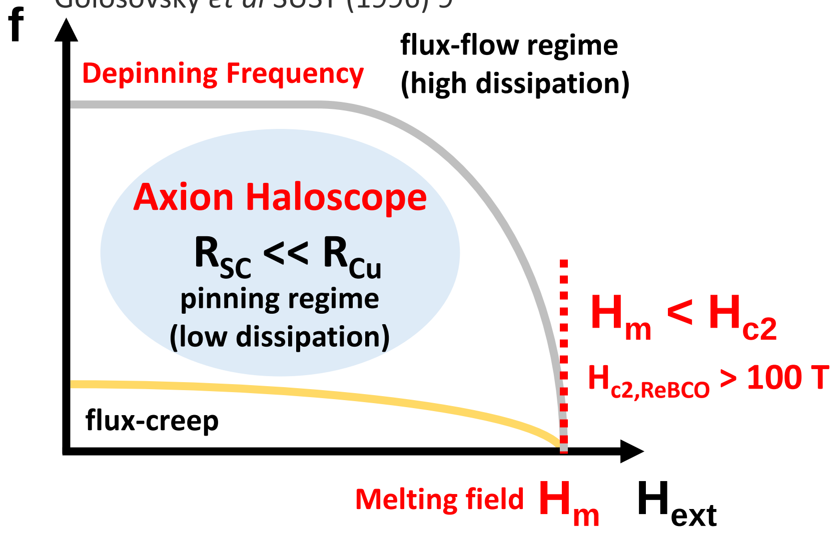
Three Phases of Type II Superconductor

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





Golosovsky *et al* SUST (1996) 9



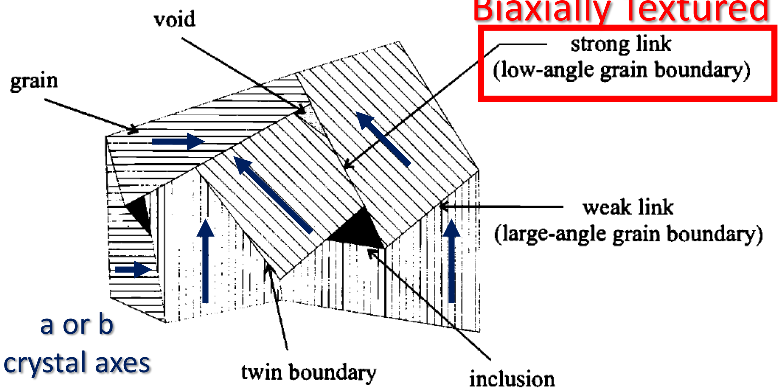
- ➢ Two criteria for evaluating materials
  - ✓ Large upper critical field ($H_{c2} > 30$ T)
    - Lower Vortex Density
  - ✓ High depinning frequency ($\omega_0 > 1$ GHz)
    - $\omega_0 = k / \eta$
    - $\omega \gg \omega_0$ (Drag force ≫ Pinning force)

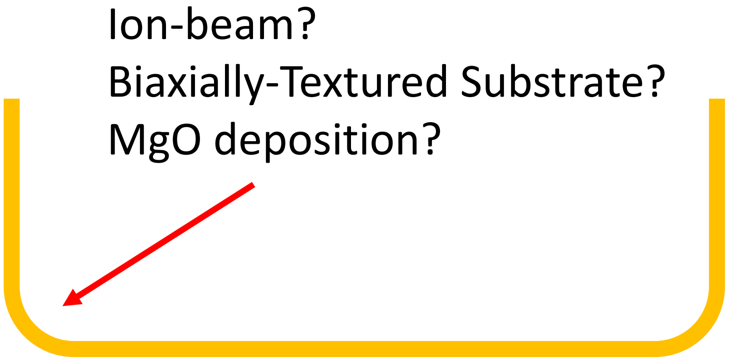
Material Evaluation

100 mK 8 GHz	R_s (B = 0 T) (Ohm)	R_s (B = 8 T, $\parallel$ c) (Ohm)	Critical Field (H_{c2})	Depinning Frequency
OFHC Cu (Metal)	~ 7E-3	~ 7E-3	None	None
Low Temperature Superconductors (LTS)				
NbTi (LTS) Gatti *et al*. PRD(2019)	~ 1E-6	~ 4e-3	Small ~ 13 T	~ 45 GHz
Nb_3Sn (LTS) Alimenti *et al*. SUST(2020)	~ 1E-6	?	~ 25 T	Small ~ 6 GHz
High Temperature Superconductors (HTS)				
Bi-2212 (HTS) Bi-2223 (HTS)	~ 1E-5	?	> 100 T ($\parallel$ ab) Larbalestier *et al*. Nature(2001)	Weak Pinning ?
Tl-1223 (HTS)	~ 1E-5	~ 1e-4 Calatroni *et al*. SUST(2017)	> 100 T ($\parallel$ ab) Larbalestier *et al*. Nature(2001)	12 – 480 MHz Calatroni *et al*. SUST(2017)
ReBCO (HTS)	~ 1E-5 Ormeno *et al*. PRB(2001)	**~ 1e-4** Romanov *et al*. Scientific Reports(2020)	**> 100 T ($\parallel$ ab)** Larbalestier *et al*. Nature(2001)	Strong Pinning **10 – 100 GHz** Romanov *et al*. Scientific Reports(2020)

Biaxially-Textured ReBCO on 3D Surface

M. J. Lancaster, “Passive microwave device applications of HTS”,
Cambridge University Press (2006).




Ion-beam?
Biaxially-Textured Substrate?
MgO deposition?

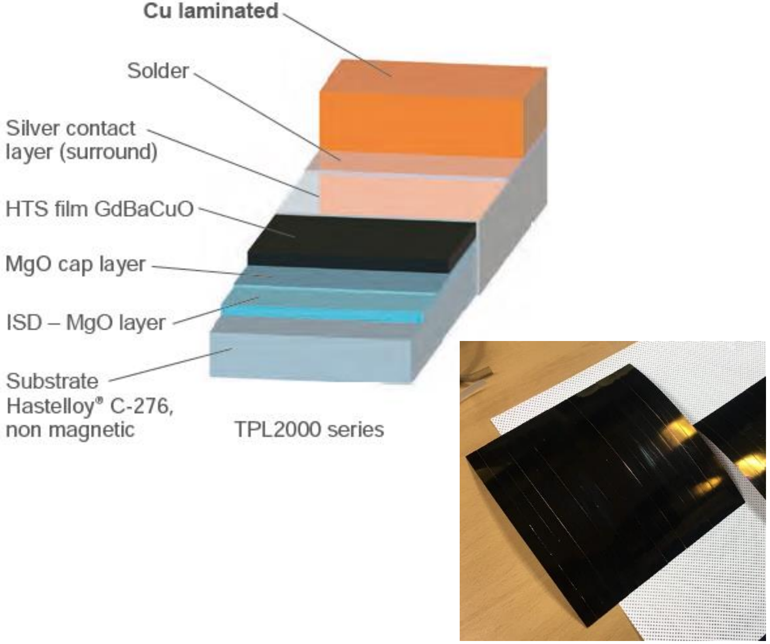
- ➢ Weak links at grain boundaries degrades surface resistance.
- ➢ Biaxial texture is essential to avoid weak links.
- ➢ Directly forming a biaxially-textured ReBCO film on the deeply concaved inner surface of the cavities is difficult.
- ➢ **Can we make a cavity with ReBCO tapes?**

HTS Cavity Development in CAPP

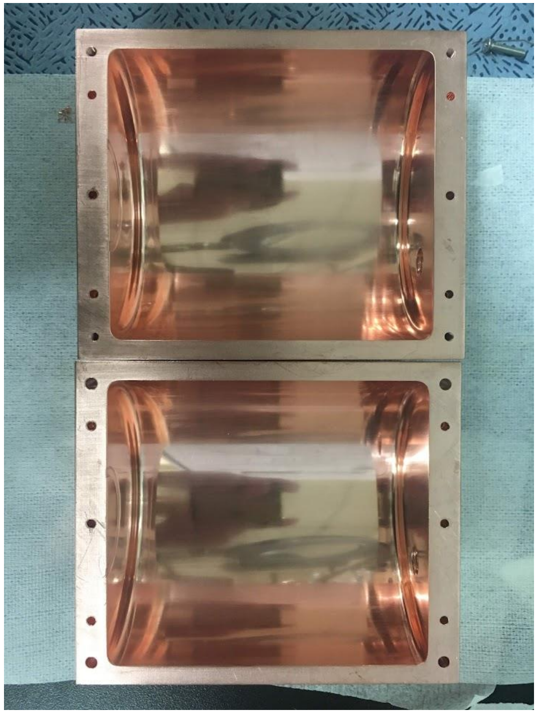
CAPP’s Solution

Well-textured Commercial ReBCO Tapes + Cavity Body → 3D HTS Cavity

THEVA Catalog (2017)



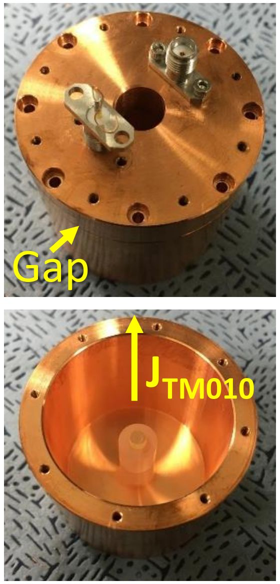
+

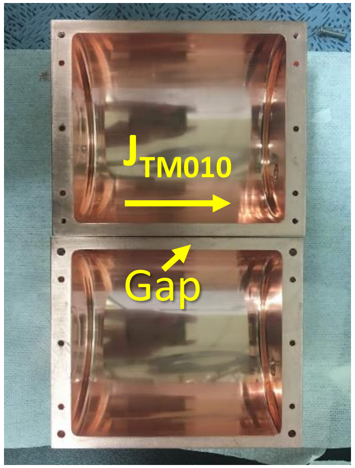


2D Material

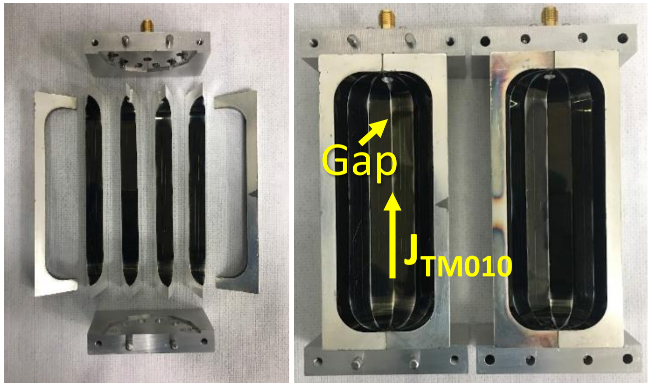
3D Surface

HTS Microwave Cavity Design Background





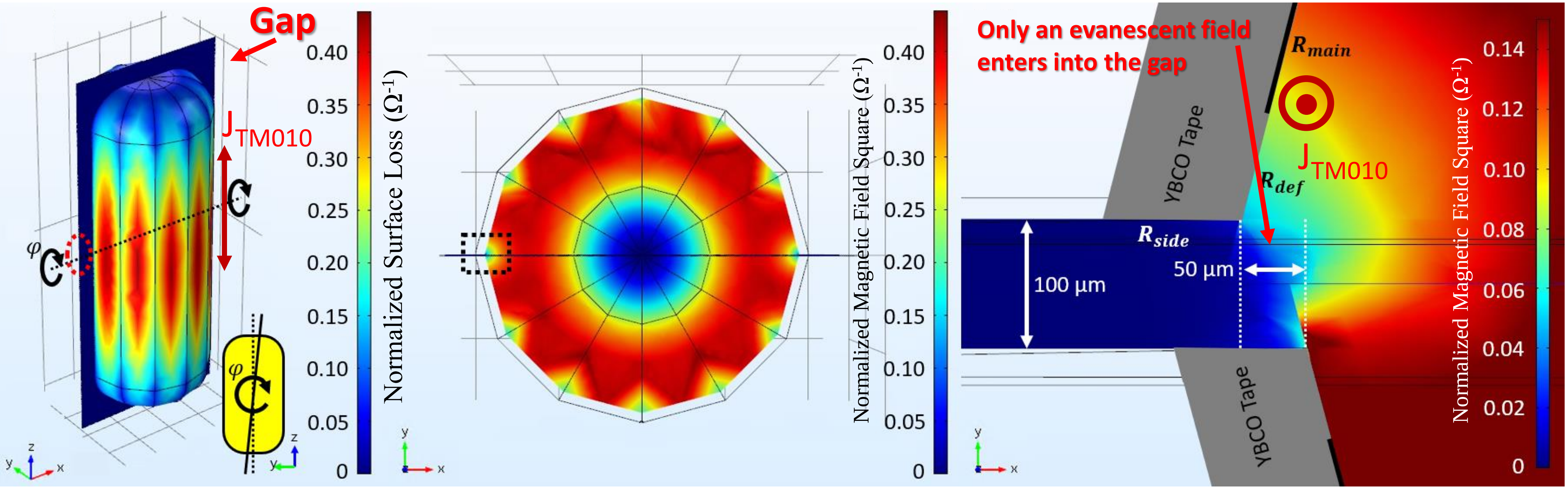
Split Cavity



Polygon Cavity

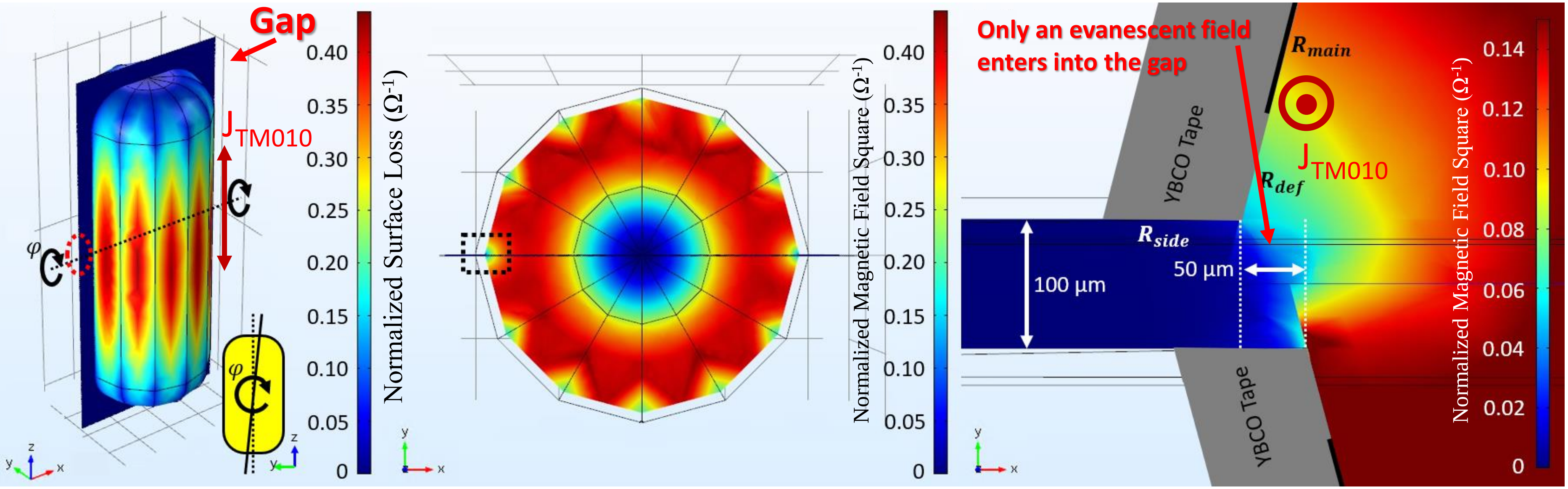
- Cutting in surface current direction in TM010 mode.
  - The split cavity has been used in axion haloscope experiment at CAPP. { Phys. Rev. Lett. 126 (2021) 191802 Phys. Rev. Lett. 125 (2020) 221302
  - Only evanescent field enter into the gaps
- We generalized split cavity concept for HTS microwave cavities.
  - **N polygon structure with N gaps**

HTS Microwave Cavity Design Simulation



- Surface current direction is parallel to the in-plane direction of gaps.
- Only evanescent field enter into a gap.
- Misalignments are considered based on fabrication error.
  - Gap geometry: Gap tilting, Step between superconducting main surfaces
  - Surface Condition: Metal on the gap sides (R_{side}, Ag), Defects on the main surface (R_{def}, Ni-9W).

N Gaps Do Not Degrade Q_{TM010}



N gaps do not degrade Q factor less than axion Q factor (10^6)

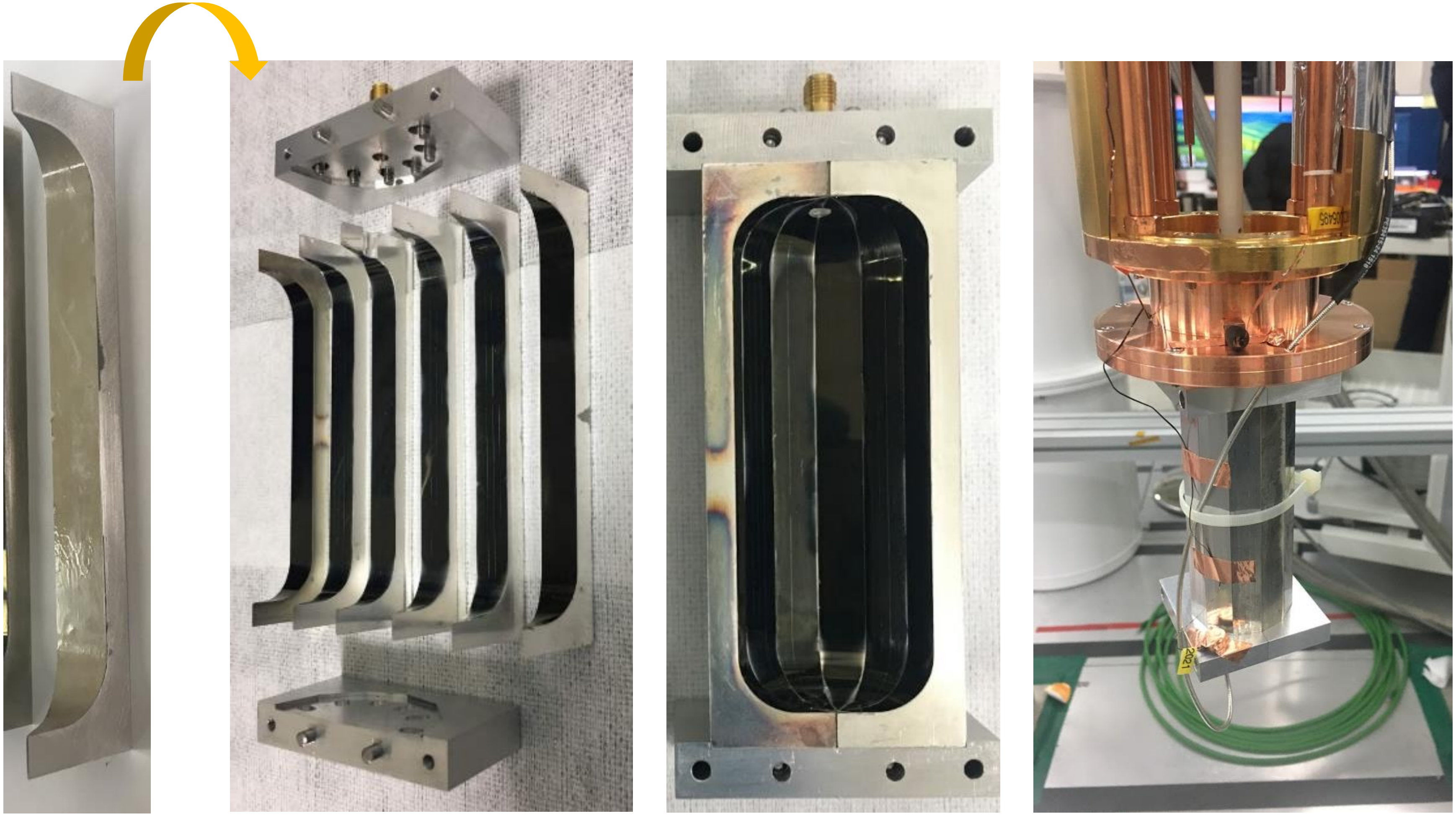
Condition	R_{side} (mΩ)	R_{def} (mΩ)	Q
VGs	0	0	$\sim 10^{12}$
TGs	0	0	$\sim 10^{8}$
TSGs	0	0	3×10^{7}
TSGs + Silver Side	Ag (5 mΩ)	0	2×10^{7}
TSGs + Silver Side + Silver Edge	Ag (5 mΩ)	1 % Ag (5 mΩ)	5×10^{6}
TSGs + Silver Side + Silver Edge + Ni-9W Defect	Ag (5 mΩ)	1 - 5 % Ni-9W (50 mΩ)	$\sim 10^{5}$

Surface defect can degrade Q factor less than 10^6

TABLE I: Quality factor results in various conditions. The Q factor values are the estimations for a case of 20 μm gaps. The first three conditions are vertical gaps (VG), tilted gaps (TG), and tilted stepped gaps (TSG).

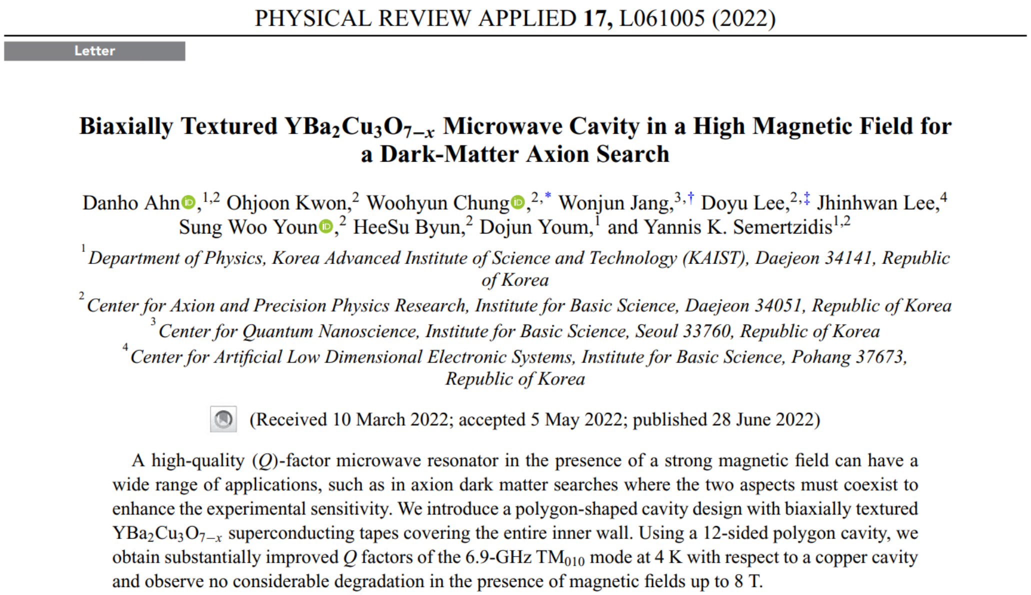
HTS Cavity Construction

Etching: Ammonia Water + Hydrogen Peroxide



6.9 GHz Polygon Cavity

- (2019) First Prototype HTS Cavity
  - ✓ (August 15th) **Q ~ 330,000 at 8 T**



PHYSICAL REVIEW APPLIED **17**, L061005 (2022)

Letter

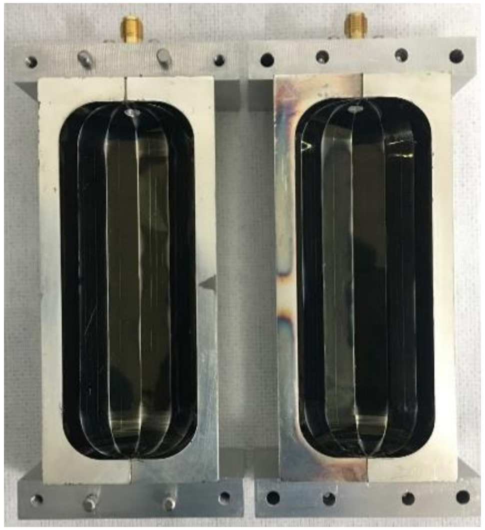
Biaxially Textured $YBa_2Cu_3O_{7-x}$ Microwave Cavity in a High Magnetic Field for a Dark-Matter Axion Search

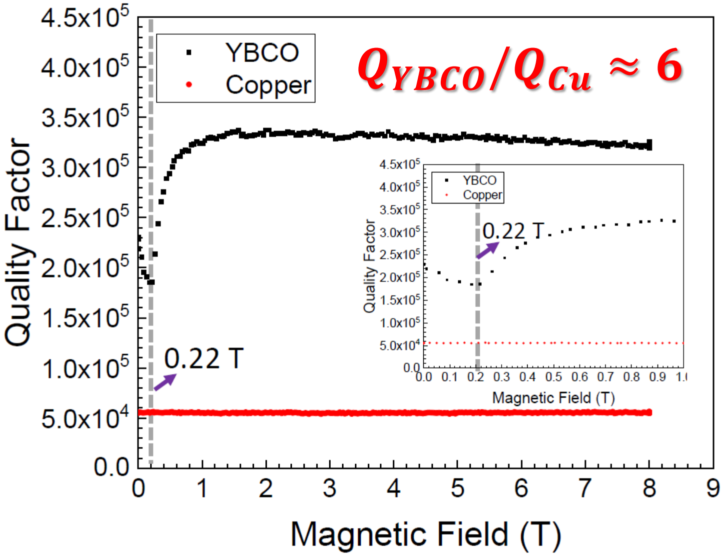
Danho Ahn,[1,2] Ohjoon Kwon,[2] Woohyun Chung,[2,*] Wonjun Jang,[3,†] Doyu Lee,[2,‡] Jhinhwan Lee,[4]
Sung Woo Youn,[2] HeeSu Byun,[2] Dojun Youm,[1] and Yannis K. Semertzidis[1,2]

[1] *Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea*
[2] *Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea*
[3] *Center for Quantum Nanoscience, Institute for Basic Science, Seoul 33760, Republic of Korea*
[4] *Center for Artificial Low Dimensional Electronic Systems, Institute for Basic Science, Pohang 37673, Republic of Korea*

(Received 10 March 2022; accepted 5 May 2022; published 28 June 2022)

A high-quality (Q)-factor microwave resonator in the presence of a strong magnetic field can have a wide range of applications, such as in axion dark matter searches where the two aspects must coexist to enhance the experimental sensitivity. We introduce a polygon-shaped cavity design with biaxially textured $YBa_2Cu_3O_{7-x}$ superconducting tapes covering the entire inner wall. Using a 12-sided polygon cavity, we obtain substantially improved Q factors of the 6.9-GHz TM_{010} mode at 4 K with respect to a copper cavity and observe no considerable degradation in the presence of magnetic fields up to 8 T.

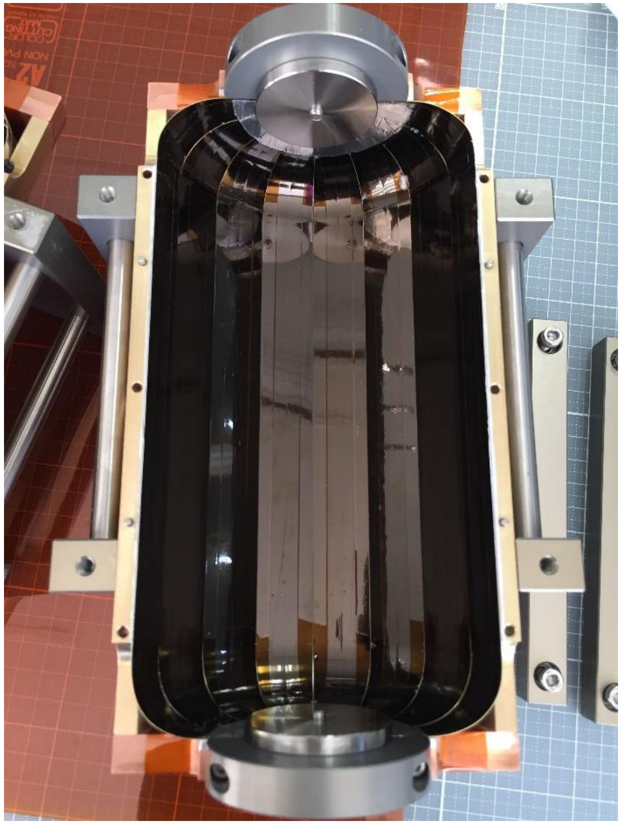


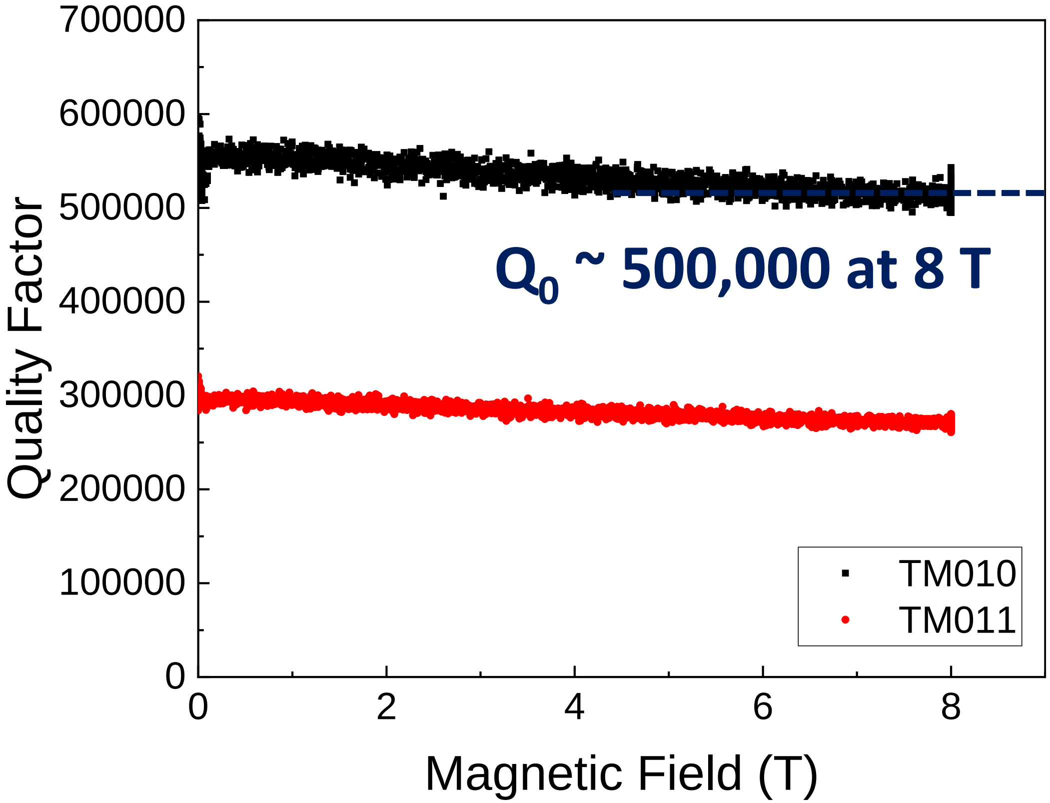


$Q_{YBCO}/Q_{Cu} \approx 6$

2.3 GHz HTS Cavity for Axion Haloscope

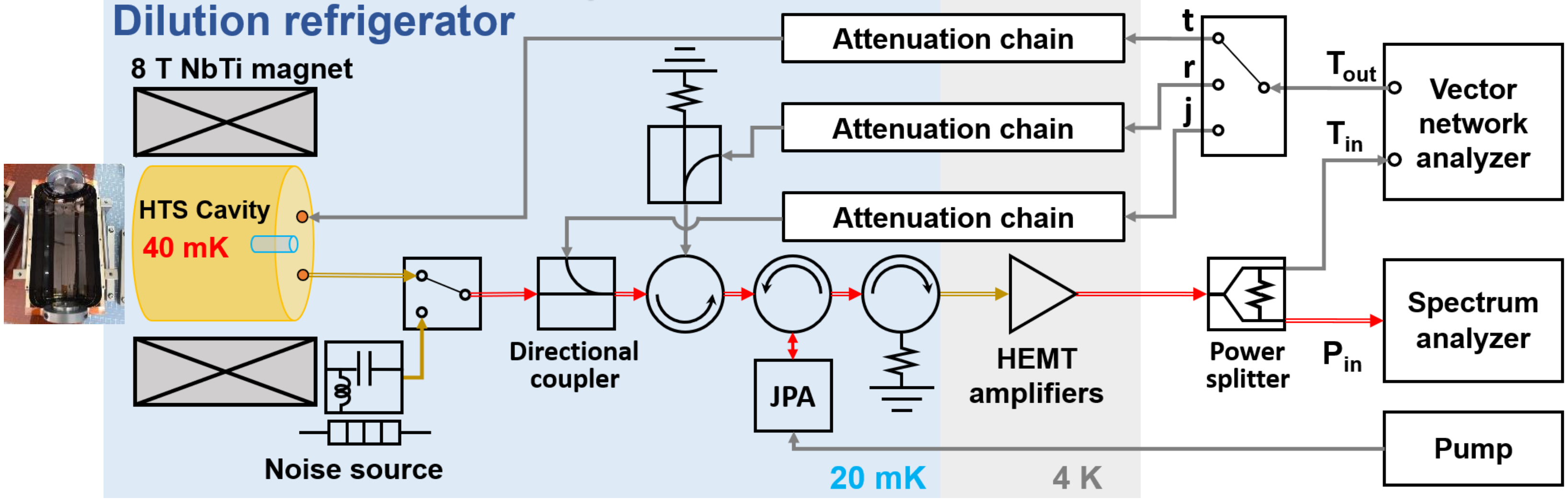
- 2.3 GHz HTS Cavity
  - ✓ (January 18th, 2020) **Q ~ 500,000 at 8 T** (THEVA GdBCO Tape, 1.5 L)





Axion Search with Superconducting Cavity

CAPP-PACE Detector Setup



- Total System Noise ($T_{sys} = T_{eff} + T_{add}$)
  - Effective cavity noise temperature ($T_{eff} \approx$ 60mK)
    - ✓ $T_{eff} = \frac{h\nu}{k_B}\left(\frac{1}{e^{h\nu/k_B T_{phy}}-1} + \frac{1}{2}\right)$, T_{phy} (cavity physical temperature ~ 40 mK)
  - Added noise by the receiver chain ($T_{add} \approx$ 120mK)
  - Spectrum Analyzer Efficiency ($\eta \approx$ 0.7)

$$\frac{df}{dt} = \boldsymbol{\eta}\frac{4}{5}\frac{1}{SNR^2}\left(\frac{P_0}{k_B \boldsymbol{T_{sys}}}\frac{\beta}{1+\beta}\right)^2 \frac{Q_l Q_a^2}{Q_l + Q_a}$$

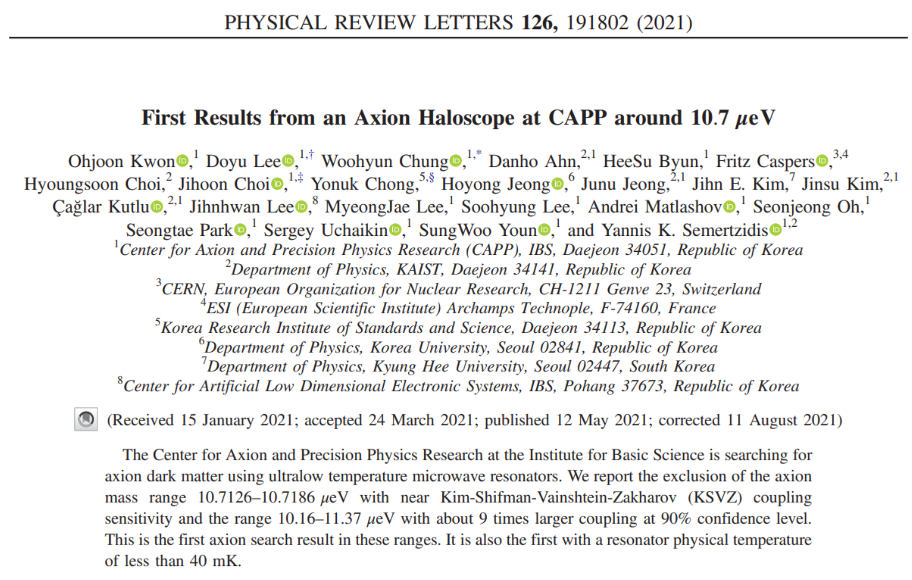
CAPP-PACE Detector History

	HEMT Run Phys. Rev. Lett. 126 (2021)	**JPA Run** On ArXiv, Will submit soon (Mr. Jinsu Kim *et al.*)	**SC Run** Re-scanning Now
Frequency Range	2.457 – 2.749 GHz	2.27 – 2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)	7.2 T	7.2 T	6.95 T
Volume (V)	1.12 L	1.12 L	**1.5 L**
Quality Factor (Q_0)	100,000	100,000	**500,000**
Geometrical Factor (C)	0.51 – 0.66	0.45	0.51 – 0.65
System Noise (T_{sys})	~ 1.1 K	**~ 200 mK**	**~ 180 mK**
Scan Rate (Arb.)	**1**	**18**	**150**

$\propto B^4 V^2 C^2 Q_0 / T_{sys}^2$

CAPP-PACE Detector History

	HEMT Run Phys. Rev. Lett. 126 (2021)	**JPA Run** On ArXiv, Will submit soon (Mr. Jinsu Kim *et al.*)	**SC Run** Re-scanning Now
Frequency Range	2.457 – 2.749 GHz	2.27 – 2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)	7.2 T		
Volume (V)	1.12 L		
Quality Factor (Q_0)	100,000		
Geometrical Factor (C)	0.51 – 0.66		
System Noise (T_{sys})	~ 1.1 K		
Scan Rate (Arb.) $\propto B^4V^2C^2Q_0/T_{sys}^2$	**1**	**18**	**150**



PHYSICAL REVIEW LETTERS **126,** 191802 (2021)

First Results from an Axion Haloscope at CAPP around 10.7 μeV

Ohjoon Kwon,[1] Doyu Lee,[1,†] Woohyun Chung,[1,*] Danho Ahn,[2,1] HeeSu Byun,[1] Fritz Caspers,[3,4] Hyoungsoon Choi,[2] Jihoon Choi,[1,‡] Yonuk Chong,[5,§] Hoyong Jeong,[6] Junu Jeong,[2,1] Jihn E. Kim,[7] Jinsu Kim,[2,1] Çağlar Kutlu,[2,1] Jihnhwan Lee,[8] MyeongJae Lee,[1] Soohyung Lee,[1] Andrei Matlashov,[1] Seonjeong Oh,[1] Seongtae Park,[1] Sergey Uchaikin,[1] SungWoo Youn,[1] and Yannis K. Semertzidis[1,2]

[1]*Center for Axion and Precision Physics Research (CAPP), IBS, Daejeon 34051, Republic of Korea*
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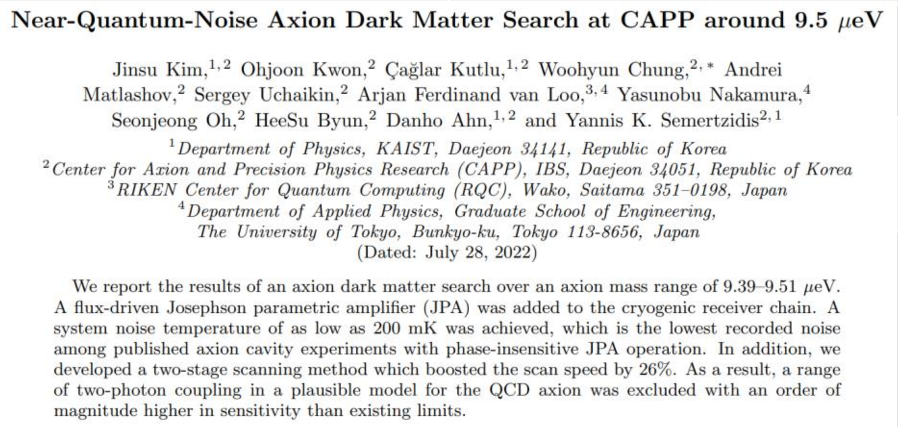
(Received 15 January 2021; accepted 24 March 2021; published 12 May 2021; corrected 11 August 2021)

The Center for Axion and Precision Physics Research at the Institute for Basic Science is searching for axion dark matter using ultralow temperature microwave resonators. We report the exclusion of the axion mass range 10.7126–10.7186 μeV with near Kim-Shifman-Vainshtein-Zakharov (KSVZ) coupling sensitivity and the range 10.16–11.37 μeV with about 9 times larger coupling at 90% confidence level. This is the first axion search result in these ranges. It is also the first with a resonator physical temperature of less than 40 mK.

CAPP-PACE Detector History

	HEMT Run Phys. Rev. Lett. 126 (2021)	**JPA Run** On ArXiv, Will submit soon (Mr. Jinsu Kim *et al.*)	**SC Run** Re-scanning Now
Frequency Range	2.457 – 2.749 GHz	2.27 – 2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)	7.2 T	7.2 T	6.95 T
		1.12 L	**1.5 L**
		100,000	**500,000**
		0.45	0.51 – 0.65
System Noise (T_{sys})	~ 1.1 K	**~ 200 mK**	**~ 180 mK**
Scan Rate (Arb.)	**1**	**18**	**150**

$\propto B^4V^2C^2Q_0/T_{sys}^2$



Near-Quantum-Noise Axion Dark Matter Search at CAPP around 9.5 μeV

Jinsu Kim,[1,2] Ohjoon Kwon,[2] Çağlar Kutlu,[1,2] Woohyun Chung,[2,*] Andrei Matlashov,[2] Sergey Uchaikin,[2] Arjan Ferdinand van Loo,[3,4] Yasunobu Nakamura,[4] Seonjeong Oh,[2] HeeSu Byun,[2] Danho Ahn,[1,2] and Yannis K. Semertzidis[2,1]

[1] *Department of Physics, KAIST, Daejeon 34141, Republic of Korea*
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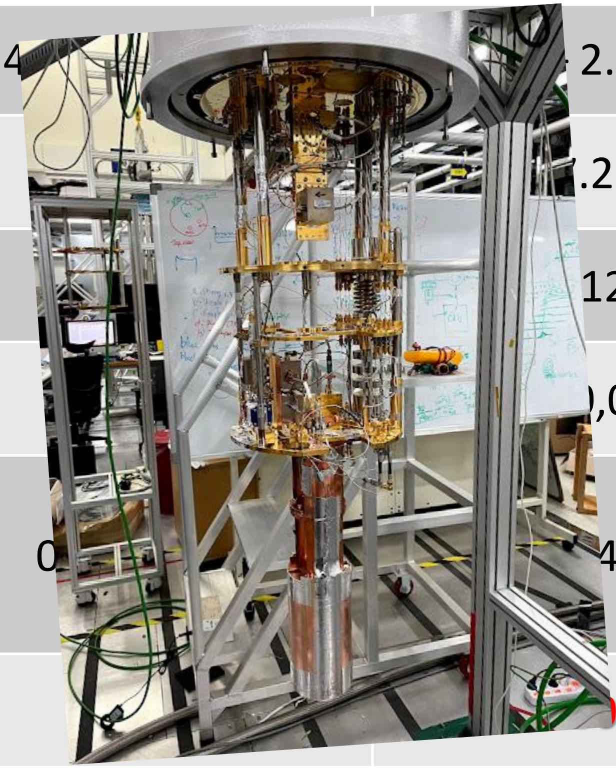
[3] *RIKEN Center for Quantum Computing (RQC), Wako, Saitama 351-0198, Japan*
[4] *Department of Applied Physics, Graduate School of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan*
(Dated: July 28, 2022)

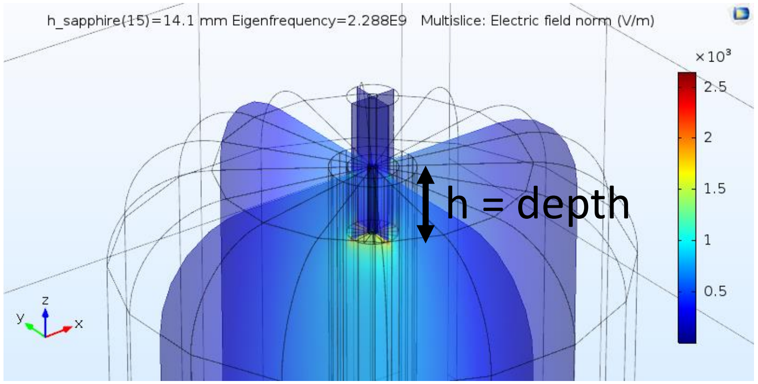
We report the results of an axion dark matter search over an axion mass range of 9.39–9.51 μeV. A flux-driven Josephson parametric amplifier (JPA) was added to the cryogenic receiver chain. A system noise temperature of as low as 200 mK was achieved, which is the lowest recorded noise among published axion cavity experiments with phase-insensitive JPA operation. In addition, we developed a two-stage scanning method which boosted the scan speed by 26%. As a result, a range of two-photon coupling in a plausible model for the QCD axion was excluded with an order of magnitude higher in sensitivity than existing limits.

CAPP-PACE Detector History

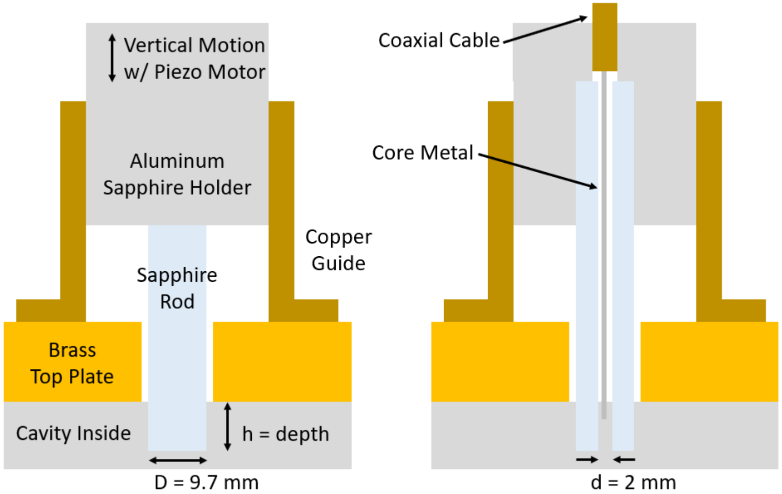
	HEMT Run Phys. Rev. Lett. 126 (2021)	**JPA Run** On ArXiv, Will submit soon (Mr. Jinsu Kim *et al.*)	**SC Run** Re-scanning Now
Frequency Range	2.4	2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)		.2 T	6.95 T
Volume (V)		12 L	**1.5 L**
Quality Factor (Q_0)		,000	**500,000**
Geometrical Factor (C)	0	45	0.51 – 0.65
System Noise (T_{sys})		**mK**	**~ 180 mK**
Scan Rate (Arb.) $\propto B^4V^2C^2Q_0/T_{sys}^2$	**1**	**18**	**150**

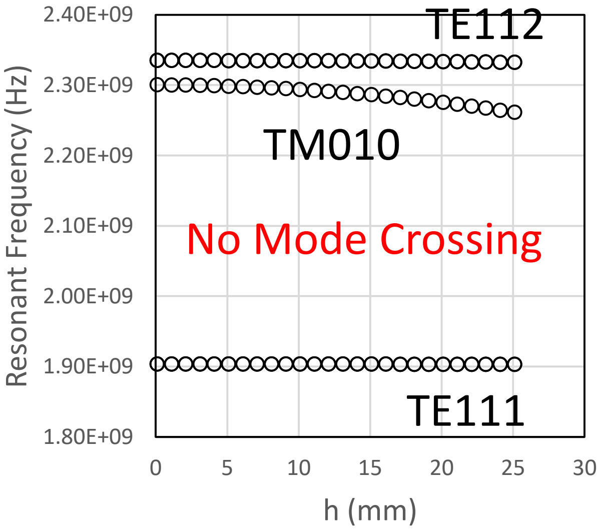


Tuning Mechanism

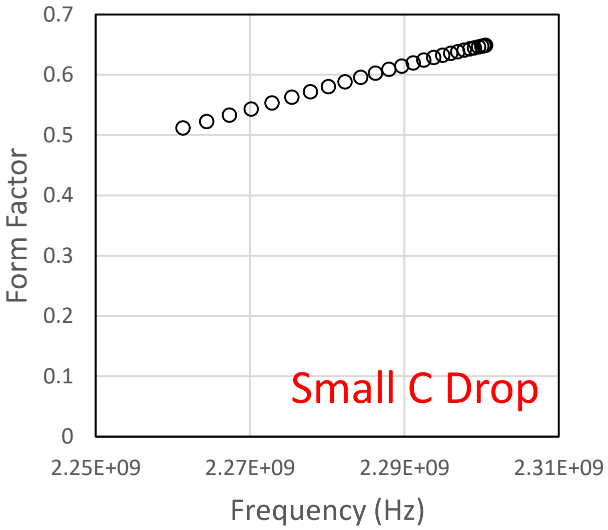


Simplified Tuning Simulation

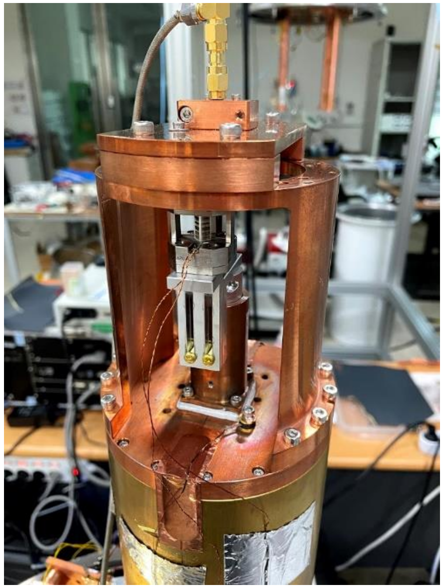




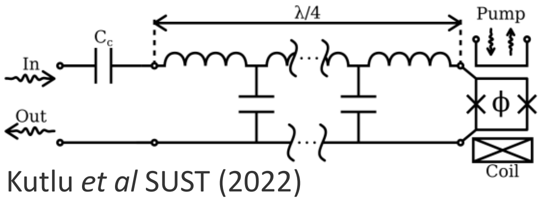
No Mode Crossing



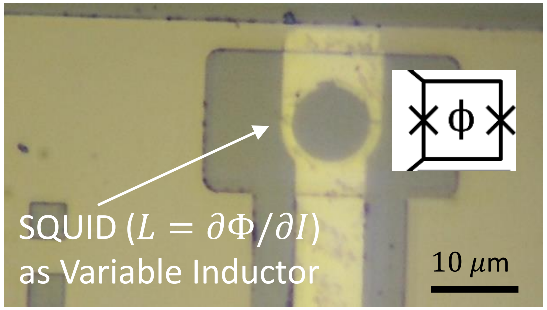
Small C Drop

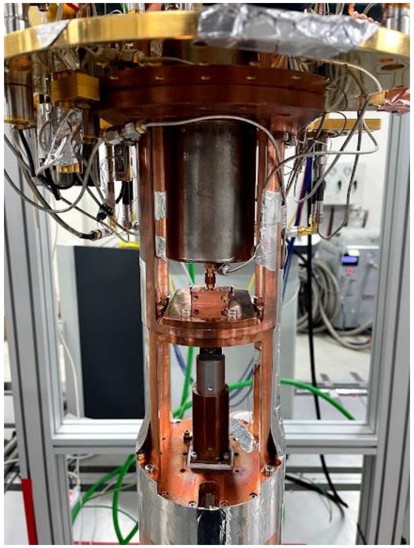


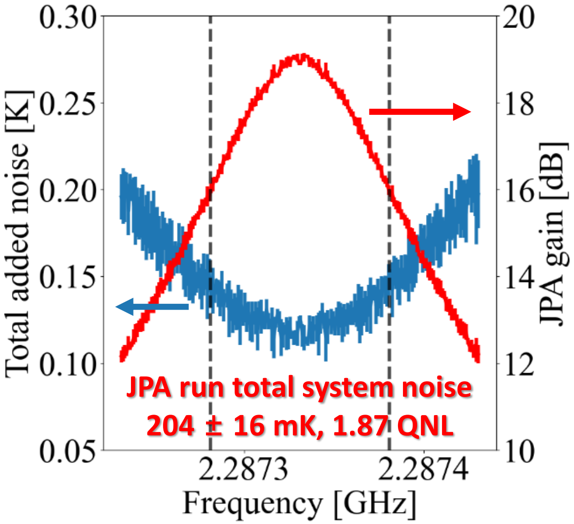
Josephson Parametric Amplifier (JPA)



Kutlu *et al* SUST (2022)







Kim *et al* ArXiv:2207.13597 (2022)

- JPA is Josephson junction based quantum-noise-limited amplifier
- CAPP Flux-driven JPA was developed in collaboration with Nakamura group at Univ. of Tokyo and RIKEN
- Operation range: 2.27 GHz – 2.30 GHz
- JPA was protected by two layer superconducting shield (shielding factor: roughly 1,500)
- Total system noise temperature

$$T_{JPA,idler} = T_{cav} = \frac{h\nu}{k_B}\left(\frac{1}{e^{h\nu/k_B T_{phy}} - 1} + \frac{1}{2}\right)$$

Noise from cavity

JPA irreducible noise in the phase-insensitive operation

$$T_{sys} = T_{cav} + T_{add}, \qquad T_{add} = \left(T_{JPA,idler} + T_{JPA,irr}\right) + \frac{T_{postJPA}}{G_{JPA}}$$

Added noise generated in the post-JPA chain

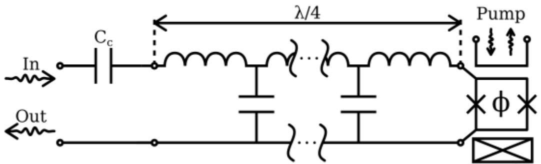
Total system noise

Chain added noise

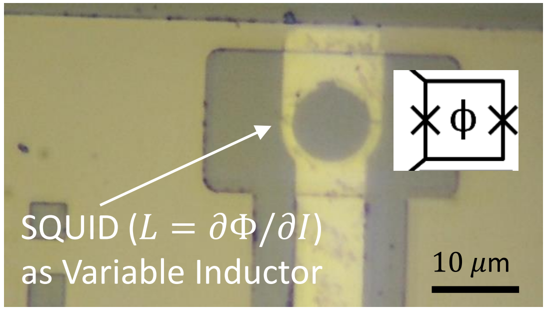
JPA added noise from idler photon

JPA Gain

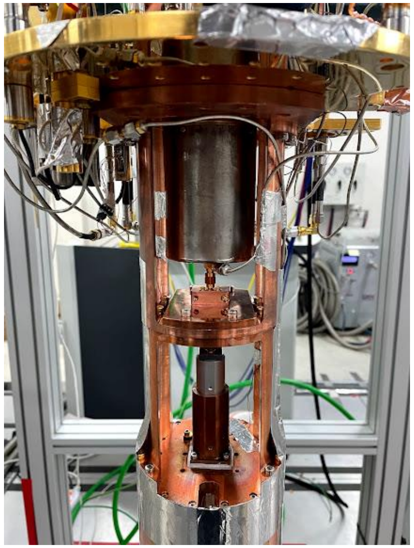
Josephson Parametric Amplifier (JPA)

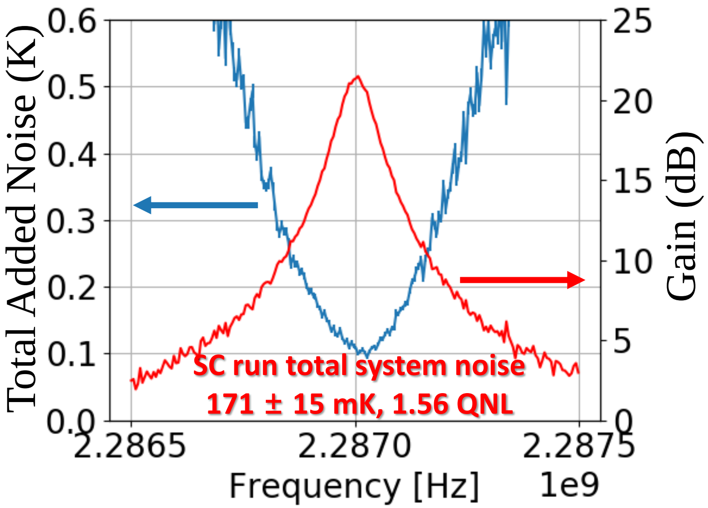


Kutlu *et al* SUST (2022)



SQUID ($L = \partial\Phi/\partial I$)
as Variable Inductor





SC run total system noise
171 ± 15 mK, 1.56 QNL

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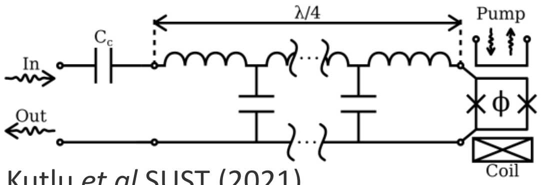
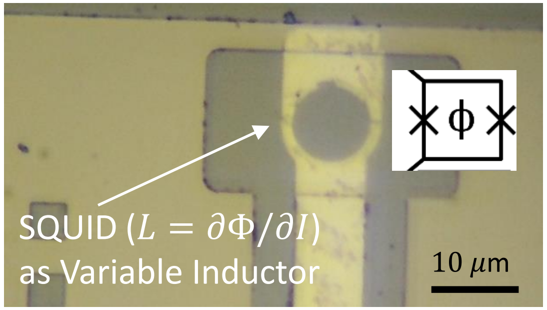


Kutlu *et al* SUST (2021)



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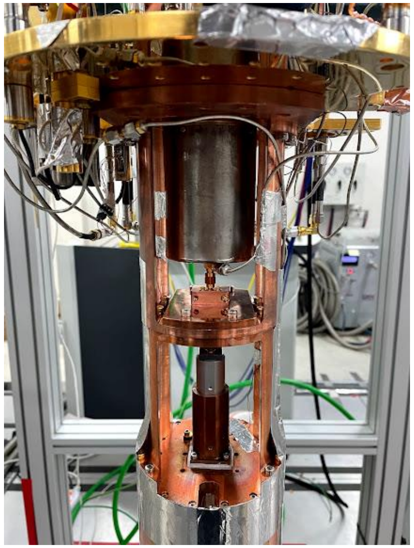

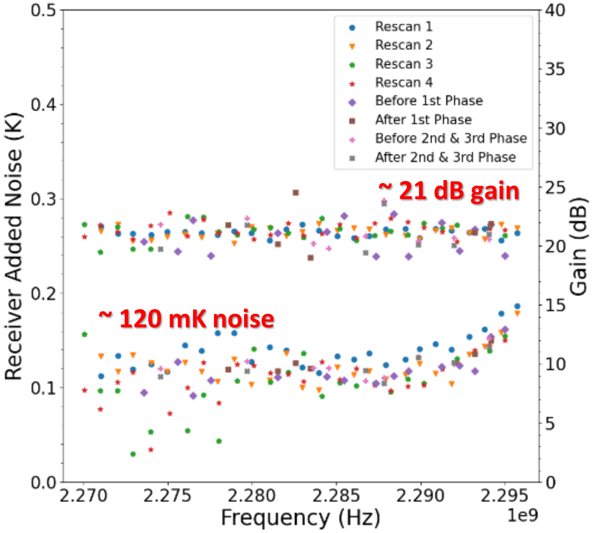

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JPA Gain

Superconducting Cavity Run Operation

- At 2.3 GHz for $g_\gamma = 0.99 \times g_\gamma^{KSVZ}$ axion

B_0	V	C	Q_0	β	SNR	η	T_{tot}
6.95 T	1.5 L	~ 0.6	430,000	~ 1.75	3.5	0.7	~ 180 mK

~ 0.6 MHz / day

- For 2272 – 2295 MHz (23 MHz), ~ 39days

- 1st phase (2284 – 2295 MHz)

  \- Oct 7 ~ Oct 16, 2021

- 2nd phase (2284 – 2295 MHz)

  \- Oct 26 ~ Nov 4, 2021

- 3rd phase (2272 – 2284 MHz)

  \- Nov 5 ~ Nov 26, 2021

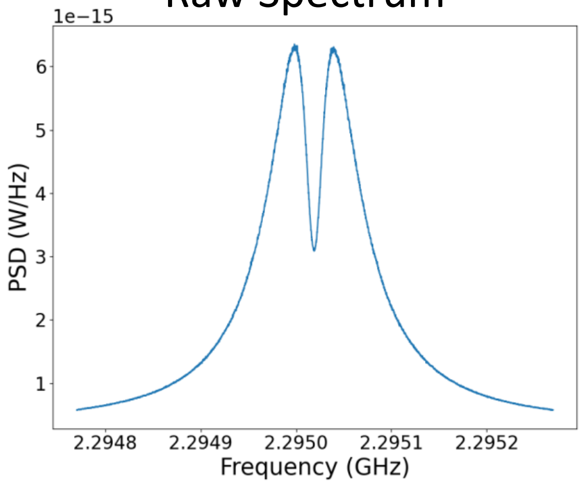
- Re-scan

  \- Jun 20 ~, 2022

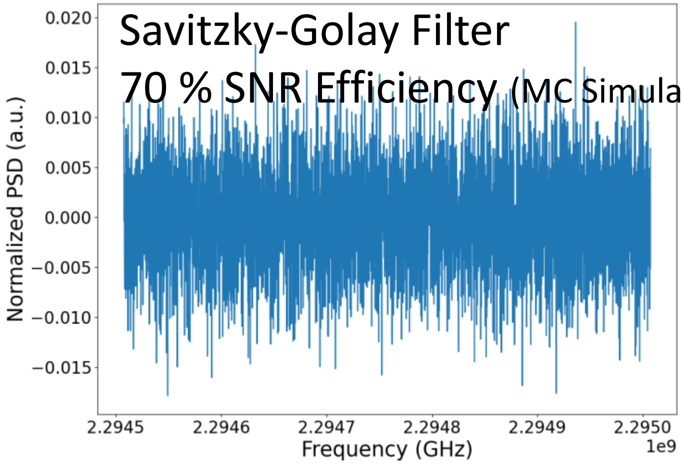
Total 8077 spectra

Analysis

Raw Spectrum



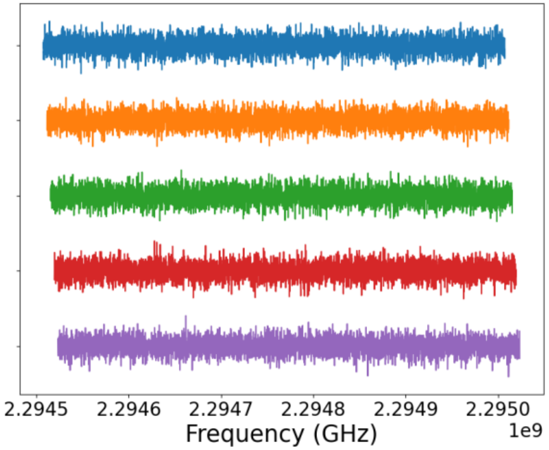
Baseline Removal



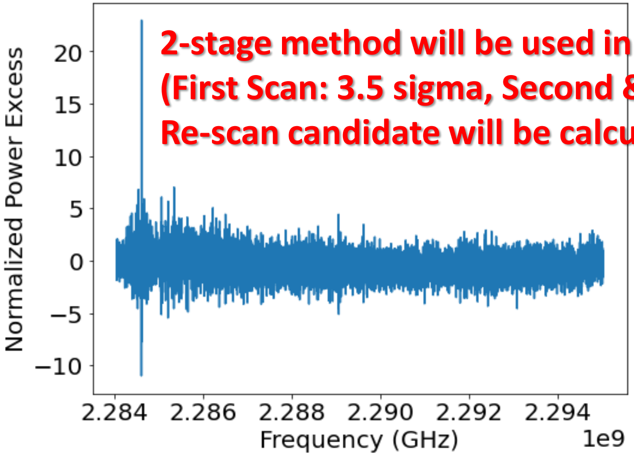
Savitzky-Golay Filter

70 % SNR Efficiency (MC Simulation Result)

Vertical Combination



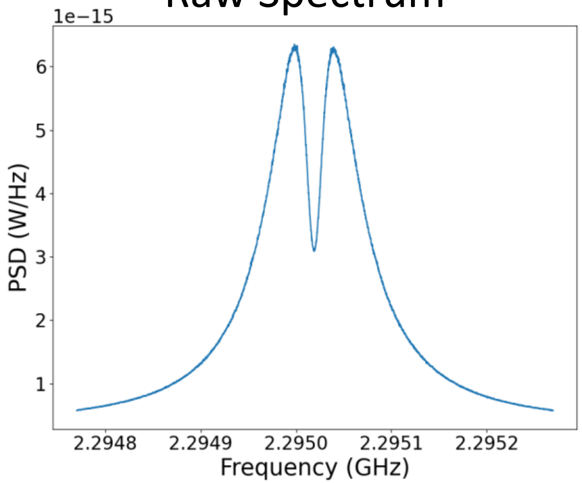
Grand Spectrum (1st & 2nd Phase)



2-stage method will be used in 2020 JPA run
(First Scan: 3.5 sigma, Second & Re-scan 5 sigma)
Re-scan candidate will be calculated

Analysis

Raw Spectrum



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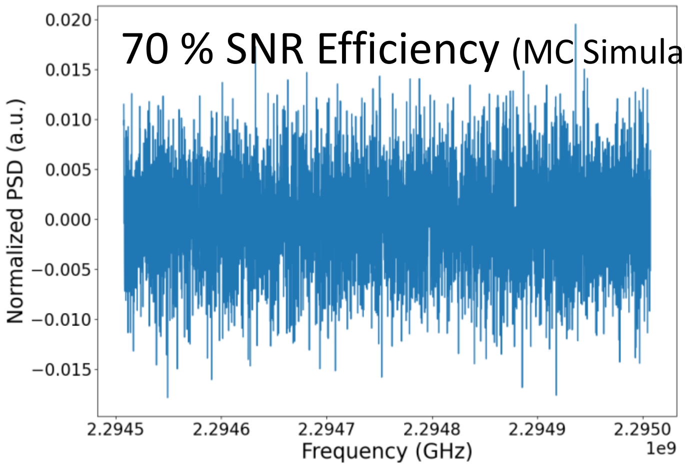

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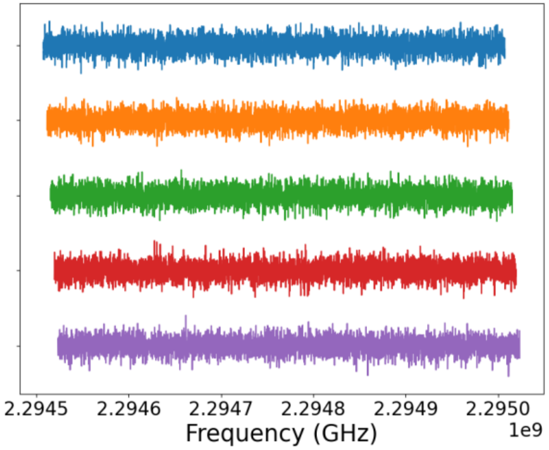

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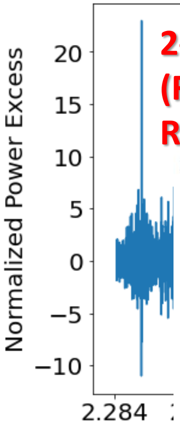

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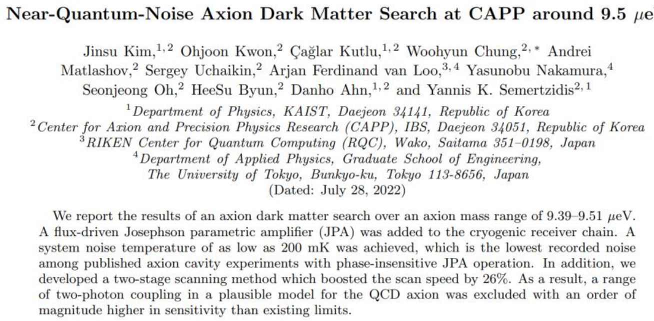


Near-Quantum-Noise Axion Dark Matter Search at CAPP around 9.5 μeV

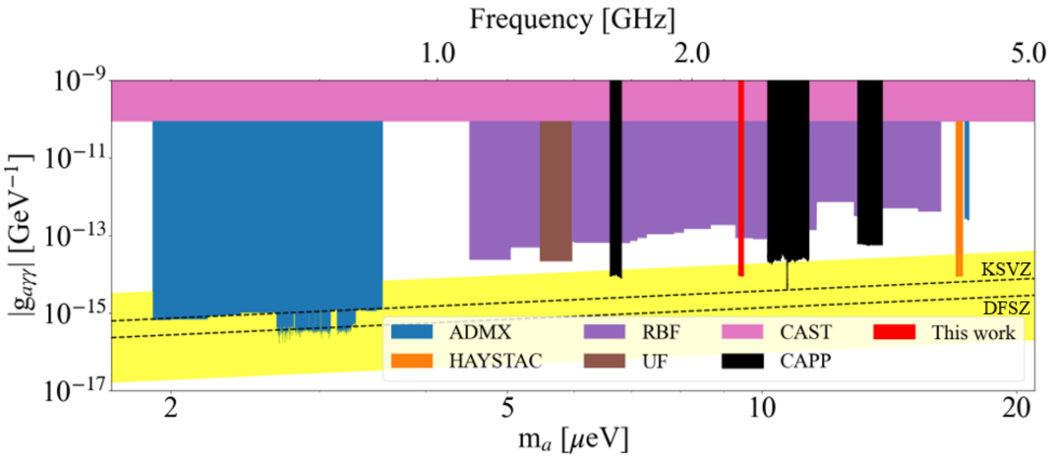
Jinsu Kim,[1,2] Ohjoon Kwon,[2] Çağlar Kutlu,[1,2] Woohyun Chung,[2,*] Andrei Matlashov,[2] Sergey Uchaikin,[2] Arjan Ferdinand van Loo,[3,4] Yasunobu Nakamura,[4] Seonjeong Oh,[2] HeeSu Byun,[2] Danho Ahn,[1,2] and Yannis K. Semertzidis[2,1]

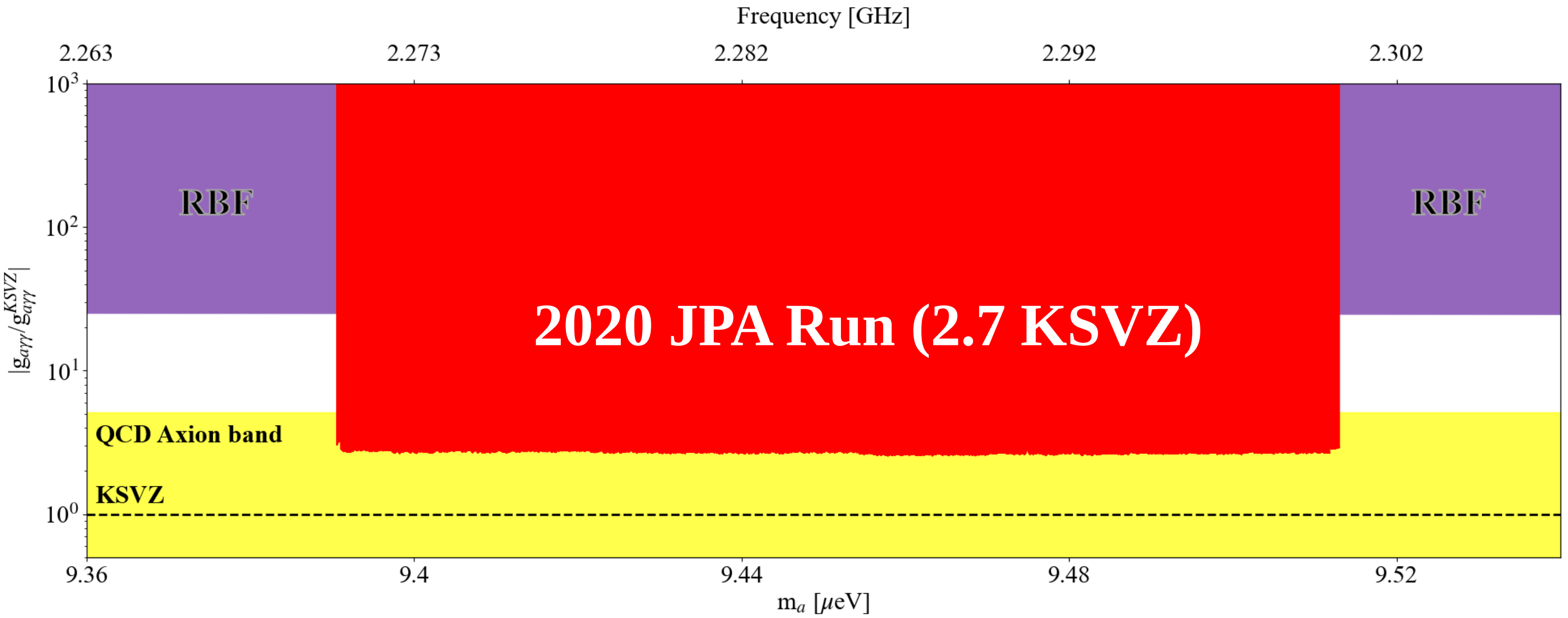
[1] *Department of Physics, KAIST, Daejeon 34141, Republic of Korea*
[2] *Center for Axion and Precision Physics Research (CAPP), IBS, Daejeon 34051, Republic of Korea*
[3] *RIKEN Center for Quantum Computing (RQC), Wako, Saitama 351–0198, Japan*
[4] *Department of Applied Physics, Graduate School of Engineering,*
The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan

(Dated: July 28, 2022)

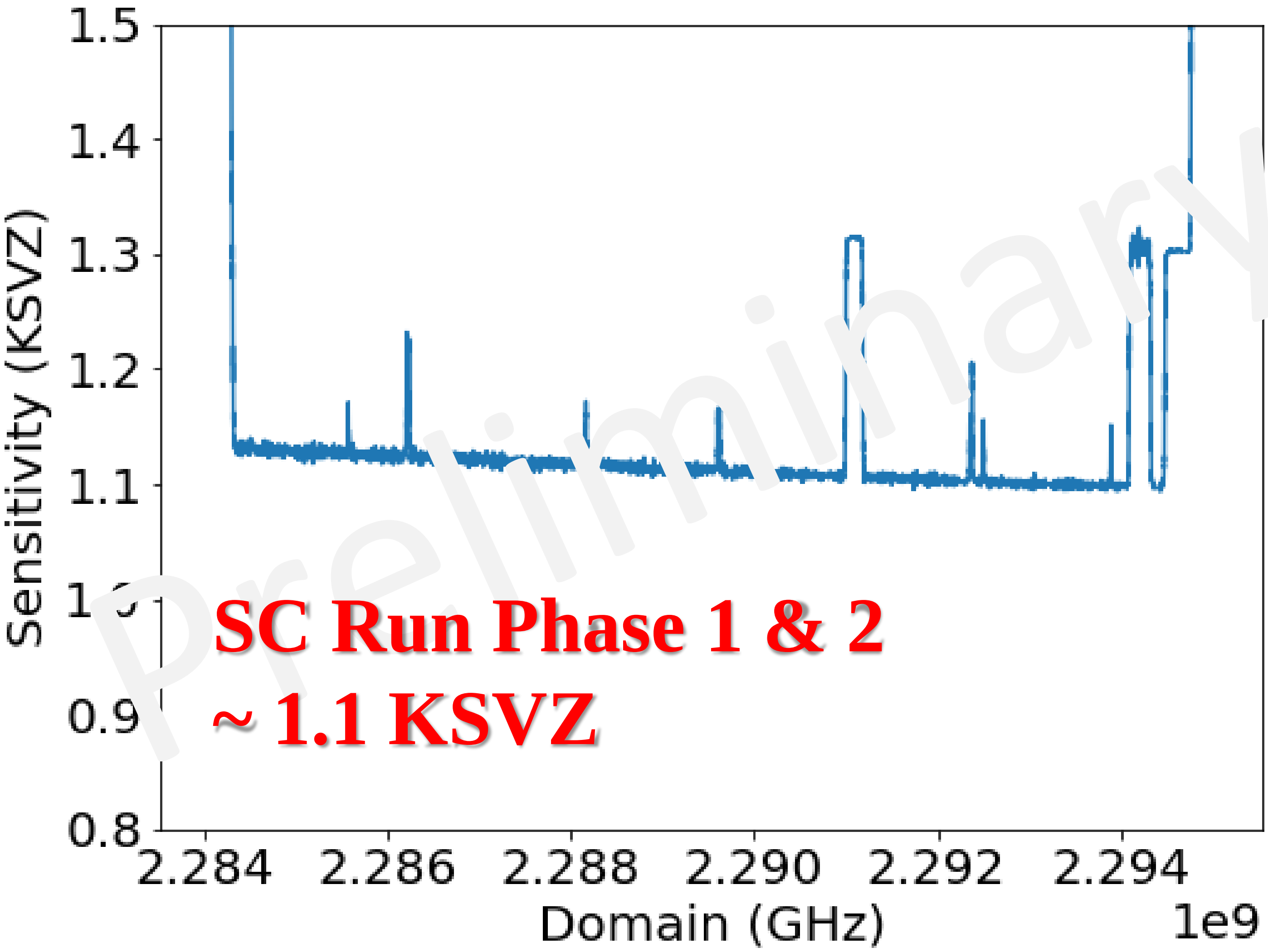
We report the results of an axion dark matter search over an axion mass range of 9.39–9.51 μeV. A flux-driven Josephson parametric amplifier (JPA) was added to the cryogenic receiver chain. A system noise temperature of as low as 200 mK was achieved, which is the lowest recorded noise among published axion cavity experiments with phase-insensitive JPA operation. In addition, we developed a two-stage scanning method which boosted the scan speed by 26%. As a result, a range of two-photon coupling in a plausible model for the QCD axion was excluded with an order of magnitude higher in sensitivity than existing limits.

Data & Exclusion Plot





Data & Exclusion Plot

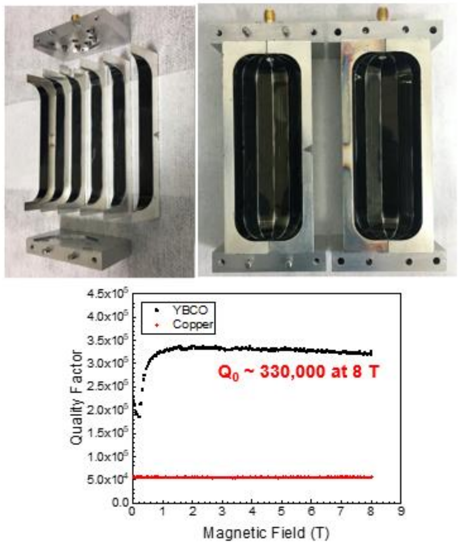


SC Run Phase 1 & 2

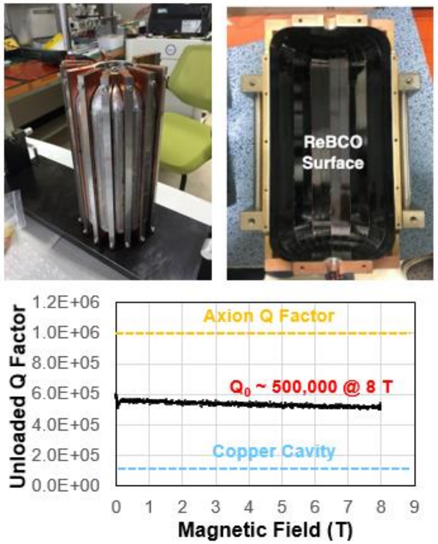
~ 1.1 KSVZ

History of Superconducting Cavity R&D

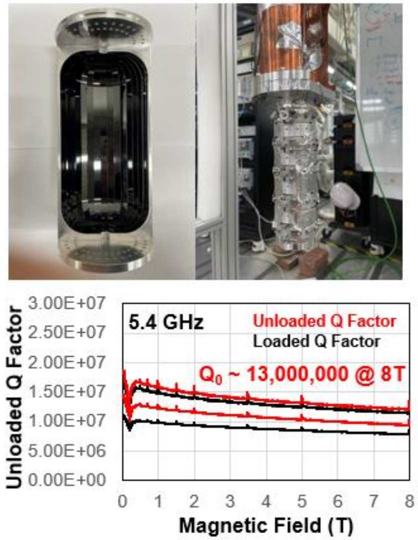
First Gen. (6.9 GHz)



Second Gen. (2.3 GHz)

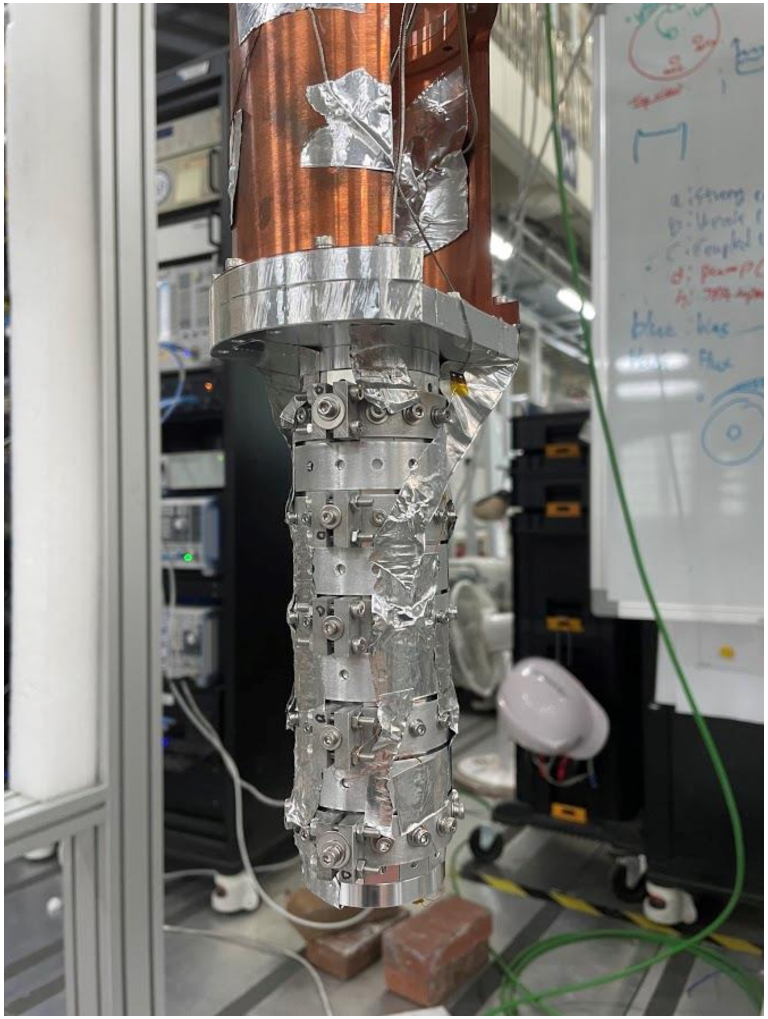


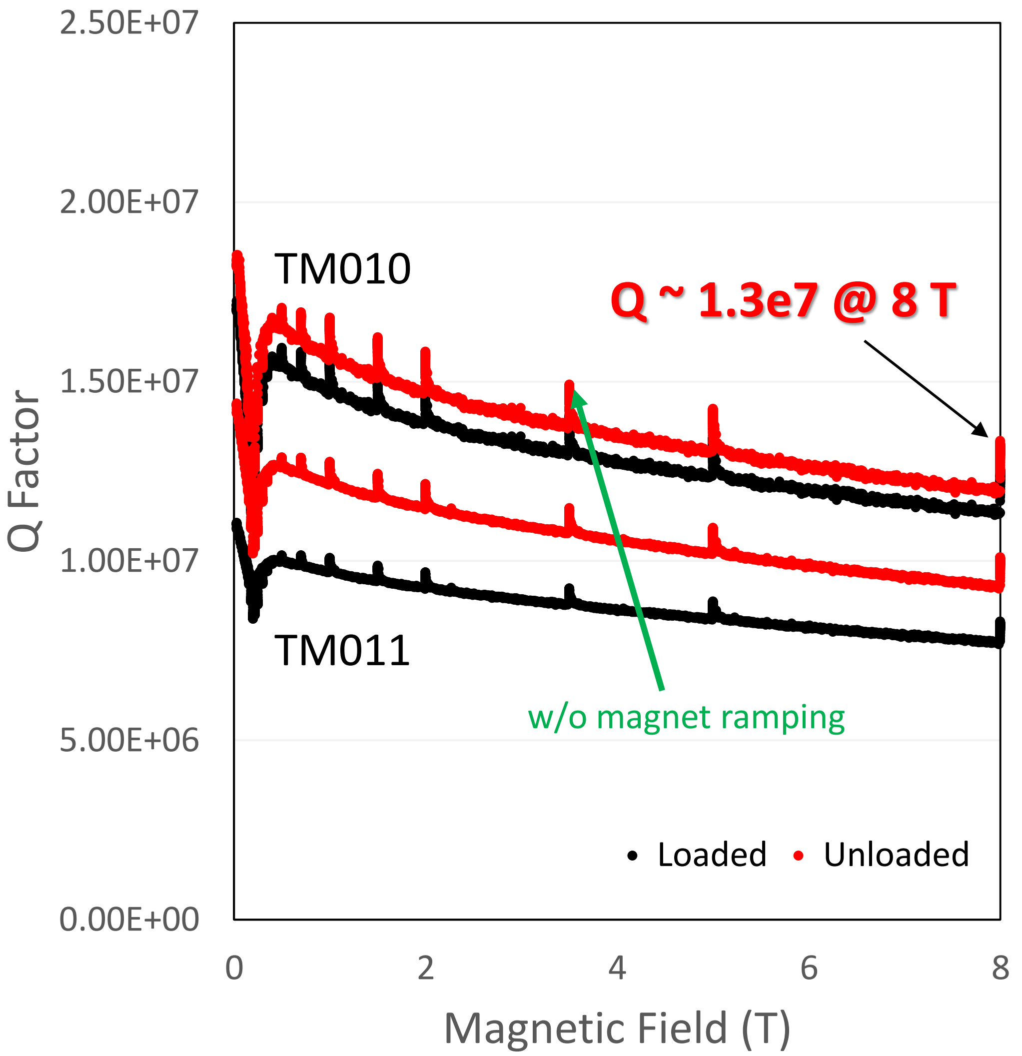
Third Gen. (2.2 GHz & 5.4 GHz)



Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T 330,000 @ 8 T
2nd Gen	GdBCO	Hastelloy	1.5	2.3	~ 500,000 @ 8 T
3rd Gen	EuBCO + APC	Hastelloy	1.5	2.2	4,500,000 @ 0 T Waiting for Magnet Test
	EuBCO + APC	Hastelloy	0.2	5.4	~ 13,000,000 @ 8 T

13 Million Q Factor Cavity at 8 T





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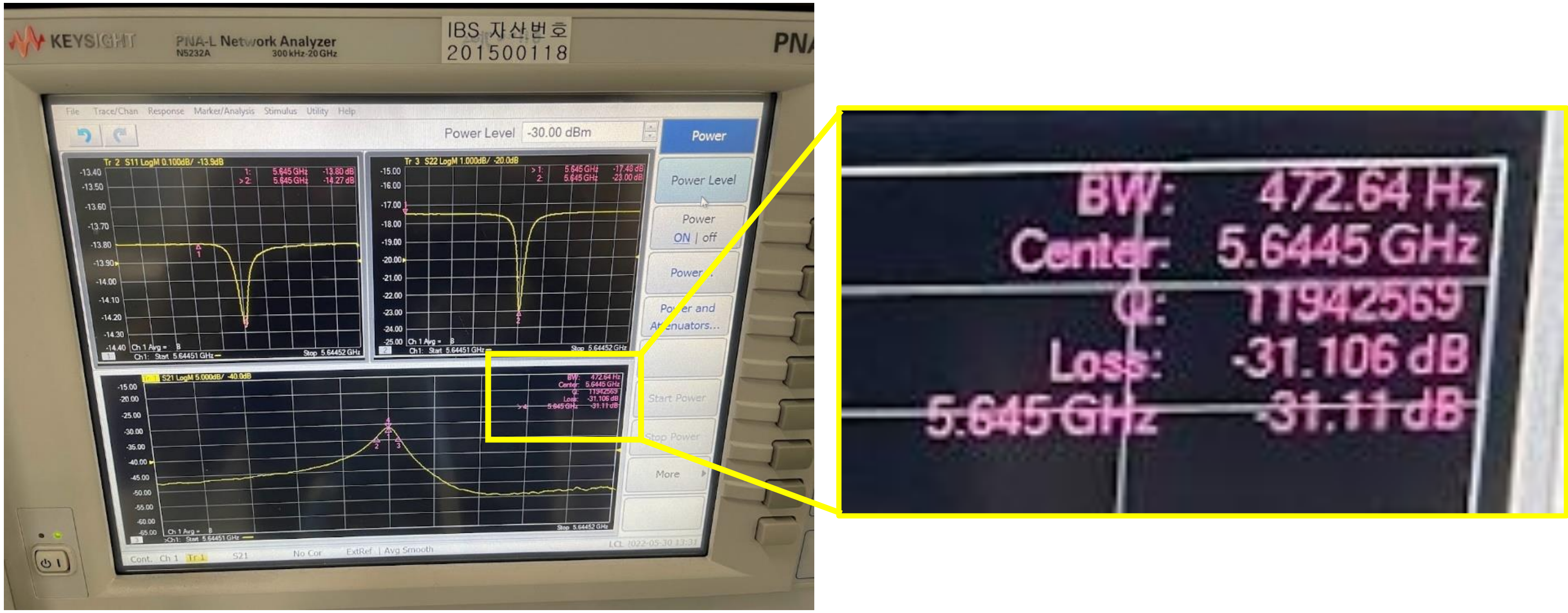


BW: 472.64 Hz
Center: 5.6445 GHz
Q: 11942569
Loss: -31.106 dB
5.645 GHz -31.11 dB

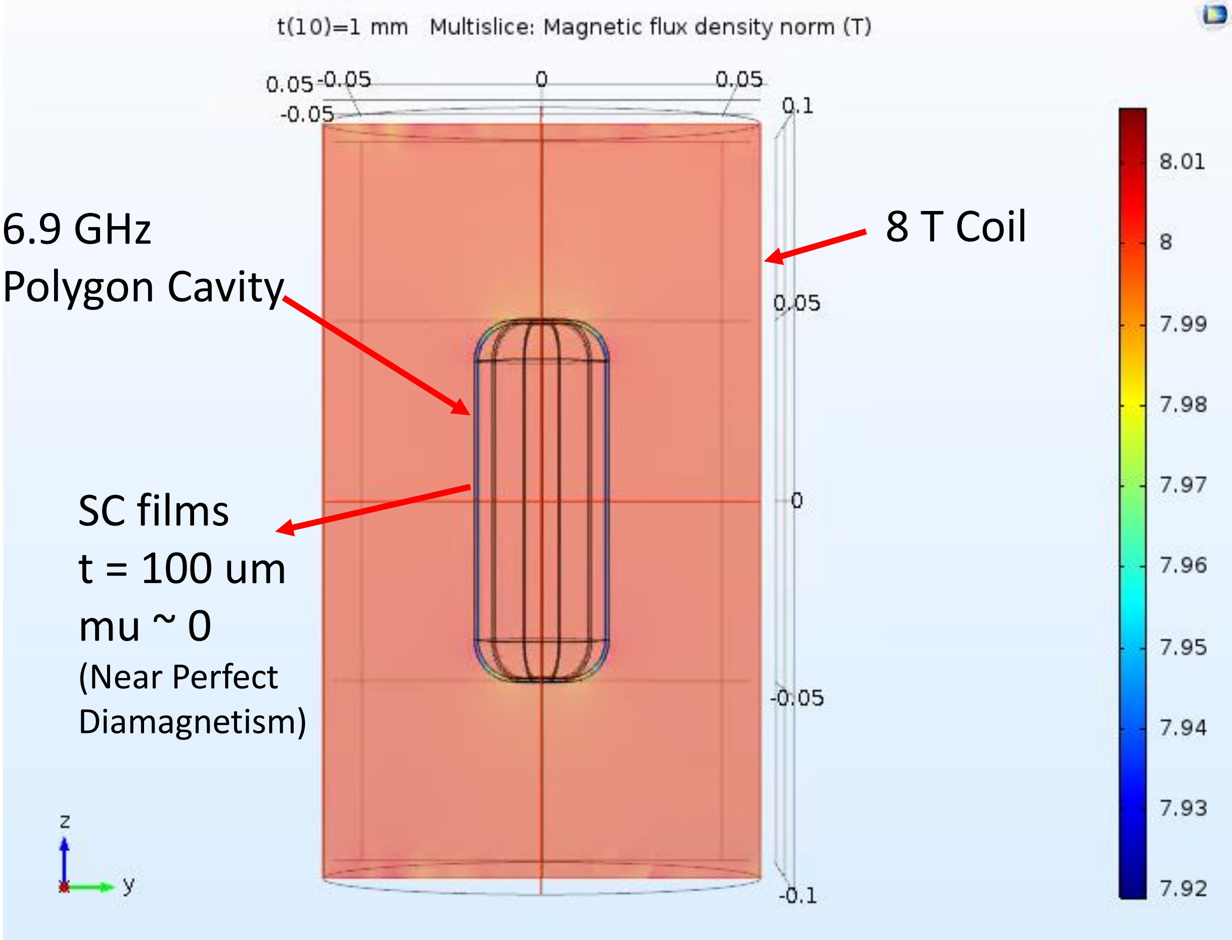
- ➢ The result shows that HTS cavity can reach 10 times larger than axion quality factor (~ 10^6).
- ➢ If we use next generation cavities, the scan rate will be more than 50 times bigger than copper cavities.
- ➢ **CAPP is also planning to construct 36 liter HTS cavity for CAPP-12TB.**

Summary

- Superconducting Cavity R&D at CAPP aims to enhance axion search with a high Q factor cavity using superconductors.
- ReBCO is one of the most promising materials for realizing a high Q cavity in a high magnetic field.
- CAPP successfully developed a half-million Q factor ReBCO cavity with a 2.3 GHz resonance frequency working in an 8 T magnetic field.
- The physics data from the 2.3 GHz ReBCO cavity was successfully taken.
- CAPP-PACE team is now planning to finalize analysis and take rescan data.
- Recently, CAPP developed 13 M Q factor cavity.
- Next generation cavities are waiting for the experiments.
  - Plan for developing high-temperature superconducting cavity for 12 TB magnet

Stay Tuned!

Magnetic Field in a Superconducting Cavity



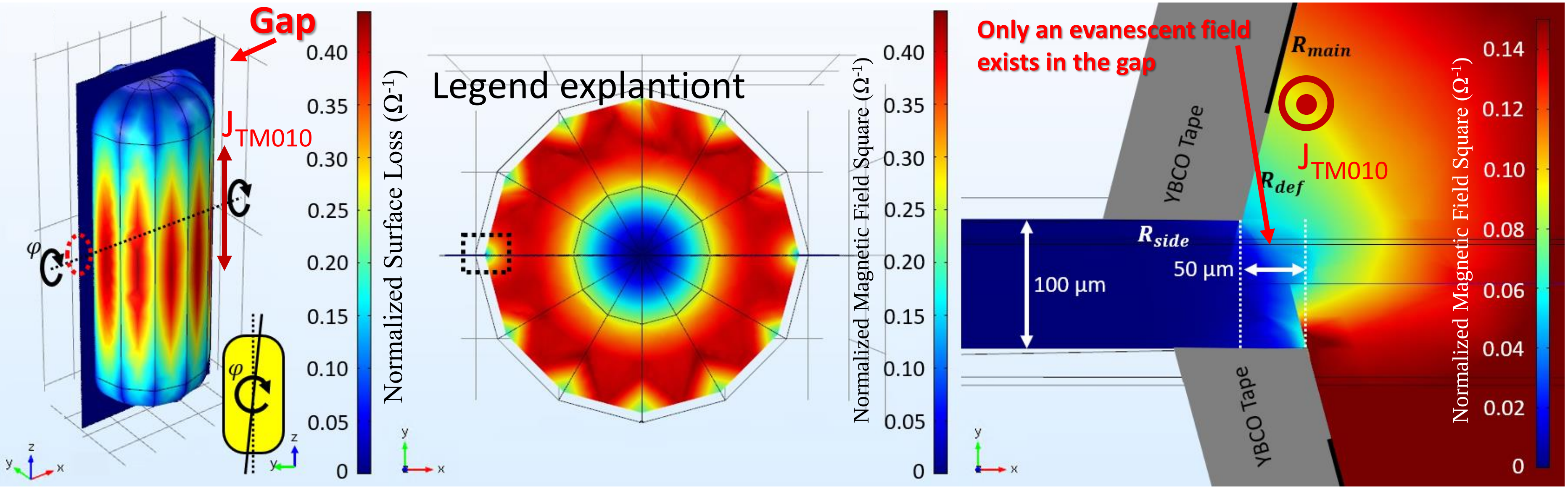
6.9 GHz
Polygon Cavity

SC films
t = 100 um
mu ~ 0
(Near Perfect
Diamagnetism)

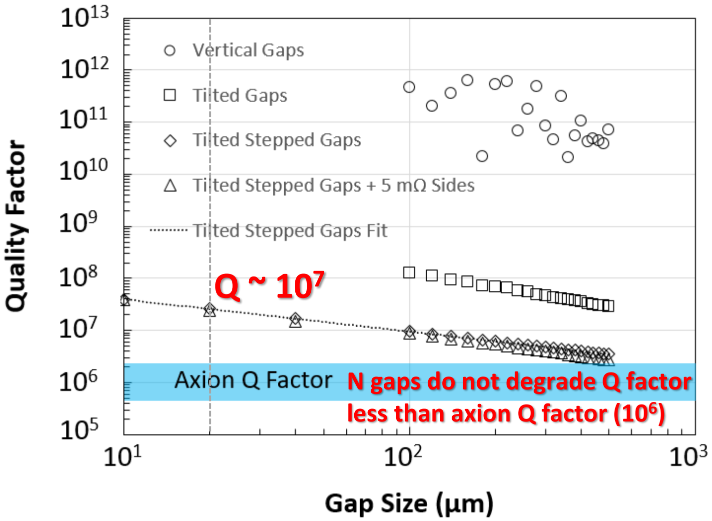
8 T Coil

- Simulation Situation: Polygon Shell with 100 μm Perfect Superconductor
- **$\Delta B_{avg}/B_{avg} \sim 10^{-4}$ even with over-estimated condition of shielding**
- Actual Situation: 1 – 5 μm Superconducting Film & Non-Perfect Diamagnetism

N Gaps Do Not Degrade Q_{TM010}

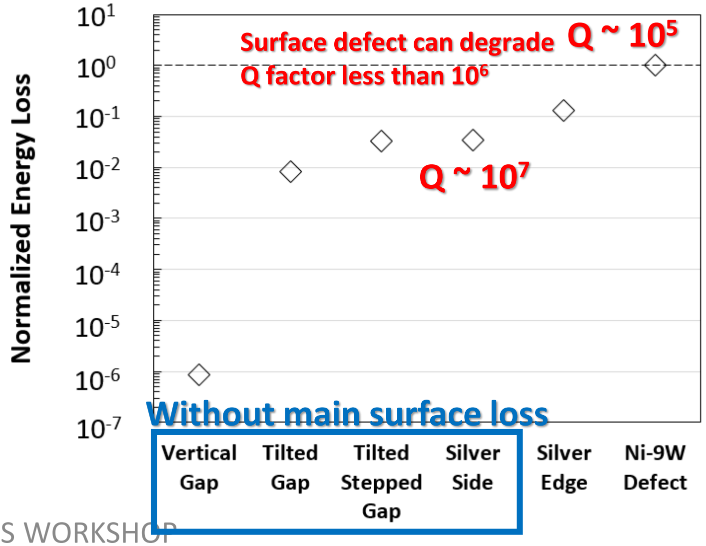


Only an evanescent field exists in the gap



Q ~ 10^7

N gaps do not degrade Q factor less than axion Q factor (10^6)



Surface defect can degrade Q factor less than 10^6

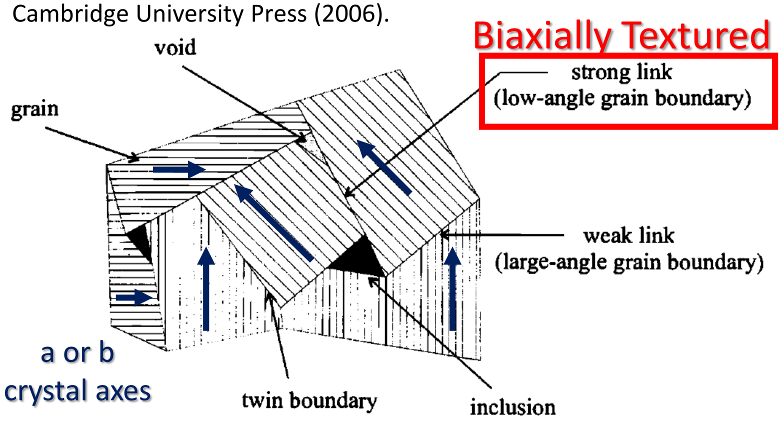
Q ~ 10^5

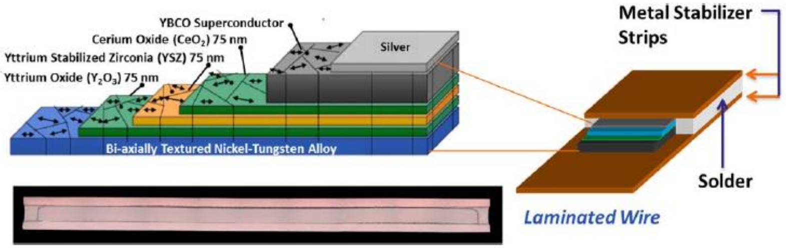
Q ~ 10^7

Without main surface loss

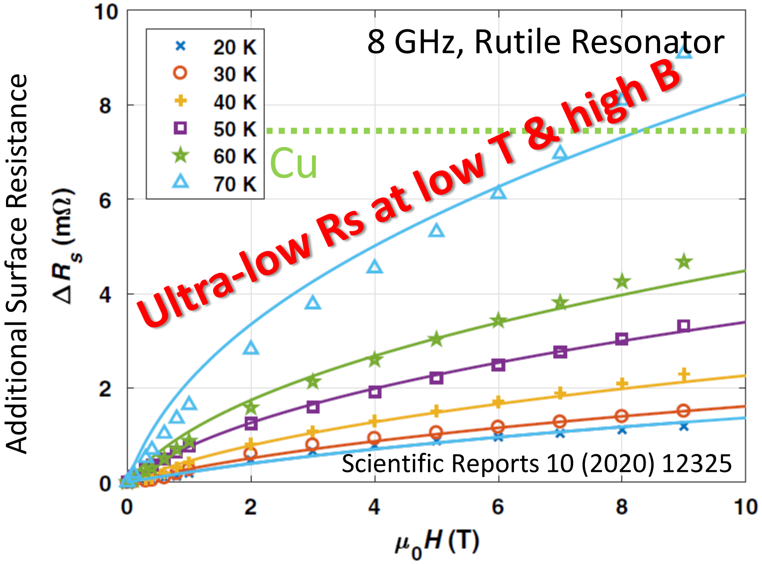
Bixaxially-Textured ReBCO

M. J. Lancaster, “Passive microwave device applications of HTS”, Cambridge University Press (2006).





IEEE Trans. Appl. Supercond. 23 (2013) 6601205



Scientific Reports 10 (2020) 12325

- ➢ Biaxial texture is essential to avoid weak links.
  - Weak links at grain boundaries degrades surface resistance.
  - Biaxially-textured ReBCO films show low surface resistance at high magnetic field
  - Biaxially-textured ReBCO films show high depinning frequency.
- ➢ Many providers can produce biaxially-textured ReBCO film.

Bixaxially-Textured ReBCO

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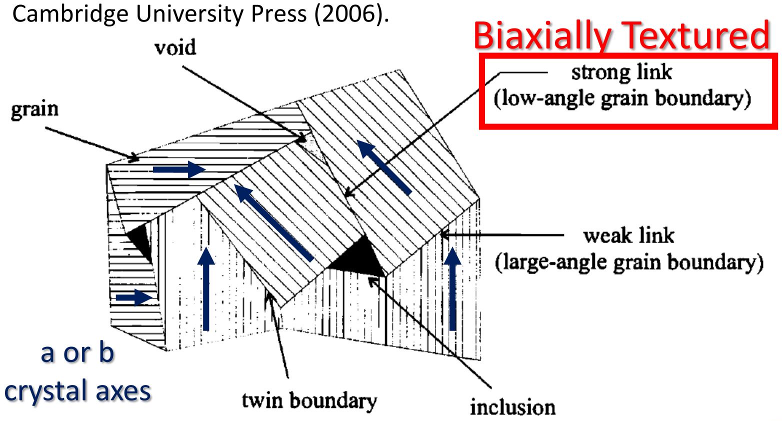

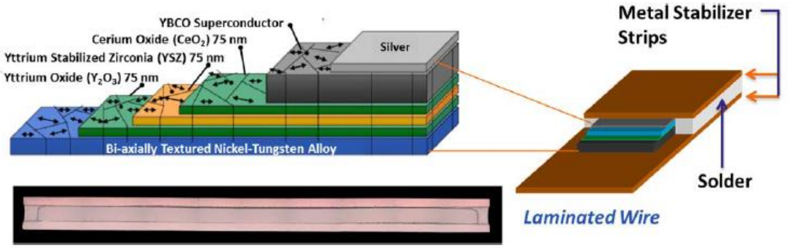

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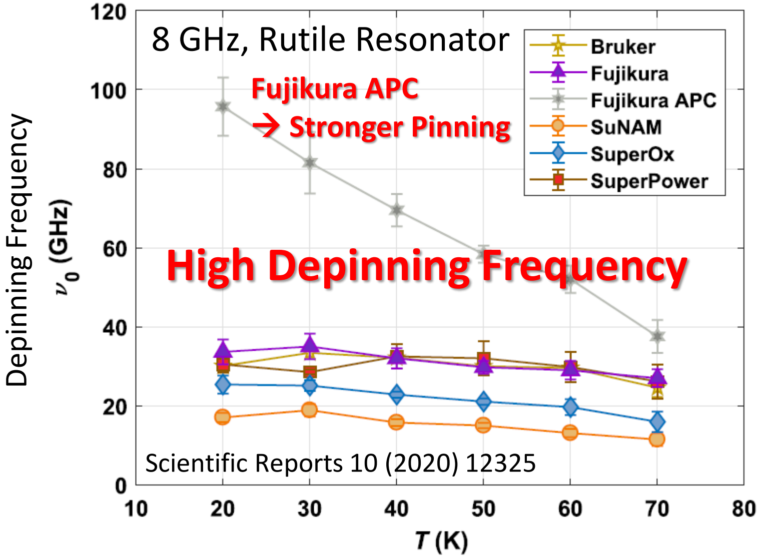

Scientific Reports 10 (2020) 12325

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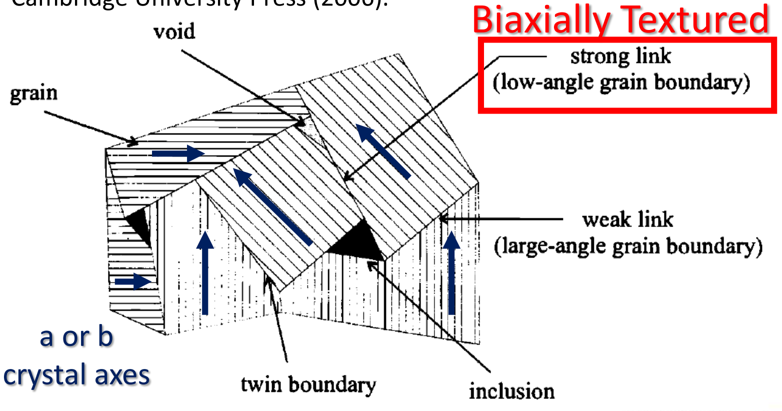

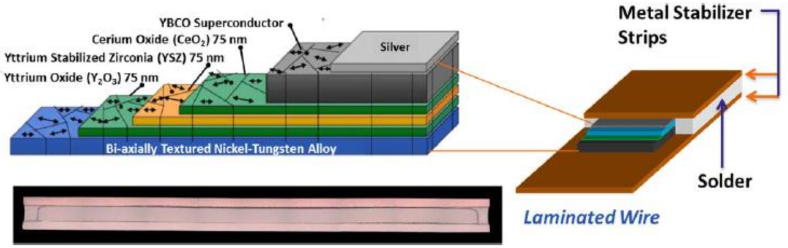

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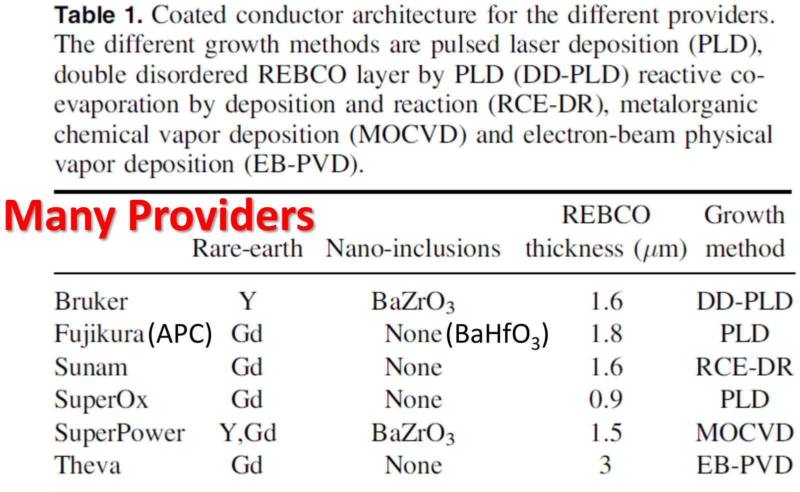


Table 1. Coated conductor architecture for the different providers. The different growth methods are pulsed laser deposition (PLD), double disordered REBCO layer by PLD (DD-PLD) reactive co-evaporation by deposition and reaction (RCE-DR), metalorganic chemical vapor deposition (MOCVD) and electron-beam physical vapor deposition (EB-PVD).

Many Providers

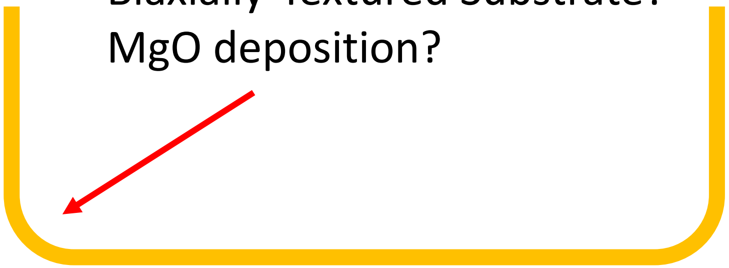
	Rare-earth	Nano-inclusions	REBCO thickness (μm)	Growth method
Bruker	Y	$BaZrO_3$	1.6	DD-PLD
Fujikura (APC)	Gd	None (BaHfO_3)	1.8	PLD
Sunam	Gd	None	1.6	RCE-DR
SuperOx	Gd	None	0.9	PLD
SuperPower	Y,Gd	$BaZrO_3$	1.5	MOCVD
Theva	Gd	None	3	EB-PVD

SUST 32 (2019) 094006

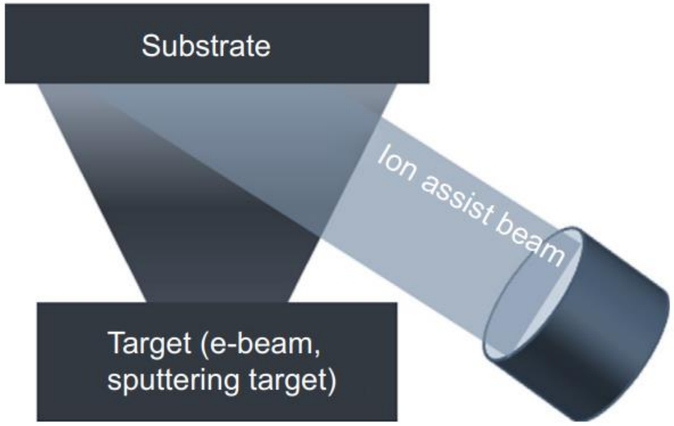
- ➢ Biaxial texture is essential to avoid weak links.
  - Weak links at grain boundaries degrades surface resistance.
  - Biaxially-textured ReBCO films show low surface resistance at high magnetic field
  - Biaxially-textured ReBCO films show high depinning frequency.
- ➢ Many providers can produce biaxially-textured ReBCO film.

Various Deposition Method for ReBCO

Ion-beam?
Biaxially-Textured Substrate?
MgO deposition?

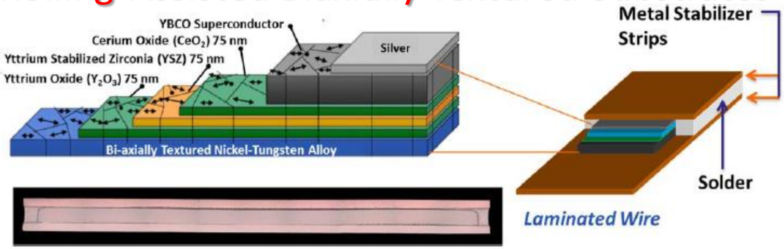


Ion-Beam Assisted Deposition (IBAD)



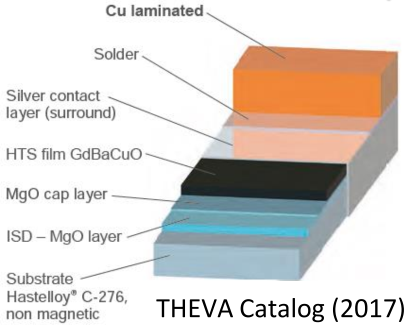
Superconductors in the Power Grid, Elsevier (2015)

Rolling-Assisted Biaxially Textured Substrates (RABiTS)

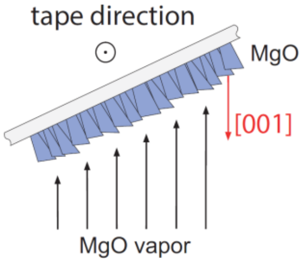


IEEE Trans. Appl. Supercond. 23 (2013) 6601205

Inclined-Substrate Deposition (ISD)



THEVA Catalog (2017)



- ➢ Directly forming a biaxially-textured ReBCO film on the deeply concaved inner surface of the cavities is difficult.
- ➢ **Can we make a cavity with ReBCO tapes?**