Axion Dark Matter Experiment in Korea

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Institute for Basic Science (IBS)

OUTLINE

- Introduction
  - Dark Matter Axion
  - CULTASK (CAPP's Ultra Low Temperature Axion Search in Korea)
- CAPP-PACE (Pilot Axion Cavity Exp.)
  - First complete axion experiment in Korea
  - Physics data (10*KSVZ and KSVZ runs) in 2018
- Improvements
  - High Field Magnets
  - Quantum Amplifiers
  - High Q-factor (superconducting) and dielectric cavity
- Summary

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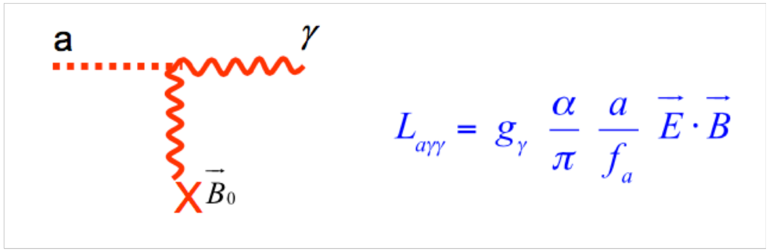
DM Axion

- Peccei and Quinn (1977) postulated an elegant solution by adding a new global symmetry to resolve the Strong CP Problem in Standard Model

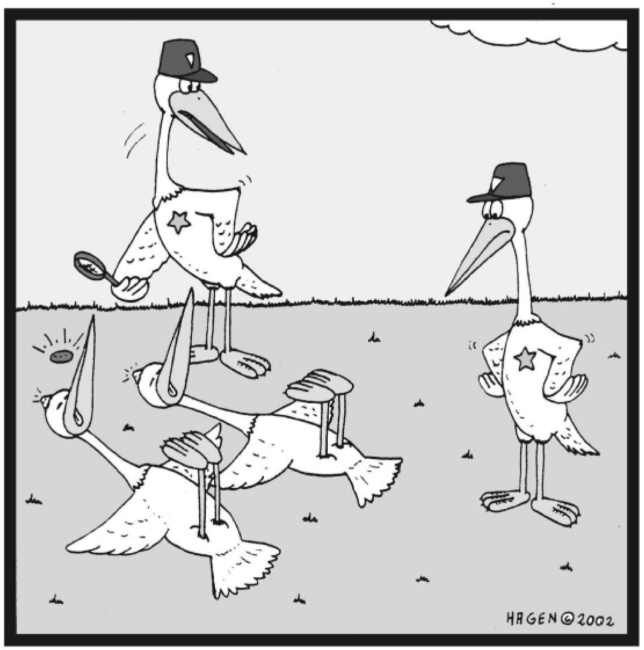
- Axion is an excellent (and attractive) dark matter candidate
  - Pseudo Goldstone Boson
  - Small Mass ($1\mu eV < m_a < 10 meV$)
  - Extremely Weakly Interacting
  - Local Halo Density of 0.45 GeV/cm^3
  - $\beta \sim 10^{-3} \rightarrow Q_a \sim 10^6$



- Detection scheme by P. Sikivie (PRL 51:1415 1983) : Haloscopy
  - Axions will convert to photons in a strong magnetic field

DM Axion

Killing Two Birds With One Stone



Unbelievable! It looks like they've
both been killed by the same stone...

Peccei-Quinn mechanism
- Solves strong CP problem
- Provides dark matter in the form of axions

Georg Raffelt, MPI Physics, Munich — Physics Colloquium, Univ. Sydney, 3 March 2014

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Axion dark matter search

- The axion mass is unknown, like any number in a phone book. The way we look for it:

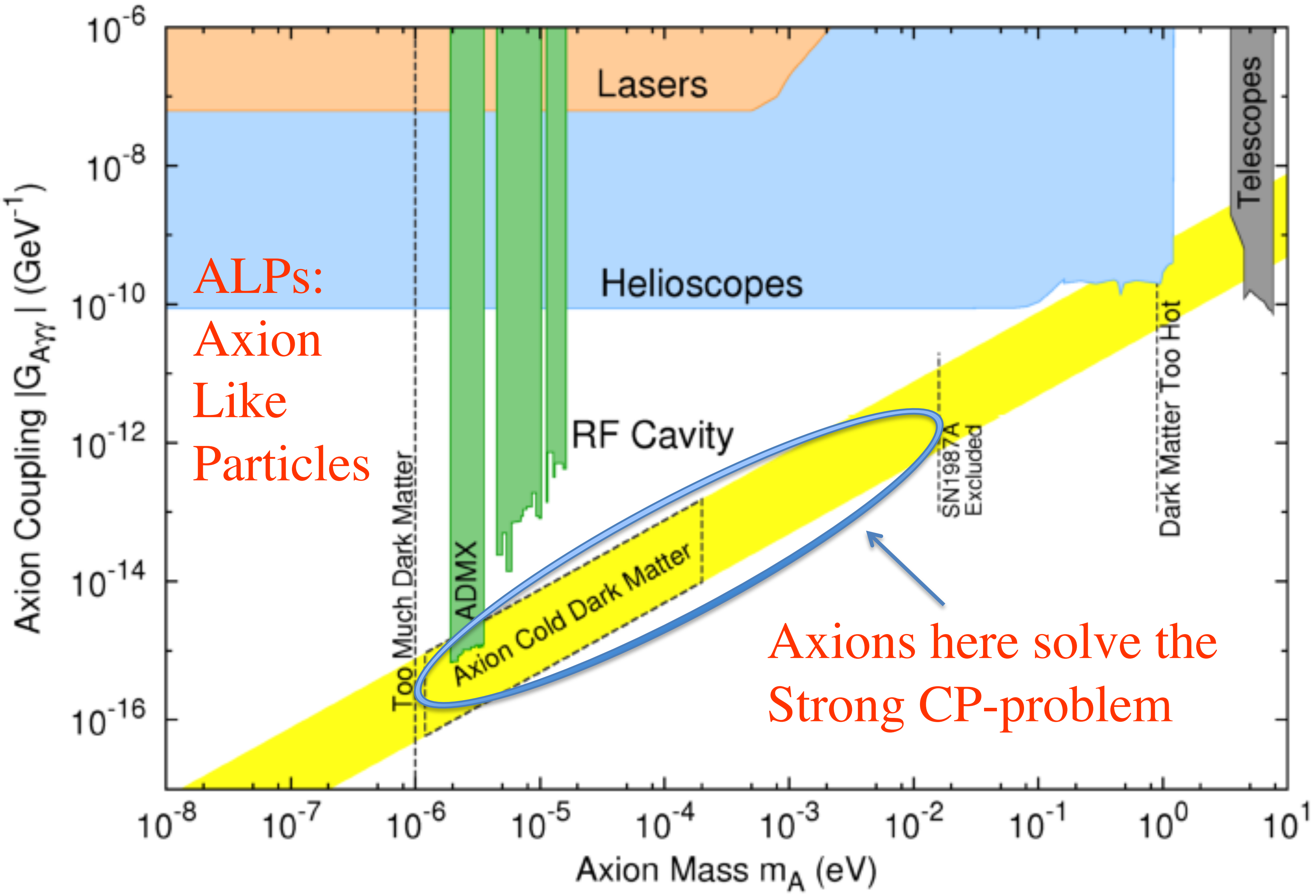


- Once it's discovered, anyone will be able to dial in… and talk to it.

Axion Search Experiments

- Cosmic Axion Search
  - Haloscopes (Microwave Cavity) ← Most sensitive so far
  - Dish Antenna
  - Dielectric Haloscope
  - LC Circuit
  - NMR techniques
  - Atomic Transitions
- Solar axion search
  - Axion Helioscopes
  - Bragg Diffraction Scattering
  - Geomagnetic Conversion
- Laboratory Axion Search
  - Light Shining through Wall
  - Polarization Experiment
  - 5^{th} Force

Axion Landscape



Axion Detection Scheme (CULTASK)

P. Sikivie's Haloscope:

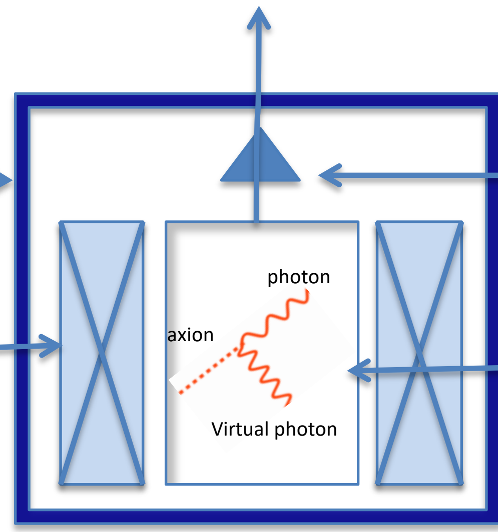
Axion Conversion Power (~10^{-24}W): $P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$

Signal to Noise Ratio: $SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}} \sqrt{\frac{t_{int}}{\Delta f_a}}$

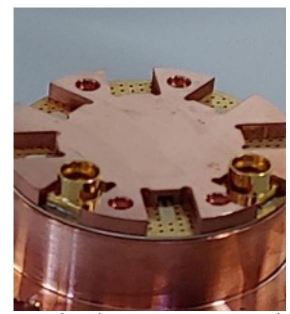
Scan rate: $\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$

Cryogenics (<50mK)

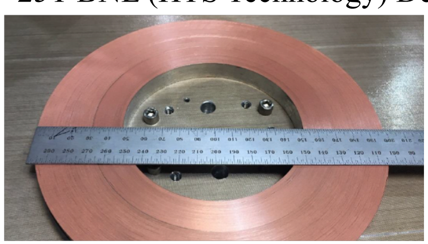
To RF Receiver



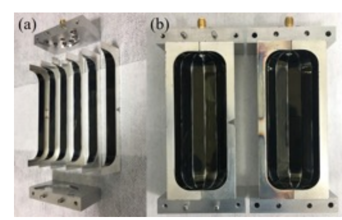
Quantum Amplifier
SQUID and/or JPA
Dr. Matlashov and Uchaikin



High Field SC Magnet
25T BNL (HTS Technology) Design



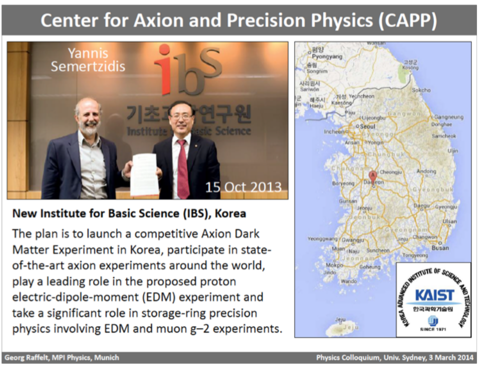
High Q Tunable Cavity
Superconducting Coating
Prof. Dojun Youm



First 5 years…

Axion Laboratory with 7 Low Vibration Pads in KAIST Munji campus

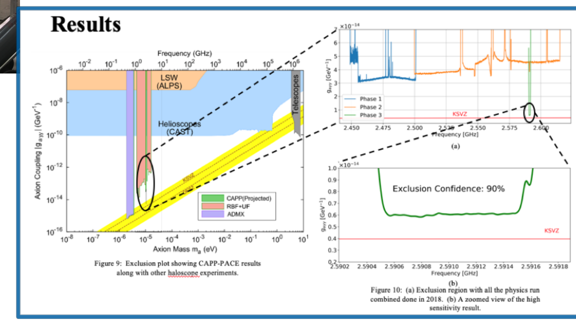
Founded in 2013 (Oct.)



BF3 & BF4

BF5 & BF6

First Axion DM data!

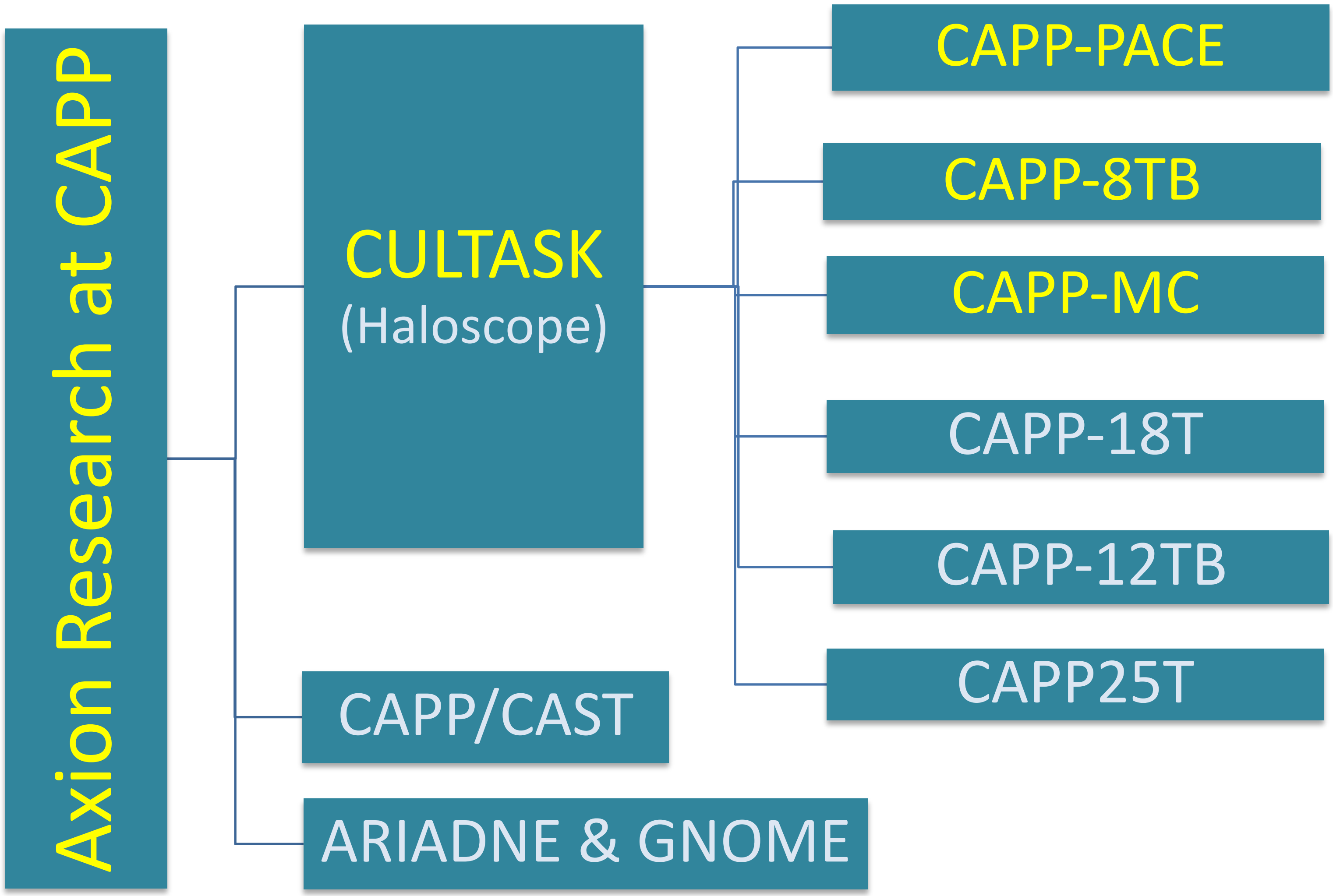


LVP

2013	2014	2015	2016	2017	2018	2019

CAPP Experimental Hall (LVP) in 2018

CAPP's Axion Research



Refrigerators and Magnets

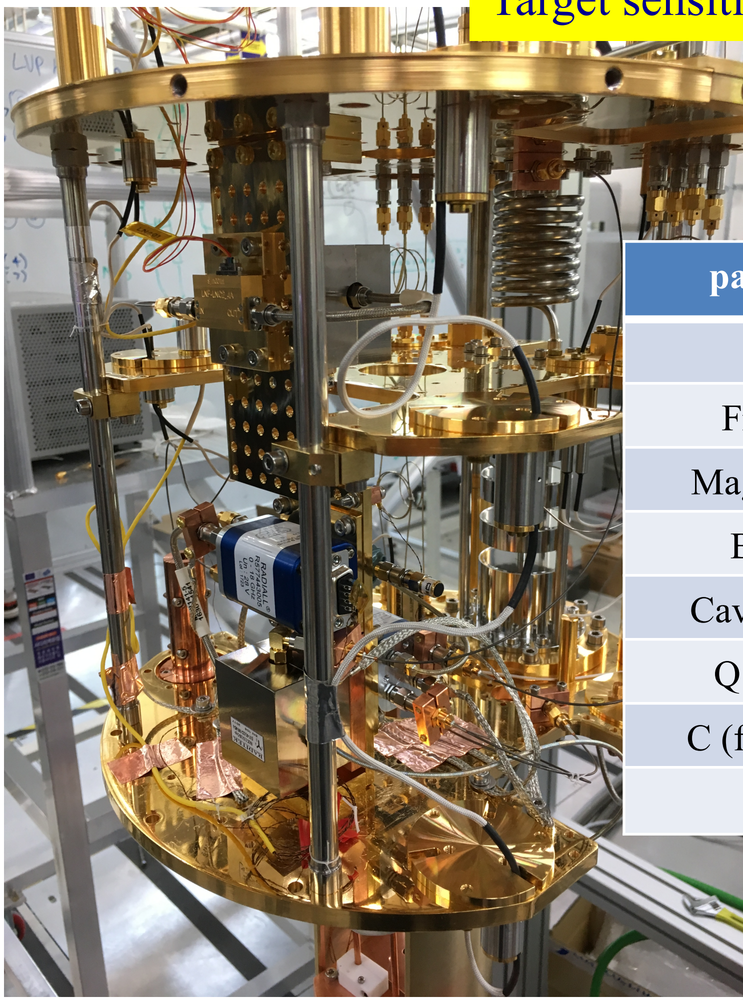
Refrigerators					Magnets					EXP
Vendor	**Model**	**Base T (mK)**	**Cooling power**	**Install**	**B field**	**Bore (cm)**	**Material**	**Vendor**	**Delivery**	
BlueFors (BF3)	LD400	10	18μW@20mK 580μW@100mK	2016	**26T**	3.5	HTS	SUNAM	2016	BF3 & BF4 for testing RF, QA and cavities
BlueFors (BF4)	LD400	10	18μW@20mK 580μW@100mK	2016	**18T**	7	HTS	SUNAM	2017	
Janis	HE3	300	25μW@300mK	2017	**9T**	12	NbTi	Cryo-Magnetics	2017	CAPP-MC
BlueFors (BF5)	**LD400**	**10**	18μW@20mK 580μW@100mK	**2017**	**8T**	**12**	**NbTi**	**AMI**	**2016**	CAPP-PACE
BlueFors (BF6)	LD400	10	18μW@20mK 580μW@100mK	2017	**8T**	16.5	NbTi	AMI	2017	CAPP-8TB
Oxford	Kelvinox	<30	400μW@120mK	2017	**25T**	**10**	HTS	BNL/CAPP	2020	Preparing for CAPP-12TB and CAPP-25T
Leiden	DRS1000	100	1.3mW @120mK	2019	**12T**	**32**	Nb_3Sn	Oxford	2020	

CAPP-PACE (Pilot Axion Cavity Experiment)

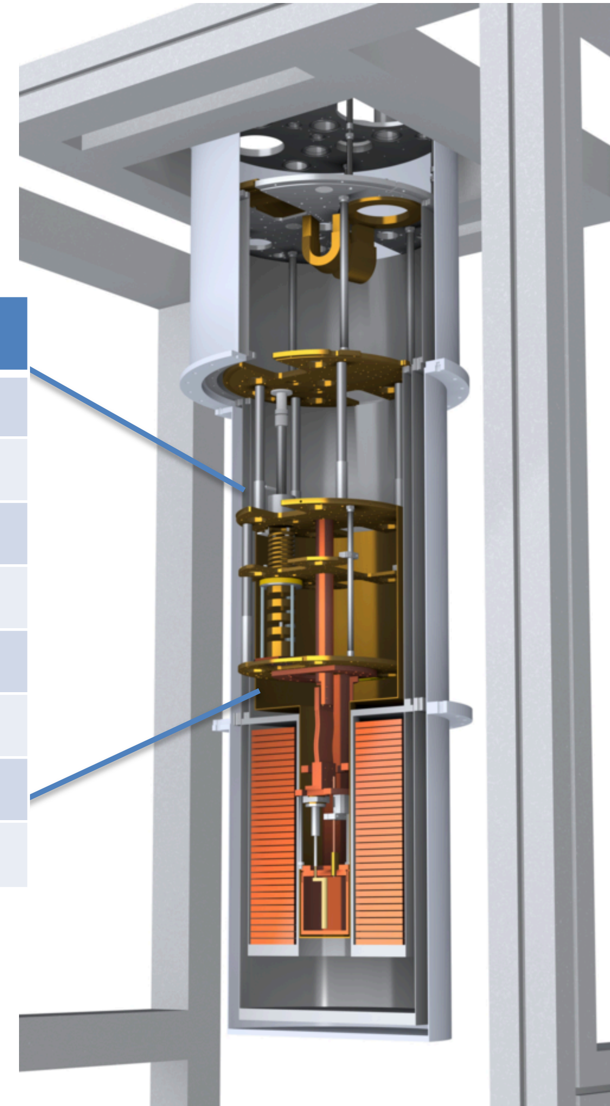
- Originally, R&D Project and testbed for
  - Cavity development
  - Frequency Tuning System (FTS)
  - RF receiver components (Optimization with cryo-RF)
  - DAQ and Controls
- Has grown into the first complete axion experiment in Korea
  - Achieved cavity physical temperature below 40 mK
  - Flawless operation of FTS w/ Piezo actuators (sapphire and Cu rod)
  - System noise temperature below 1.2 K
  - Complete DAQ and Controls including automatic Safety Warnings
- Physics Data in 2018
  - 10*KSVZ runs: 2.45 – 2.70 GHz scanned
  - KSVZ run: around 2.59 GHz, ~ 1 MHz scanned

CAPP-PACE

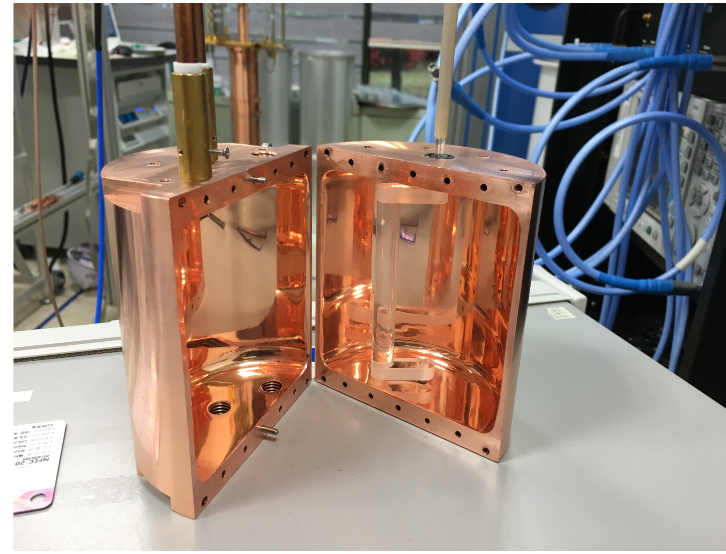
Target sensitivity: 10*KSVZ, KSVZ



parameters	value
T_{cavity}	**<40mK (WR)**
Frequency	**2.45~2.70GHz**
Magnetic field	**8 T**
Bore size	**11.8 cm**
Cavity volume	**1.12 L**
Q unloaded	**~ 100,000**
C (form factor)	**~ 0.6**
T_{system}	**< 1.5 K**



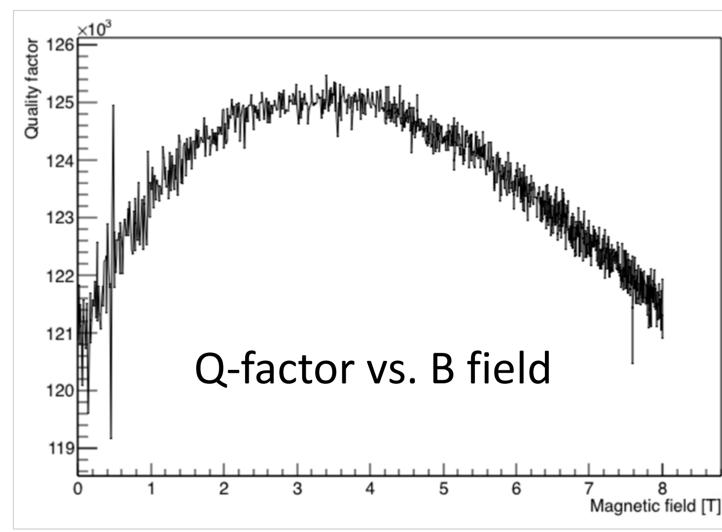
CAPP-PACE (innovations)



Cavity: OFHC Cu "split" type
Unloaded Q-factor of ~100,000

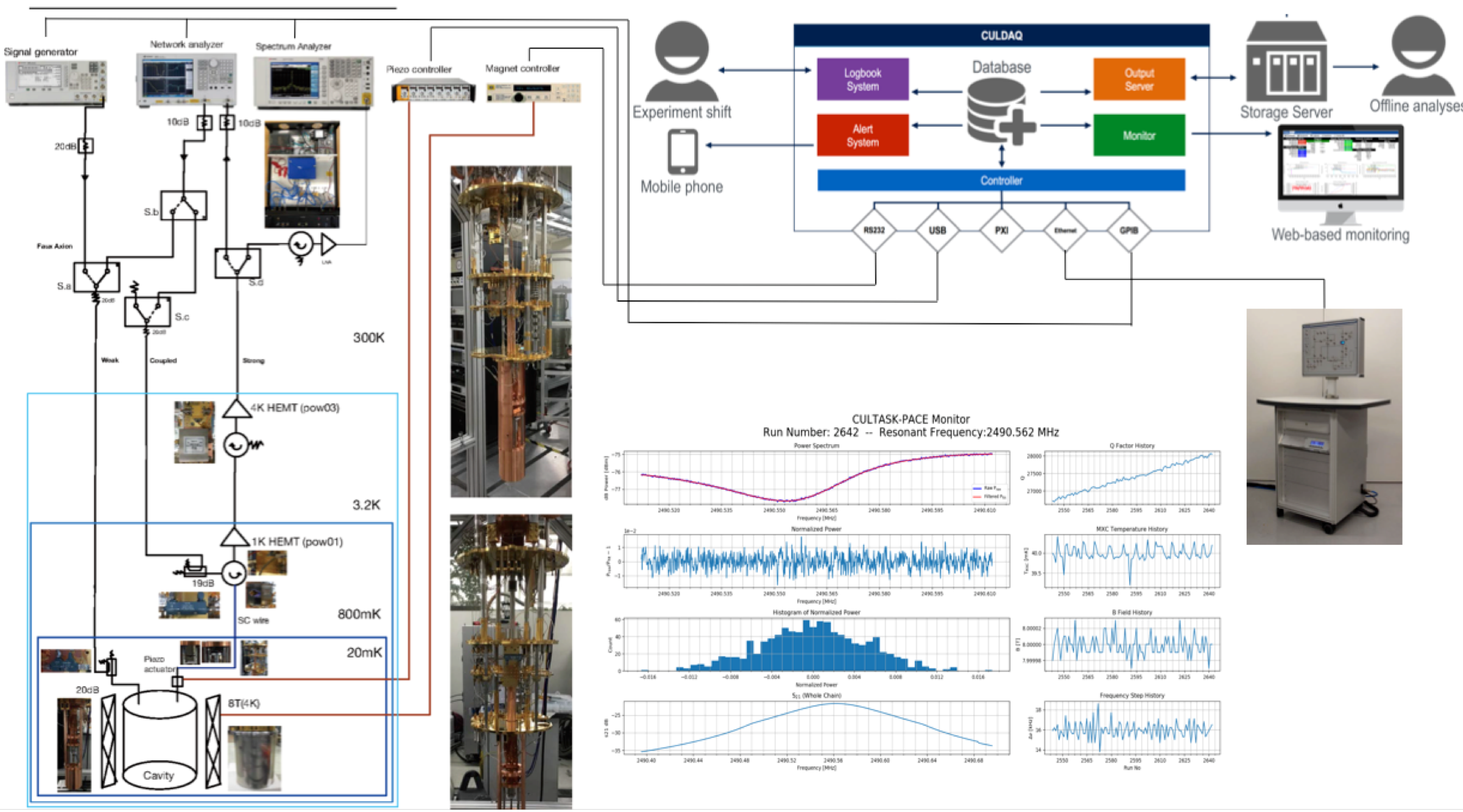
Tuning: Piezoelectric actuators (Attocube)
Thermal link to 1K plate
Sapphire rod to cavity by cryo bearing
Rotator resolution of 1/1000 deg → 16 kHz/step
Vibration free: w/ ball and spring

Linear and Rotational Piezo Actuators

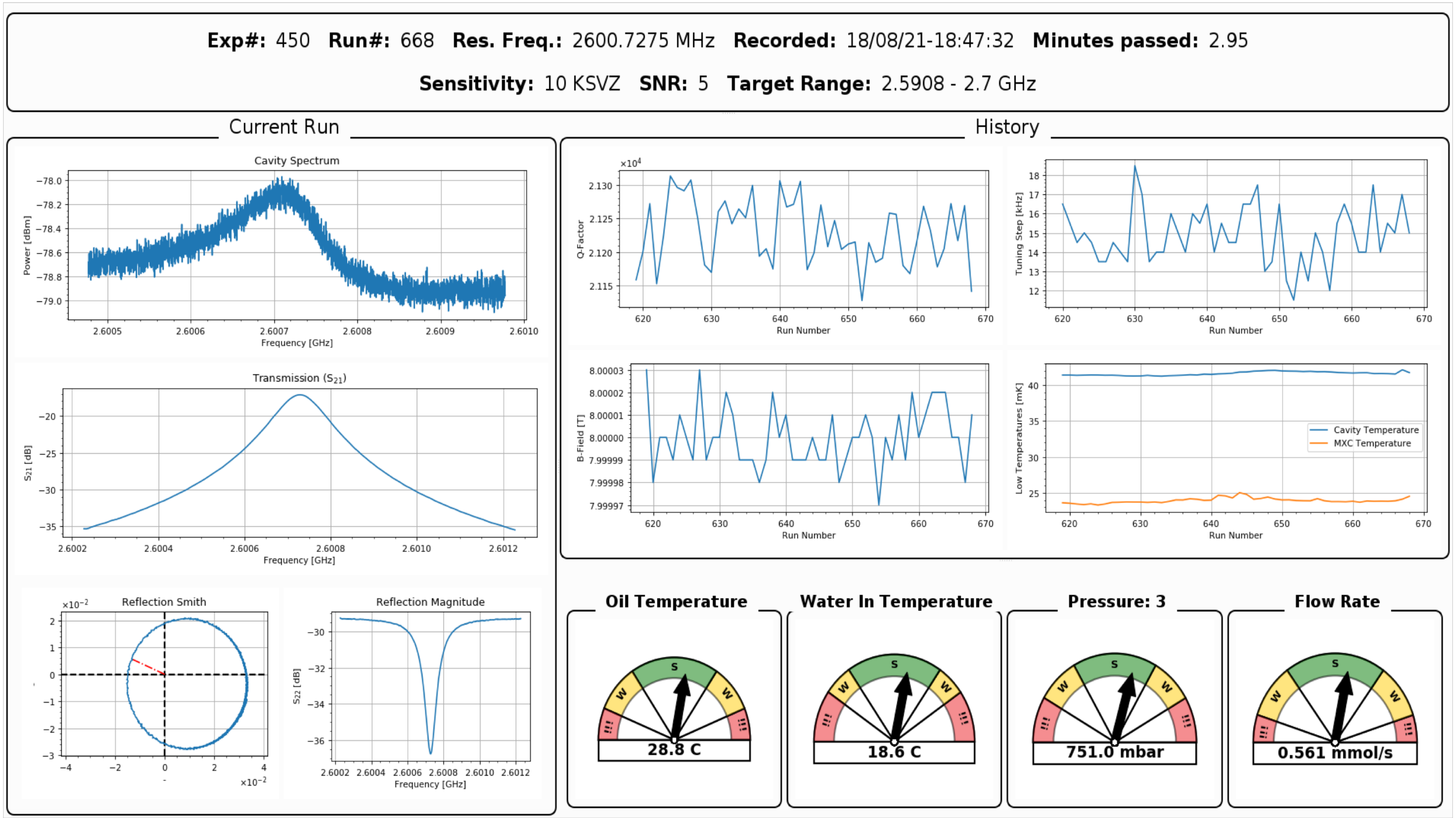


CAPP-PACE (RF receiver chain)

RF read-out chain & Controls



CAPP-PACE (DAQ and Monitoring)



CAPP-PACE (Online Monitor)

CAPP-PACE axion data

In 2018

	10*KSVZ (1)	10*KSVZ (2)	10*KSVZ (3)	KSVZ	10*KSVZ (4)
Date	1/19 – 2/13	7/23 – 8/01	8/14 – 8/23	9/01 – 10/26	11/1 – 11/24
Frequency [GHz]	2.450 – 2.500	2.500 – 2.548	2.547 – 2.613	2.5905 – 2.5915	2.613 – 2.710
Volume [liter]	0.59	0.59	1.12	1.12	1.12
T_{system} [K]	1.05	1.05	1.14	1.16	1.16
$\langle B_0 \rangle$ [T]	7.0	7.0	7.2	7.2	7.2
coupling	1.9	1.9	2.0	1.9	2.0
C (form factor)	.50	.50	0.55	0.66	0.55

CAPP-PACE results

Results (Mr. Caglar Kutlu's)

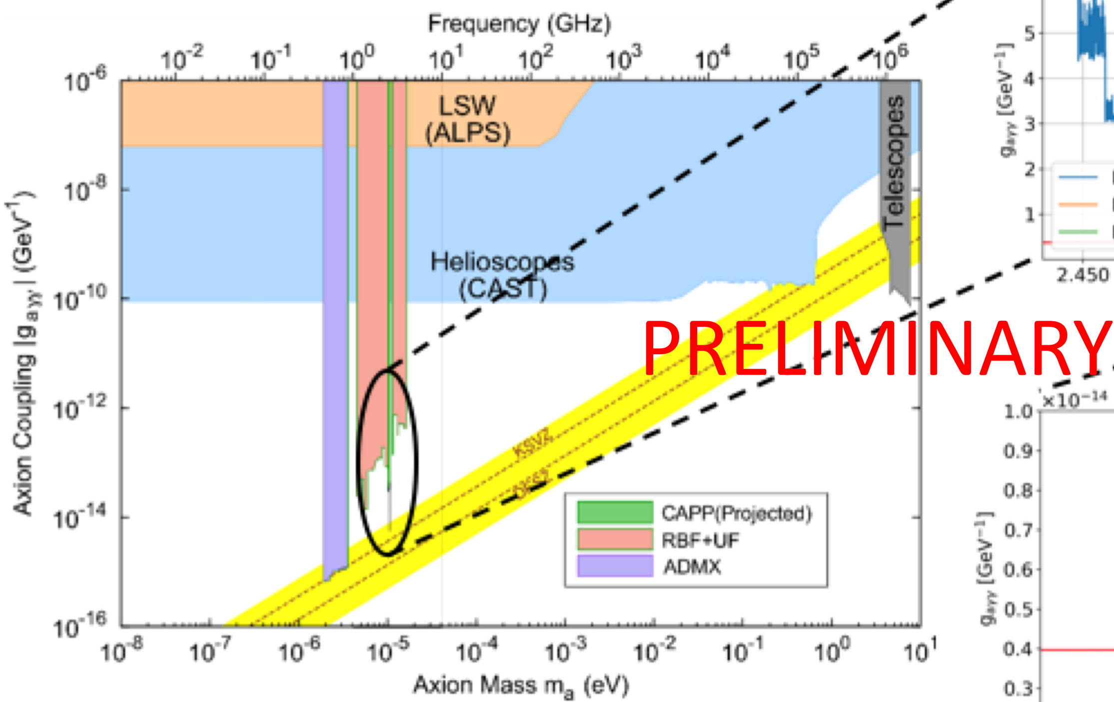


Figure 9: Exclusion plot showing CAPP-PACE results along with other haloscope experiments.

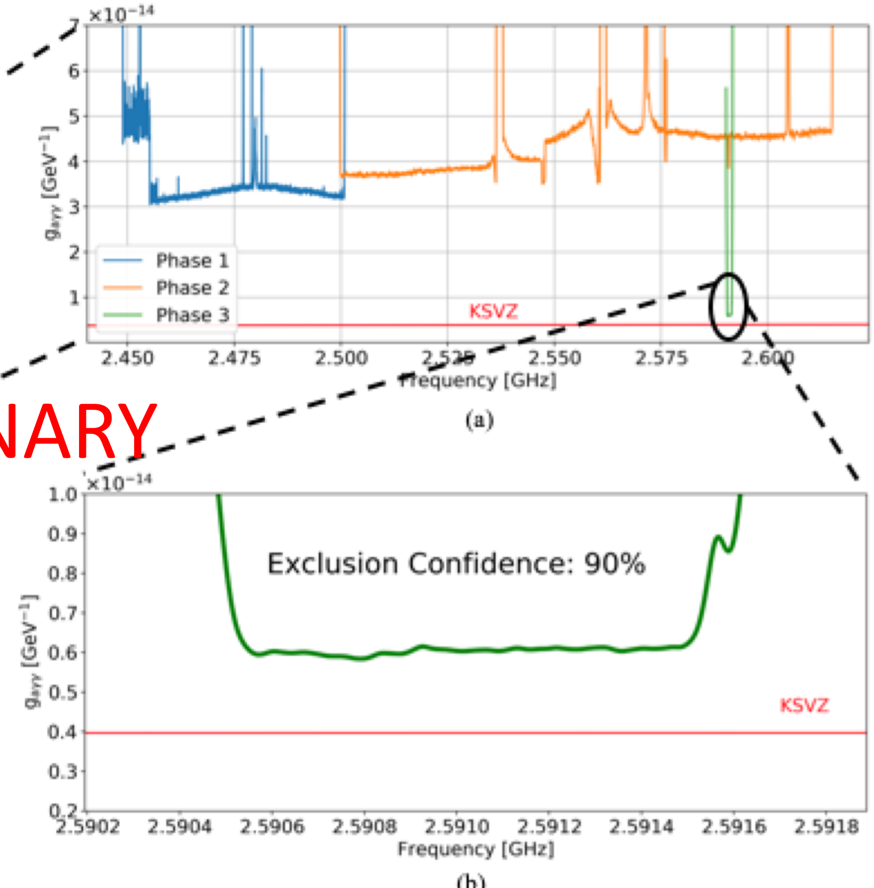


Figure 10: (a) Exclusion region with all the physics run combined done in 2018. (b) A zoomed view of the high sensitivity result.

How to improve?

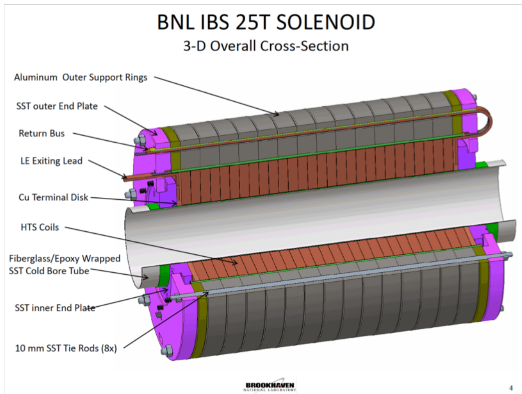
- Maximize Signal (B^2VQ)
  - 25T 10cm bore HTS magnet by BNL (2021)
  - 12T 32cm bore LTS magnet by Oxford (2019)
  - Higher frequencies without shrinking volume
    - Pizza Cavity (S. Youn)
    - Dielectric rings (TM_{030} and TM_{050}) (O. Kwon)
  - Improve Q-factor of cavity – YBCO cavity (D. Ahn)

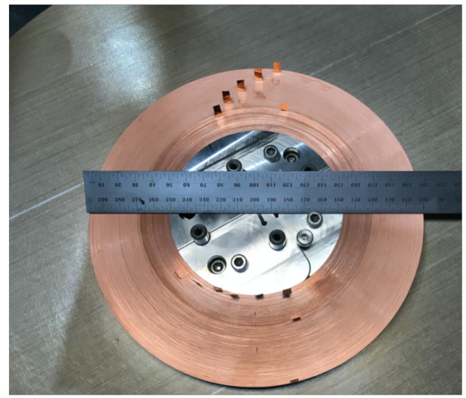
- Minimize Noise ($T_{system} = T_{physical} + T_{amp}$)
  - Quantum Amplifier - SQUID and/or JPA
  - Optimize cryo-RF receiver chain

- Others (DAQ efficiency)
  - Dead-time-less DAQ

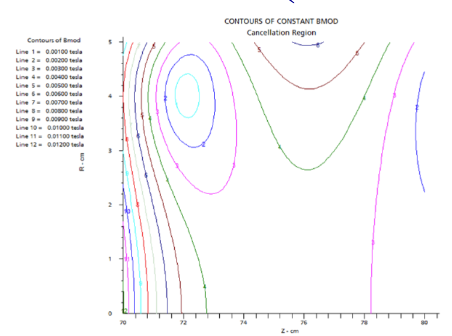
High Field & Big Bore Magnets

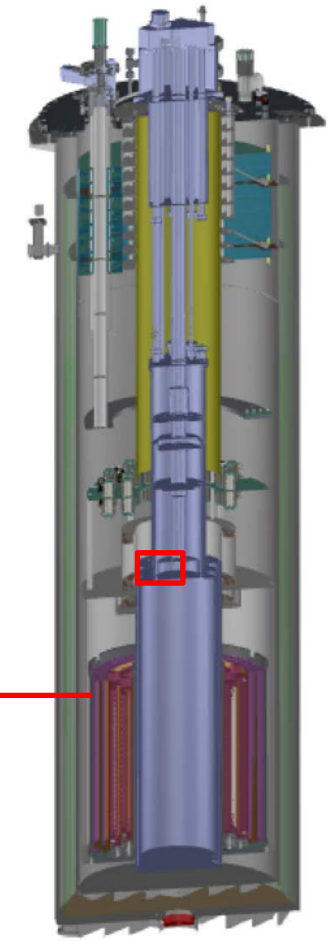
- 25T 10cm bore HTS magnet by BNL (2021) – Funding limited!
  - ➢ The first 16 (of 28) pancakes wound!
  - ➢ No-insulation coil design (ReBCO tapes)
  - ➢ 5 km of SC tape will be delivered





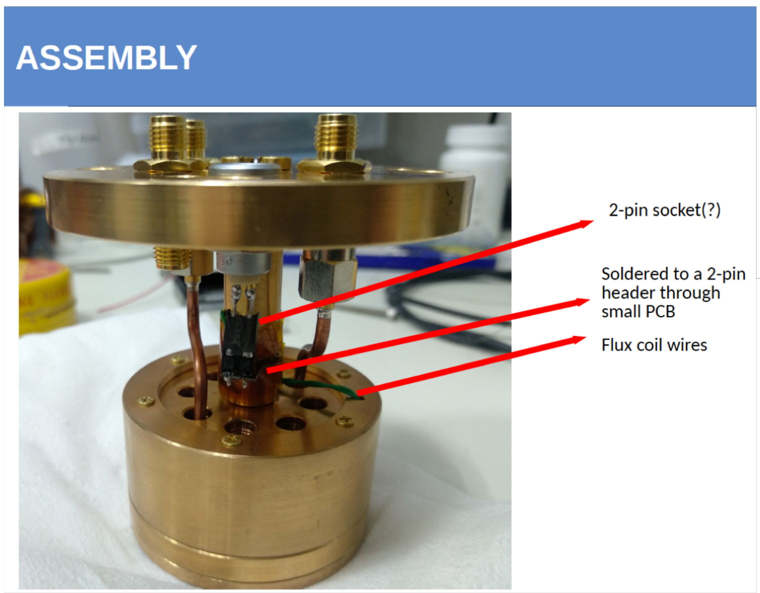
- 12 T 32 cm bore LTS magnet by Oxford Inst. (end of 2019)
  - ➢ Nb_3Sn
  - ➢ Powerful Leiden DRS1000

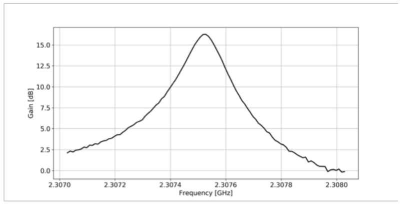


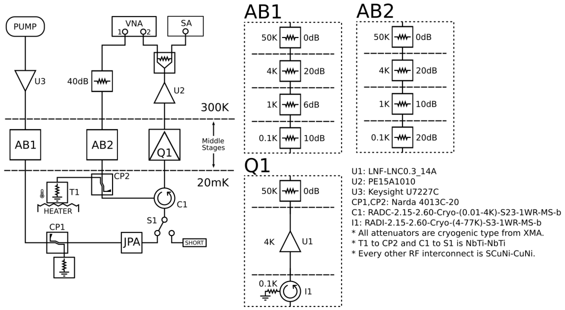


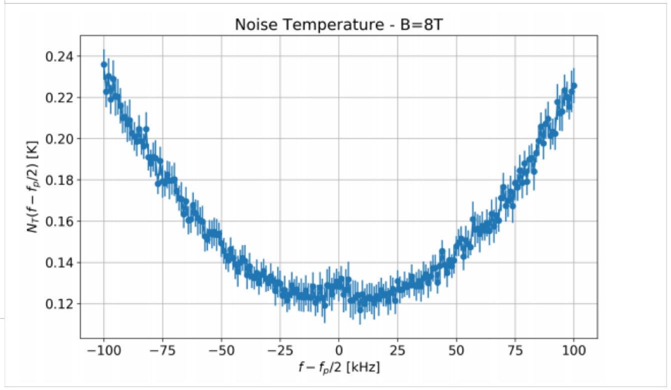
R&D Projects (JPA)

- Led by A. Matlashov and S. Uchaikin (from D-Wave)
- First batch of JPAs for PACE frequency range (2.4 GHz) from U. of Tokyo (Nakamura's group): taking adv. of their know-hows
- Noise measurement in test bench: < 200 mK and keeps shrinking…
- Implemented into CAPP-PACE in Aug. (2019)
- Crucial to speed up the search (20~100 times) w/ squeezing



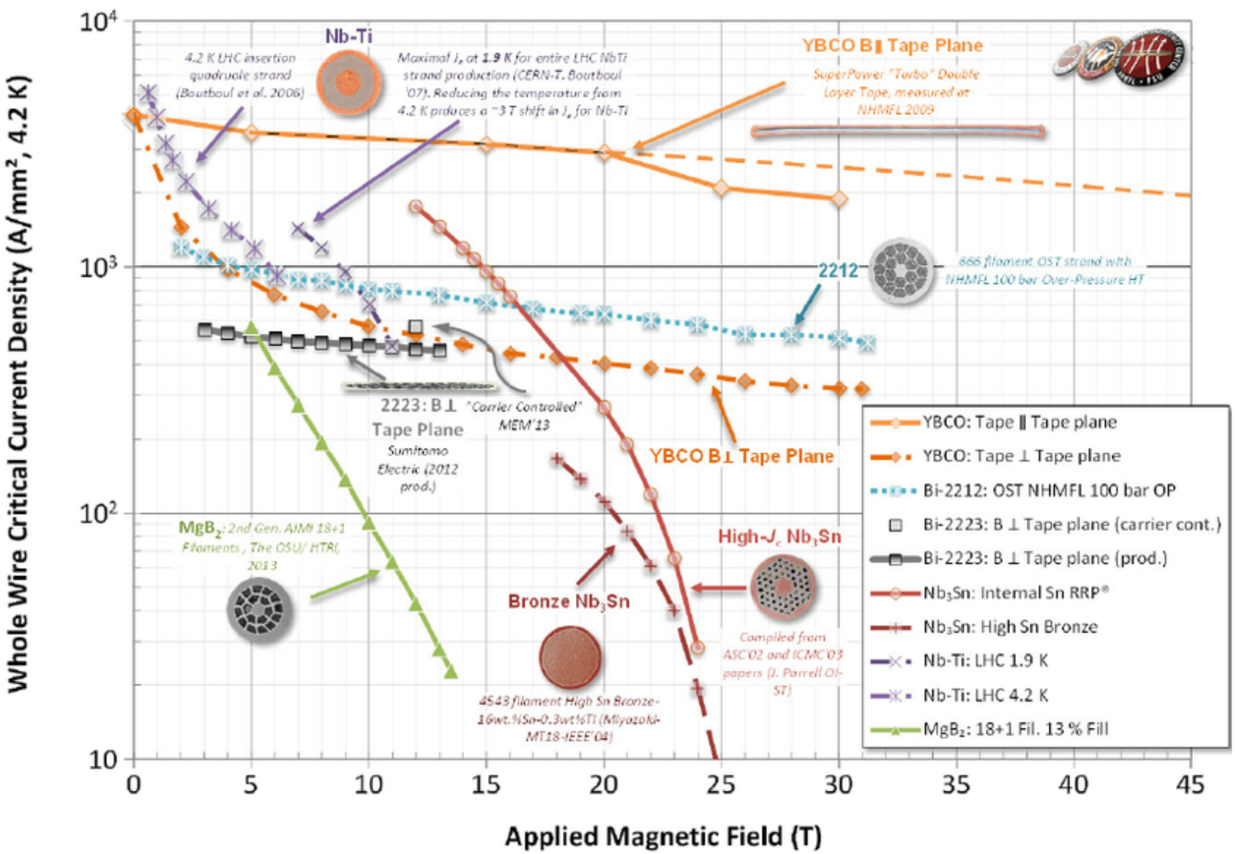






R&D Projects (Superconducting cavity)

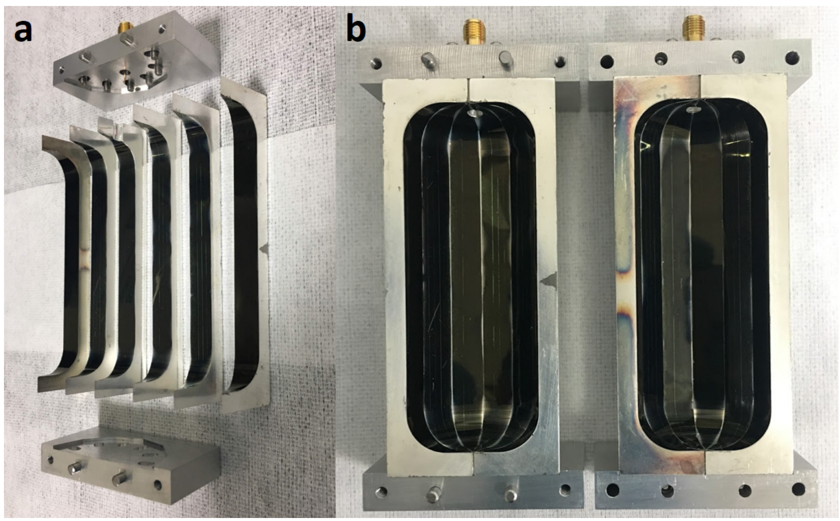
Superconductivity disappears in high magnetic field!

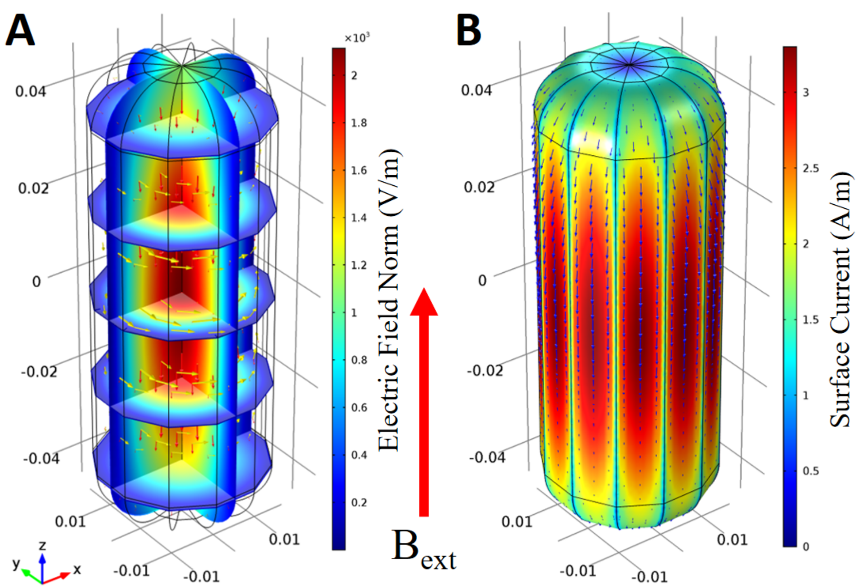


R&D Projects (YBCO cavity)

Superconducting cavity with YBCO tapes (grain alignment)

- 12 piece polygon cavity concept works!





TM_{010} mode

R&D Projects (YBCO cavity)

➢Maintains Q-factor up to 8 T!

Maintaining high Q-factor of superconducting $YBa_2Cu_3O_{7-x}$ microwave cavity in a high magnetic field

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

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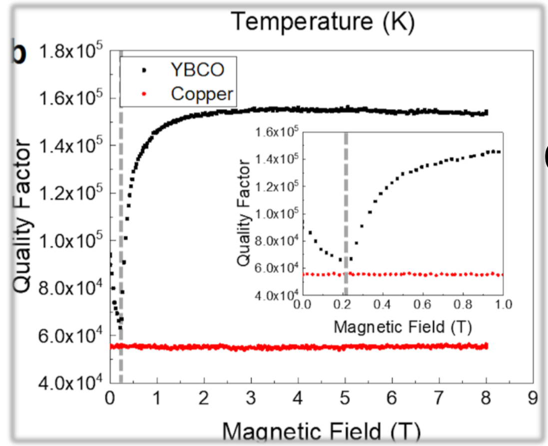
[2]*Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea*
[3]*Center for Quantum Nanoscience, Institute for Basic Science, Seoul 33760, Republic of Korea*
[4]*Center for Artificial Low Dimensional Electronic Systems, Institute for Basic Science,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

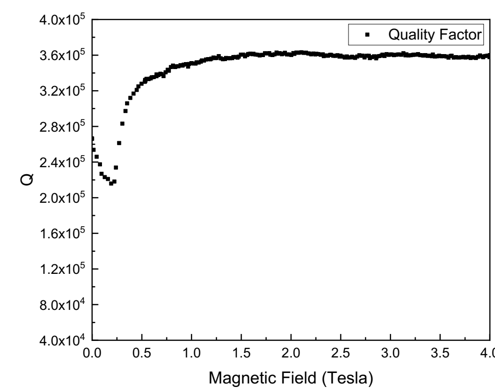
(Dated: May 23, 2019)

A high Q-factor microwave resonator in a high magnetic field could be of great use in a wide range of fields, from accelerator design to axion dark matter search. The natural choice of material for the superconducting cavity to be placed in a high field is a high temperature superconductor (HTS) with a high critical field (>100 T) and depinning frequency (>10 GHz). The deposition, however, of a high-quality, grain-aligned HTS film on a three-dimensional surface is technically challenging. As a technical solution for the problem, we introduce a polygon-shaped resonant cavity with commercial



Q ~ 155,000

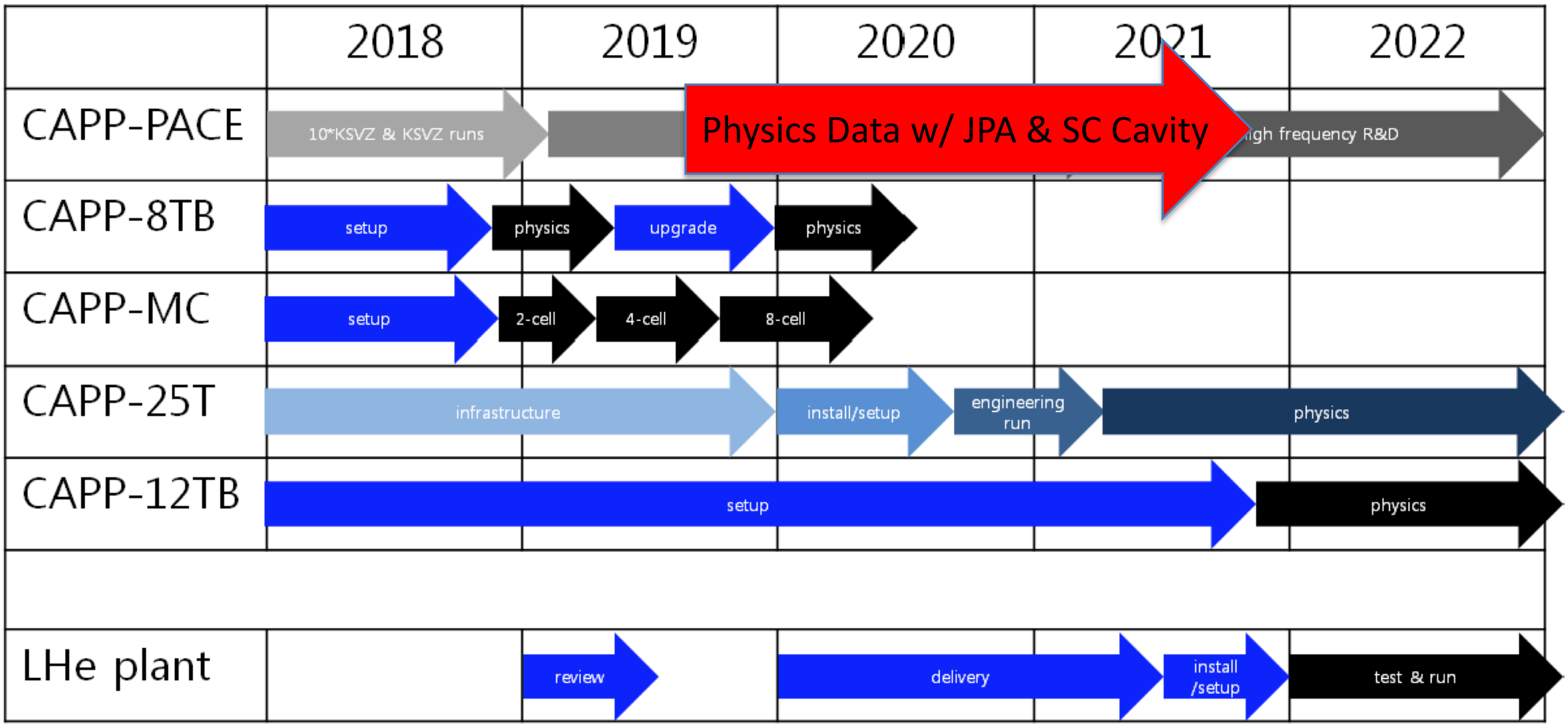
Q ~ 350,000



- It was only our first (and 2nd) Try…
- Improvement in YBCO surface is in order

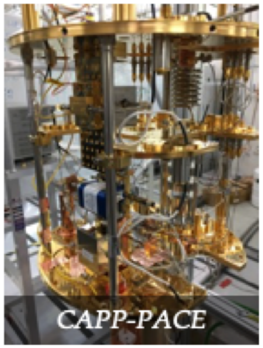
Timeline

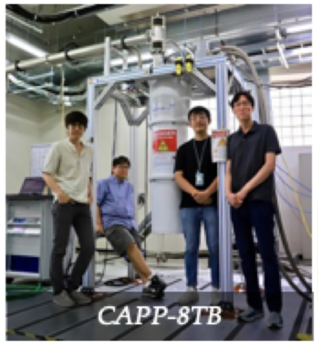
CAPP Axion Dark Matter Search Timeline

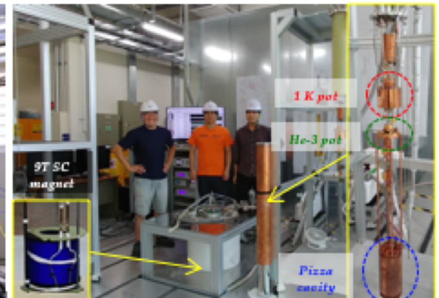


CULTASK Prospects

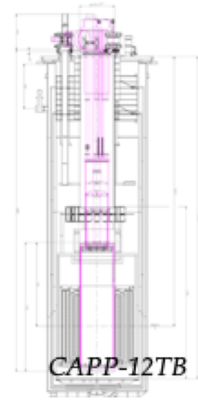
- *All the ingredients together, we will reach the DFSZ sensitivity even for 10% axion content in the local dark matter halo.*



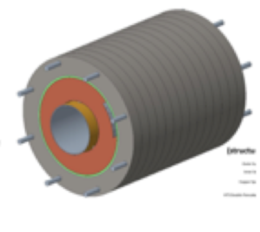




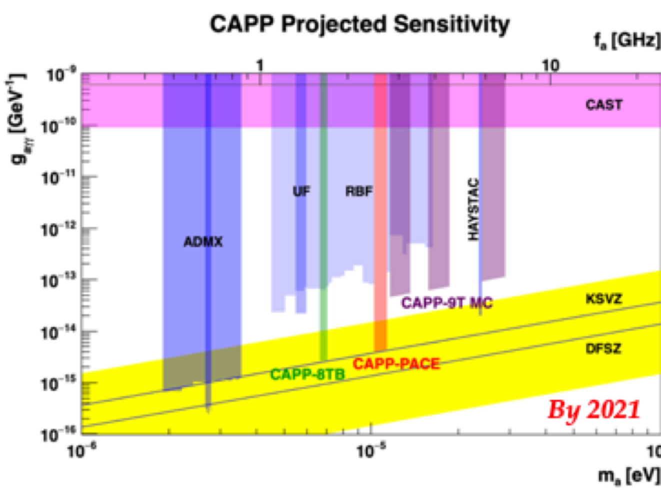
CAPP-9T MC

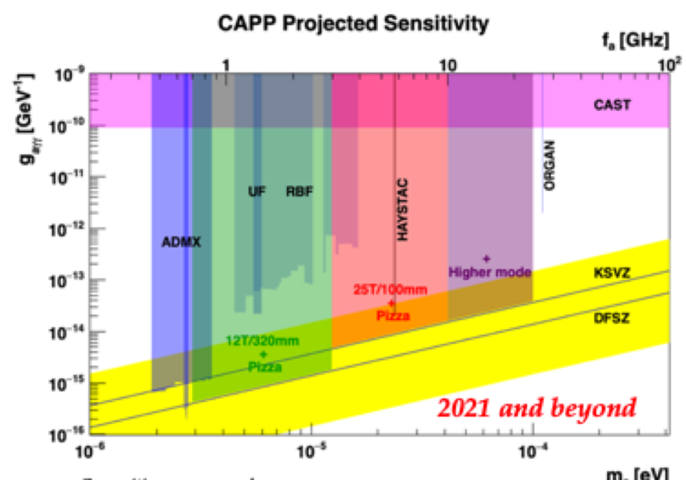


CAPP-12TB



CAPP-25T





- *Cu cavities are assumed*
- *W/ SC cavities, down to 10% of axion dark matter content can be probed*

Summary

- **CAPP has successfully established multiple haloscope axion dark matter experiments in Korea.**
- **CAPP's pilot experiment, CAPP-PACE started to take physics data in 2018 (10*KSVZ and KSVZ runs).**
- **2 more experiments, CAPP-8TB and CAPP-MC, are ready to take data soon.**
- **CAPP will focus on taking data with JPA and YBCO cavity for axion search in 2019.**
- **Major improvement is expected with big bore (12 T, 32 cm bore) magnet (end of 2019) and high field (25 T, 10 cm bore) HTS magnet delivery.**
- **R&D on superconducting cavity looks promising!**

Upcoming Publications in 2019

- **Design and Operation of a Microwave Cavity Axion Detector for the 10 – 20 μeV**
  For PRD
- **First results from the CAPP-PACE microwave cavity axion experiment**
  For Physical Review Letters
- **A superconducting microwave cavity made of YBCO tapes in a high magnetic field**
  For Nature (rapid communication) or PRR

- **And Many More on…**
  - **SQUID and/or JPA test results**
  - **LVP**
  - **Physics results from CAPP-8TB**
  - **Results from CAPP-MC**
  - **Another from SC cavity development**
  - **Dielectric cavity for high frequency results**
  - **….**

Thank You For Your Attention!

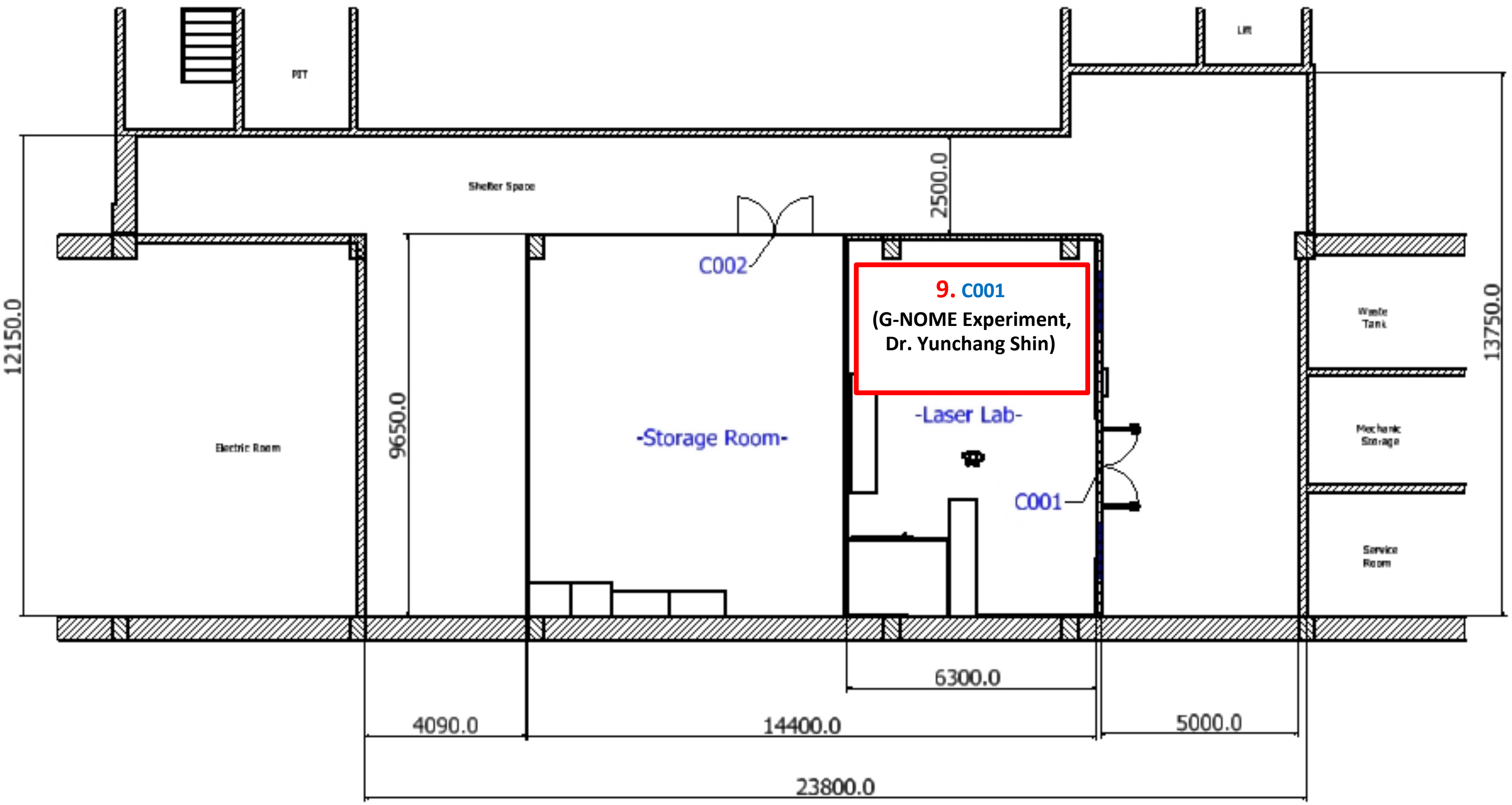
IBS/CAPP

Center for Axion and Precision Physics Research (CAPP)

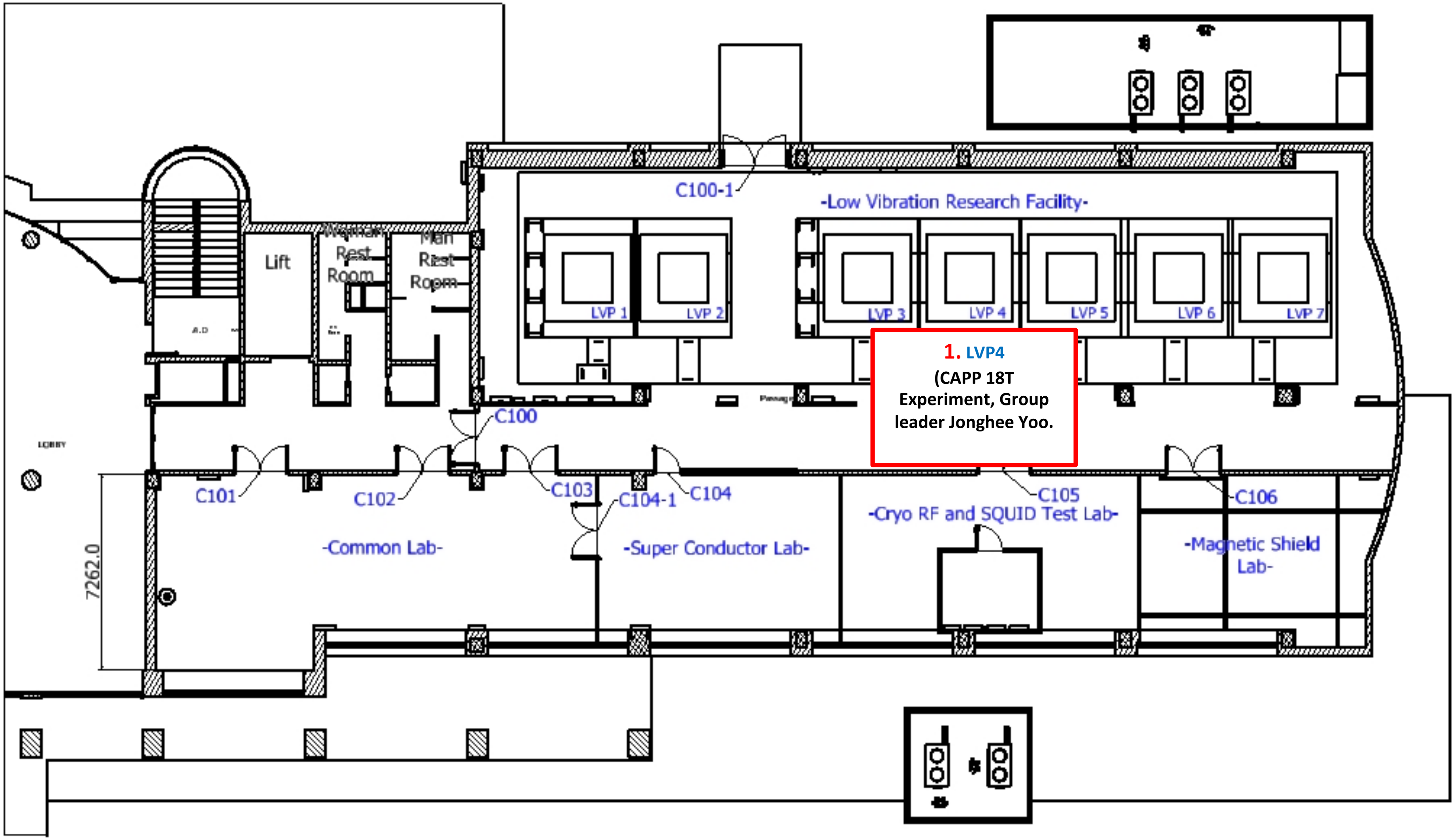
Funded by the Institute for Basic Science (IBS)

- 6 years old in Oct.
- Led by Director, Yannis Semertzidis (first gen. axion hunter)
- Physics at CAPP:
  - Dark Matter Axion Search (Cosmic Frontier)
  - Storage Ring Proton EDM (Strong CP Problem, BAU)
  - Muon g-2, J-PARC, COMET, CAST, ARIADNE
- Located at and working with KAIST (Korea Advanced Institute of Science and Technology)
- ~50 members

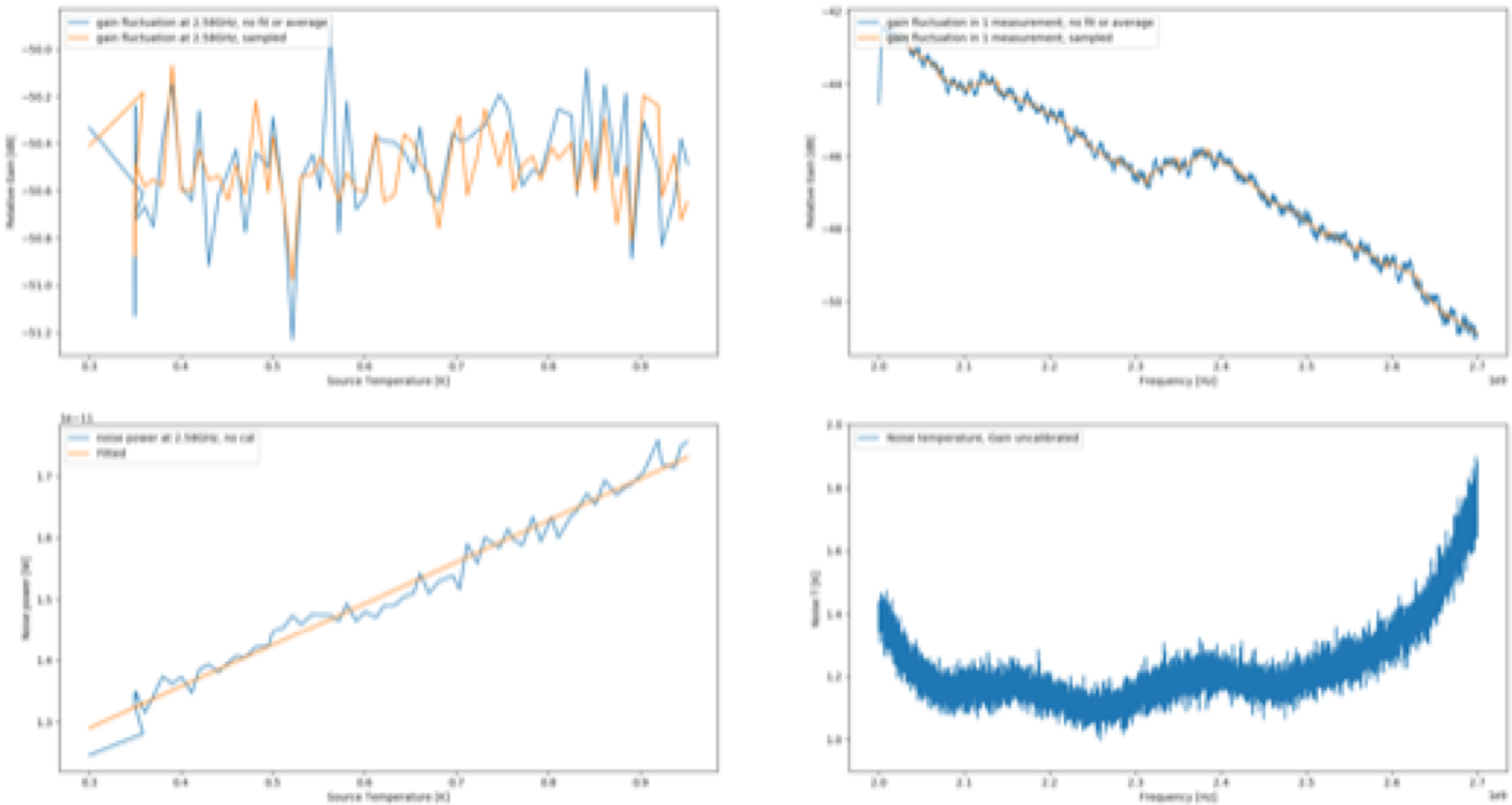
Director's Lab Tour Course.



Group Leader's Lab Tour Course.



Backup Slides



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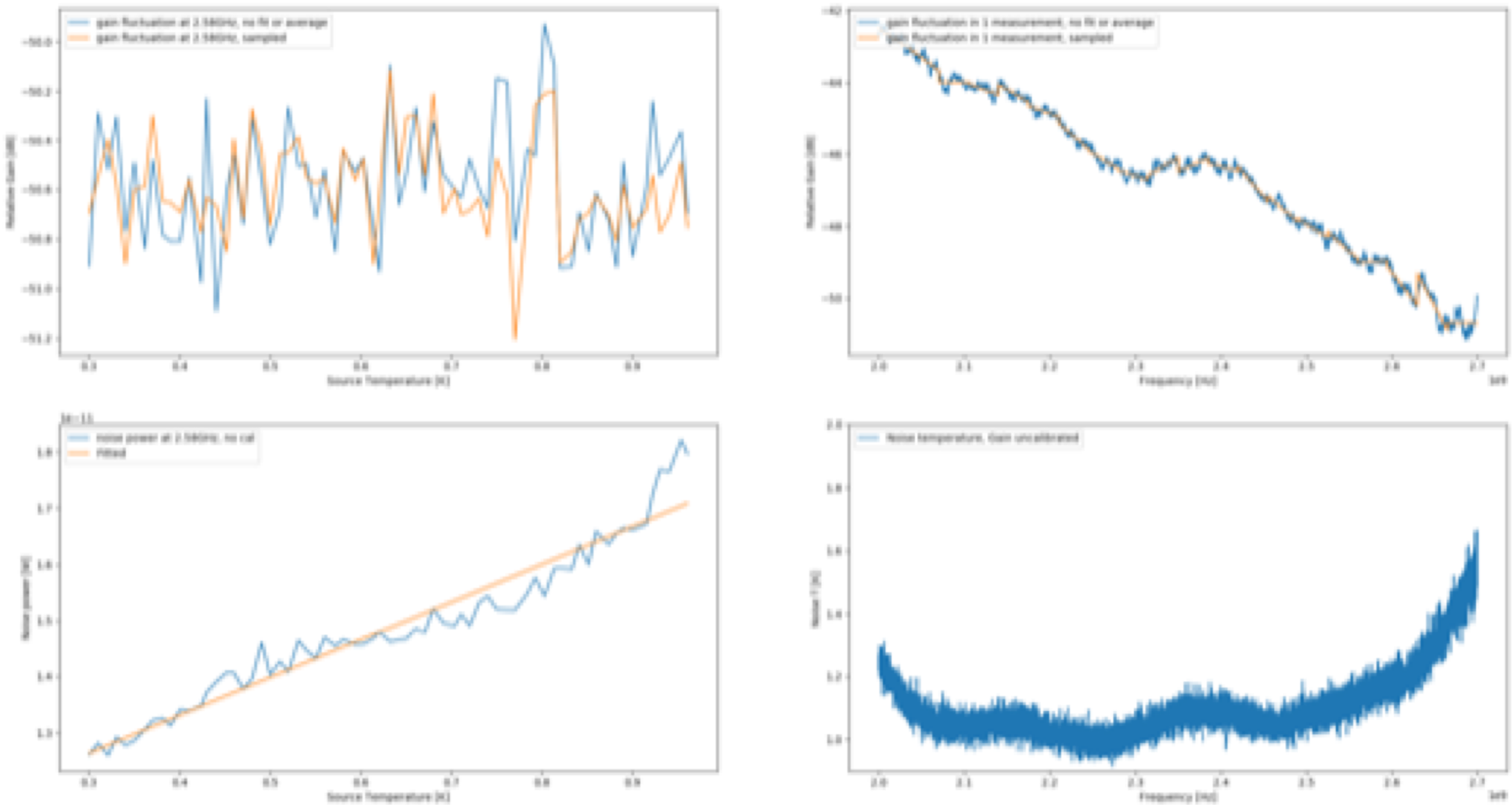
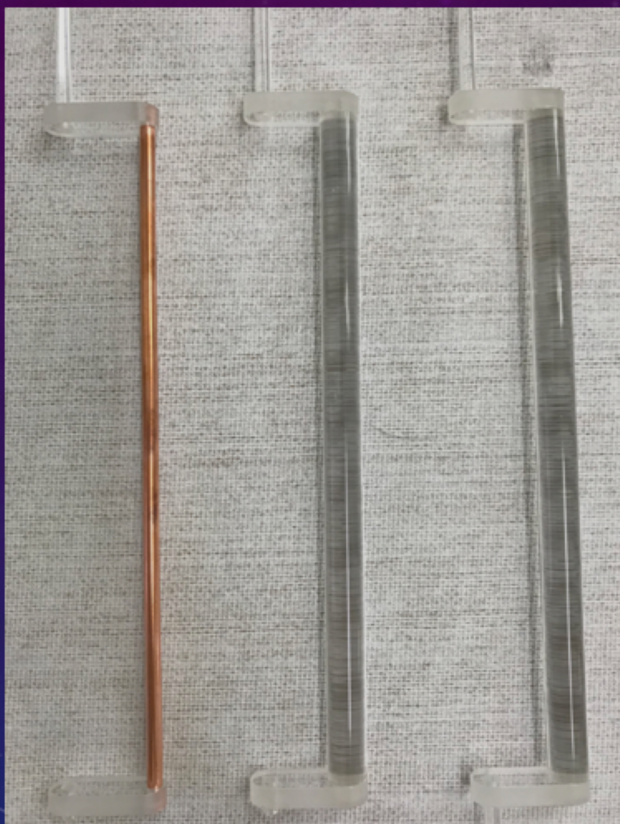


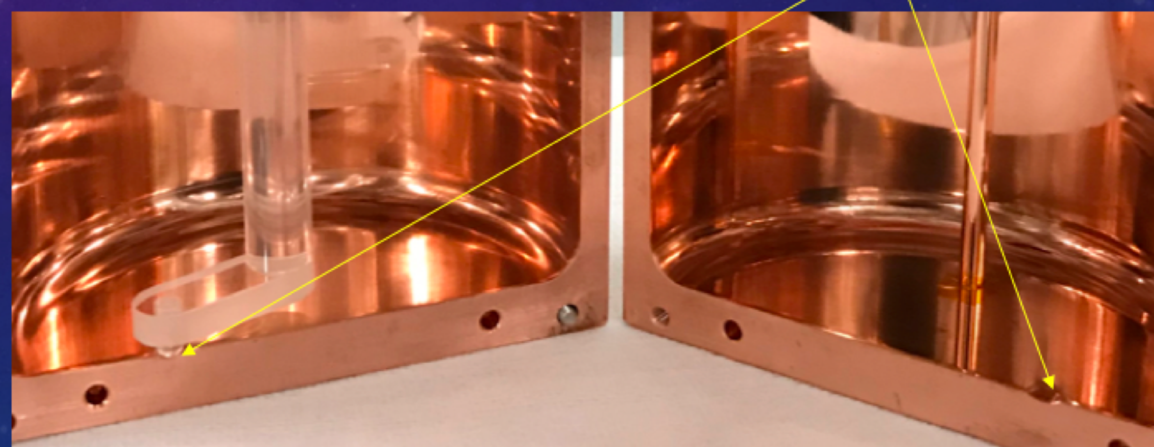
Backup Slides

– direct touch between tuning rod and cavity wall

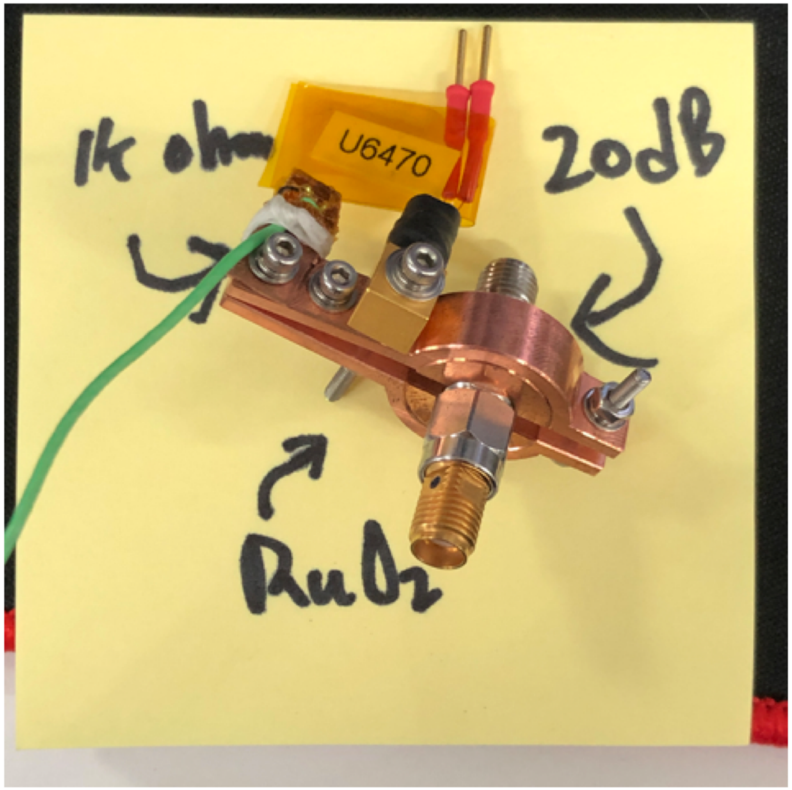
VIBRATION FREE DESIGN

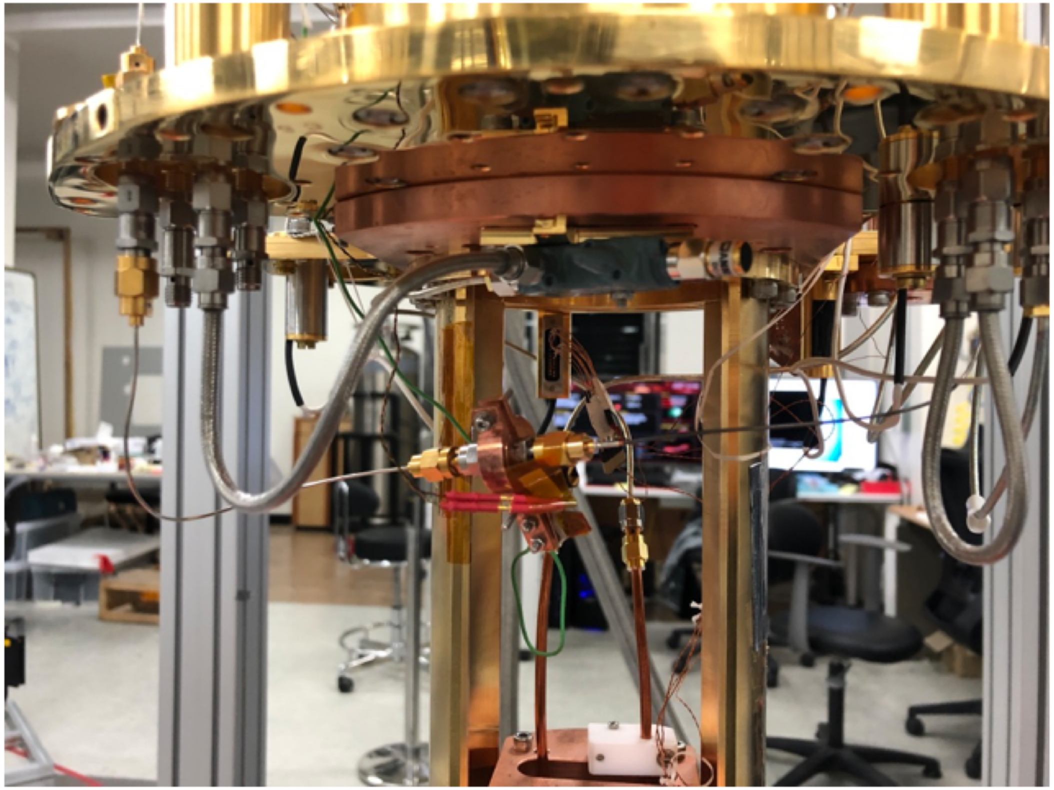


Slightly bigger radius of well



Setup - Photos

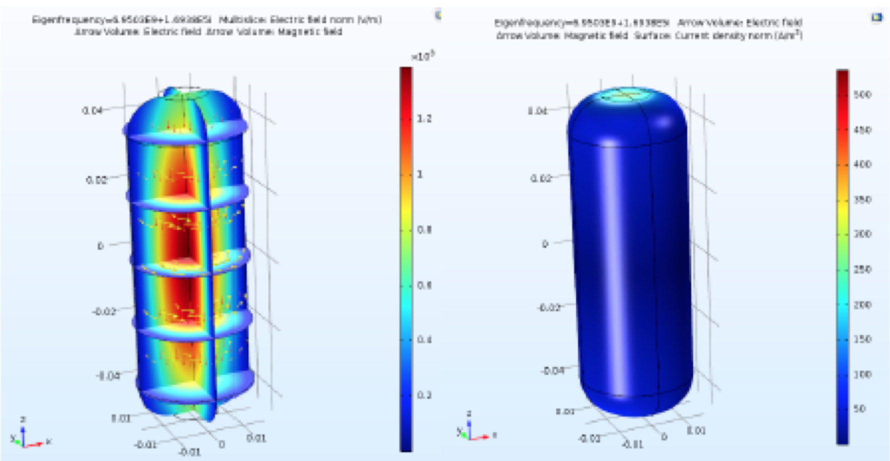




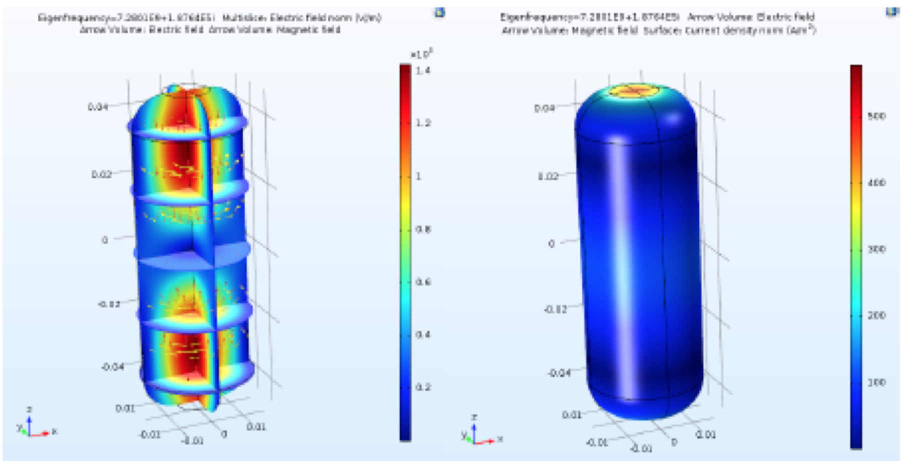
Backup Slides(YBCO Cavity)

TM010 & TM011 modes

TM010



TM011



- TM010: Current density is large at the middle wall.
- TM011: Current density is large at the top and bottom.

Backup Slides(YBCO Cavity)

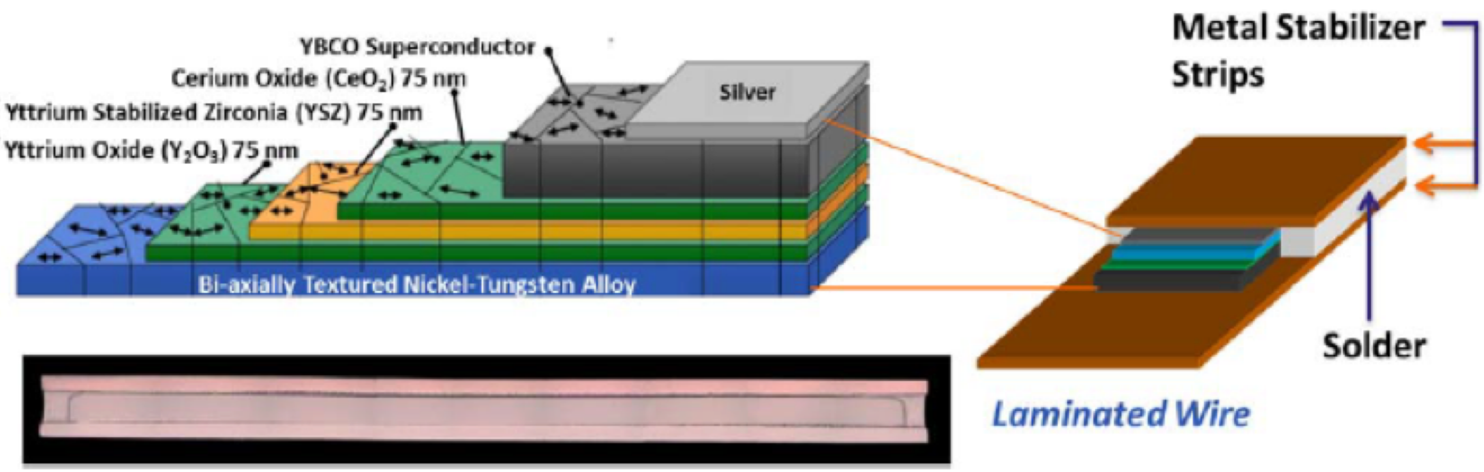


Figure 1 The architecture of the AMSC tape [19]

Backup Slides(YBCO Cavity)

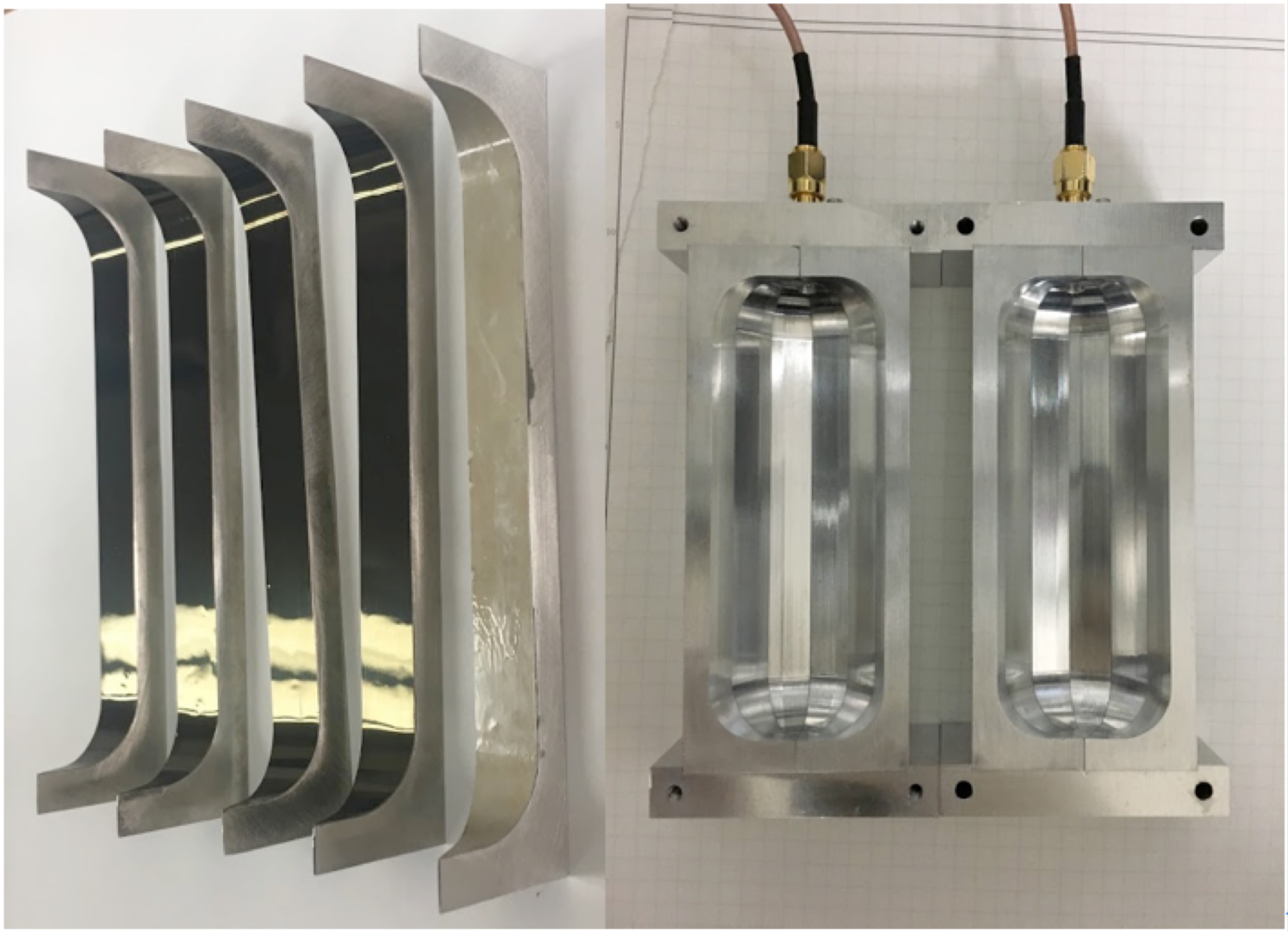
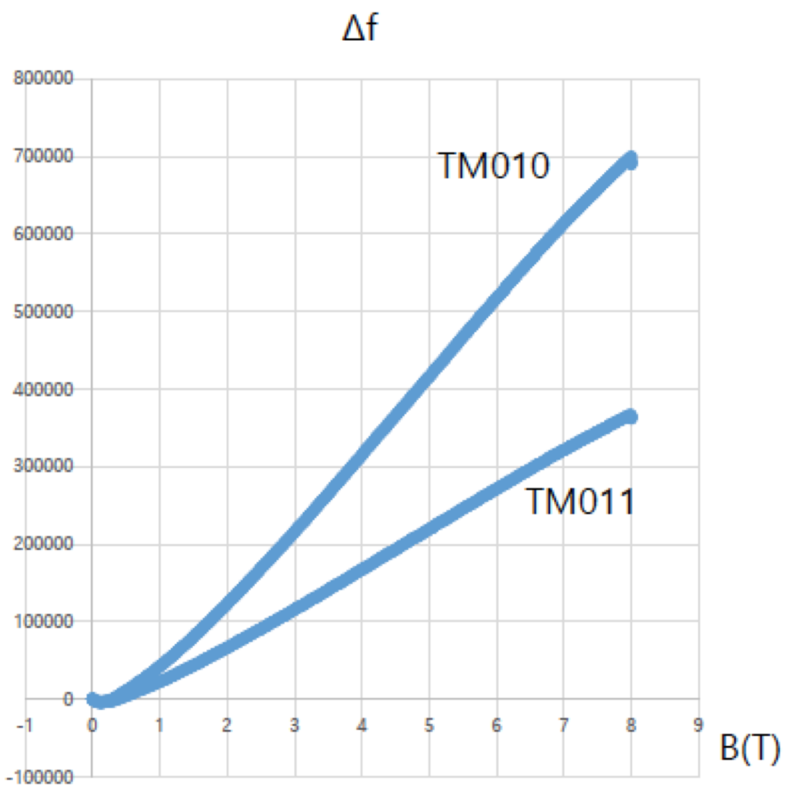
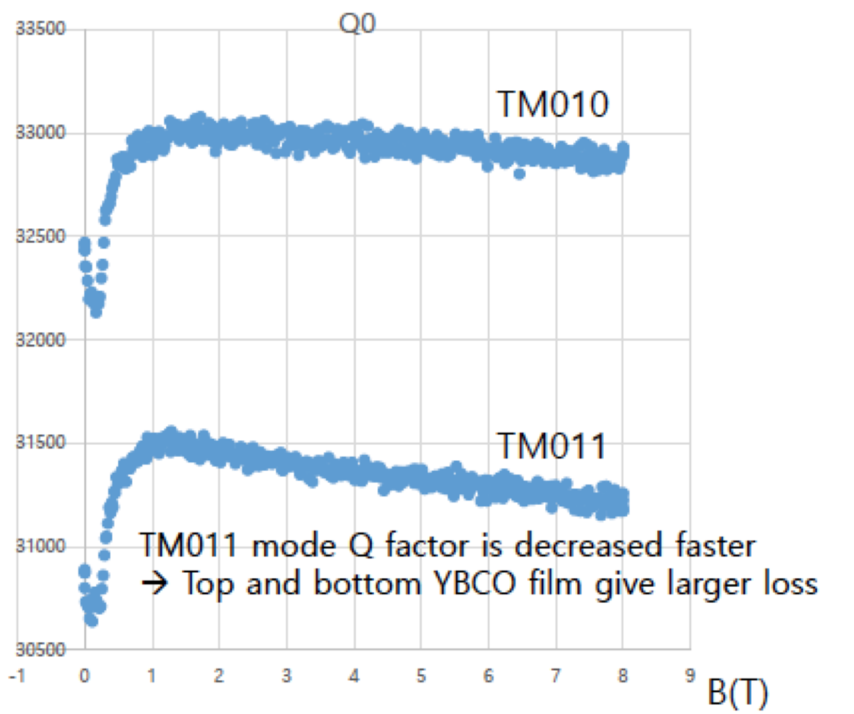


Figure 2 The structure of polygon cavity.

Magnetic Field Dependency





TM011 mode Q factor is decreased faster
→ Top and bottom YBCO film give larger loss

Backup Slides