CULTASK: State of art axion search experiment in Korea

[1]***Ohjoon Kwon***, [1]Woohyun Chung, [1]Soohyung Lee, [2]Doyu Lee,
[2]Jinsu Kim, Jihoon Choi, and [1,2]Yannis K. Semertzidis

[1]**C**enter for **A**xion and **P**recision **P**hysics Research (CAPP) at **I**nstitute for **B**asics **S**cience (IBS), Daejon, Korea
[2]**K**orea **A**dvanced **I**nstitute of **S**cience and **T**echnology(KAIST), Daejon, Korea

Contents

- Overview
  - CAPP's Axion Research
  - CULTASK
- CULTASK 2016
- CULTASK 2017 & beyond 2017
- Summary

CAPP overview

CAPP

- IBS -

Director
Dr. Yannis Semertzidis

Axion research

- **CULTASK**
  (**C**APP's **U**ltra-**L**ow **T**emperature **A**xion **S**earch in **K**orea)
- CAST-CAPP/IBS
- ADRIADNE
- Toroidal cavity

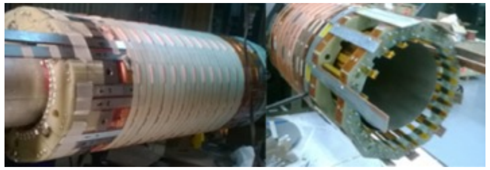
Non-axion research

- Storage ring proton proton EDM
- Muon g-2 (Fermilab/ J-PARC)
- COMET

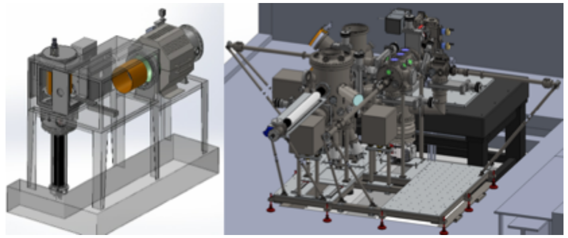
*Scanning rate

$$\frac{d\nu}{dt} \approx \frac{4}{5}\frac{Q_L Q_a}{\Sigma^2}\left(g_\gamma^2 \frac{\alpha^2}{\pi^2}\frac{\hbar^3 c^3 \rho_a}{\Lambda^4}\right)^2 \times \left(\frac{1}{\hbar\mu_0}\frac{\beta}{1+\beta}B_0^2 V C_{mn\ell}\frac{1}{N_{\mathrm{sys}}}\right)^2$$

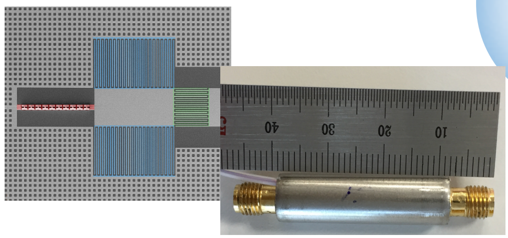
CAPP's R&D for axion search



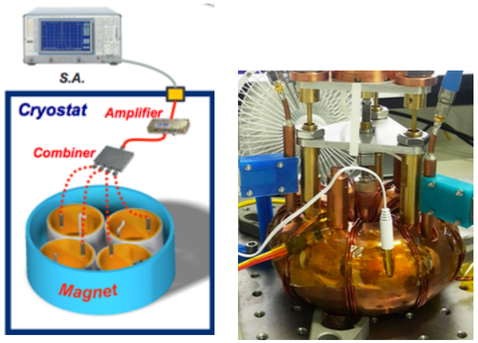
HTS 25T-10cm (->35T or 40T) by BNL
HTS 18T-7cm (SuNAM)
HTS 26T-3.5cm (SuNAM:WR)
LTS 12T-32 cm (Oxford)
Small Toroid 12T, V=80 L
Giant Toroid 5T, V=9900 L



Pure metal R&D
SC cavity R&D
Structure R&D
New concept cavity?

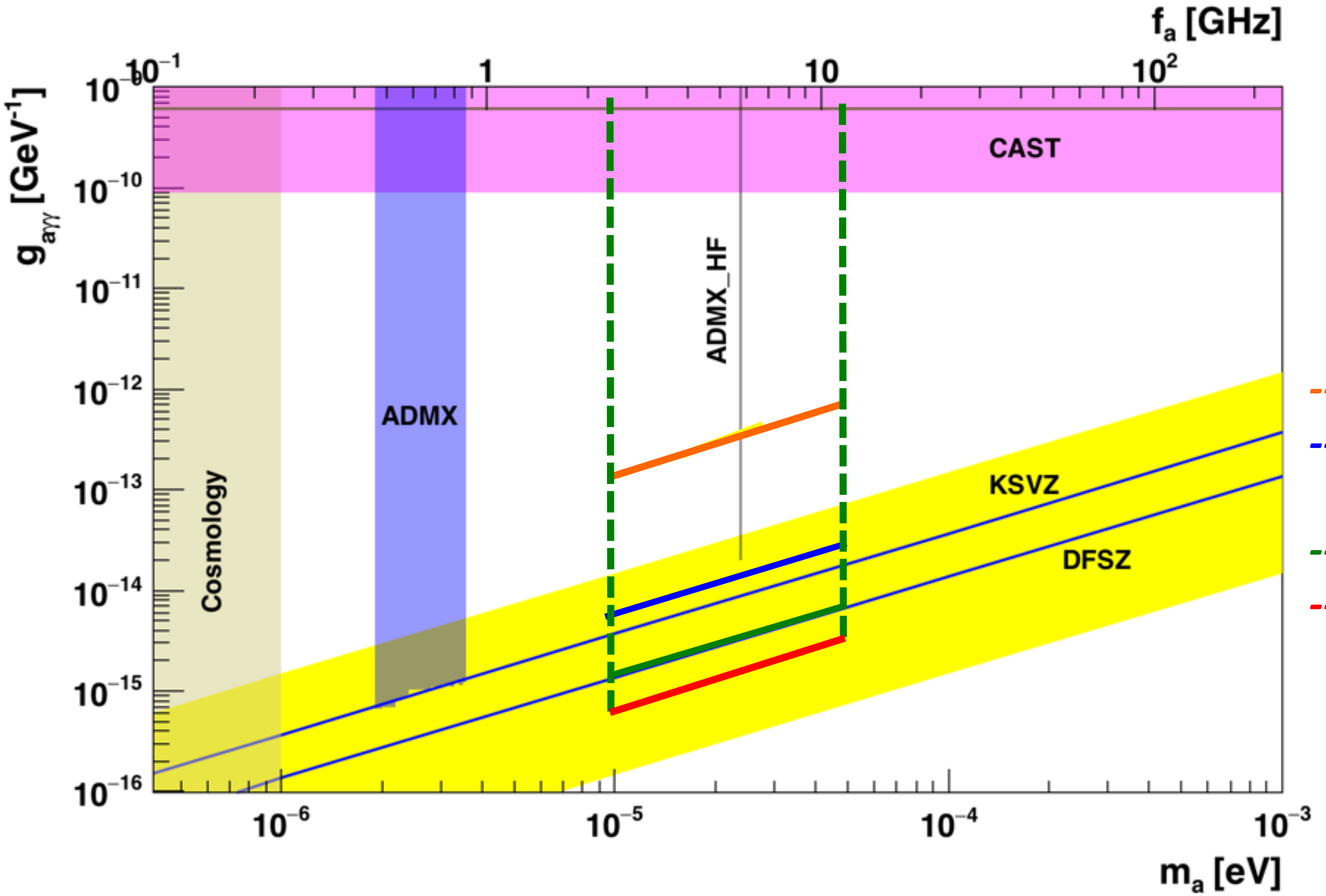


JPA from K. Lehnert (JILA)
JBA/JPC from Yale (QCI)
MSA from M. Mueck (ez-SQUID)



Multiple cavity
Toroidal cavity

CAPP projected sensitivity



--- *8T w/ 1K HEMT*

--- *SQUID or JPA (+SC coating?)*

--- *B field 25 T*

--- *B field 35 T*

CULTASK 2016

CULTASK 2016 w/ two DRs

Two BlueFors Dilution Refrigerators were delivered, installed and are operational!

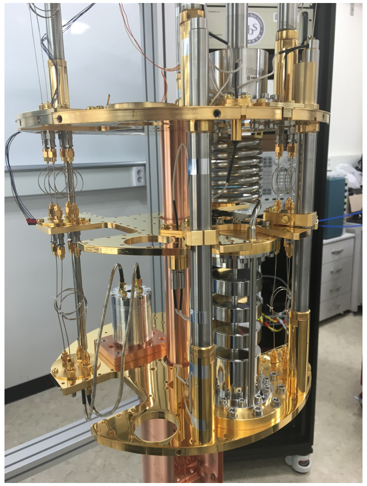
FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC

Delivered (FEB)

Installed (MAR)

Refrigerator Test and Training (JUN)

JUL – DEC:
- Cavity Development w/ pure Cu and Al
- Noise Figure Measurement w/ HEMT amp
- DAQ setup
- Complete RF receiver chain



BF3

NbTi 8T-12cm

Bluefors DRs completely installed

BF3

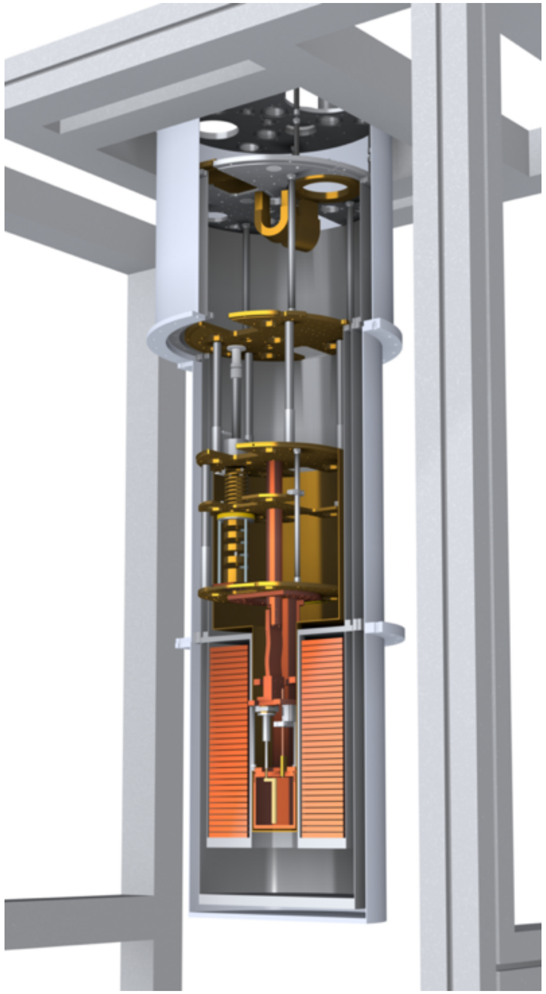
	BF3	BF4
Model	BlueFors LD400	BlueFors LD400
Magnet	None	**8T (AMI), 12cm ID**
RF lines	24	8
DC lines	72	72
Cool down to <10 mK	20 ~ 24 hours	40 ~ 48 hours
Base temp at MXC	9 mK	7 mK w/ SC magnet
MXC temp w/ Load	11 mk w/ Al cavity (4cm id) & HEMT amp	<30 mk w/ 10 kg OFHC copper support structure and cavity + HEMT amp + Network Analyzer + Piezo Controller

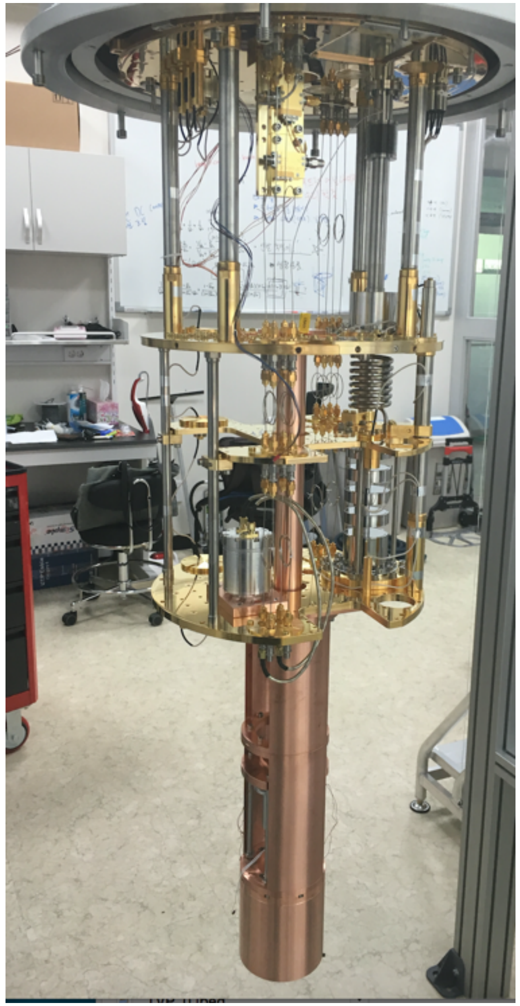
1st test system overview

Axion searching
@ **2.0GHz ~2.5 GHz,**
w/ **8T** magnet
w/ MSA or 1K HEMT

OFHC Support Structure and
Frequency Tuning System

- Cu Cavity of 10cm OD
- Modular design
- **Sapphire tuning rod**, 1cm OD
- Rotational piezo for tuning
- Linear piezo for antenna
- Piezo holder thermally linked to 1K plate



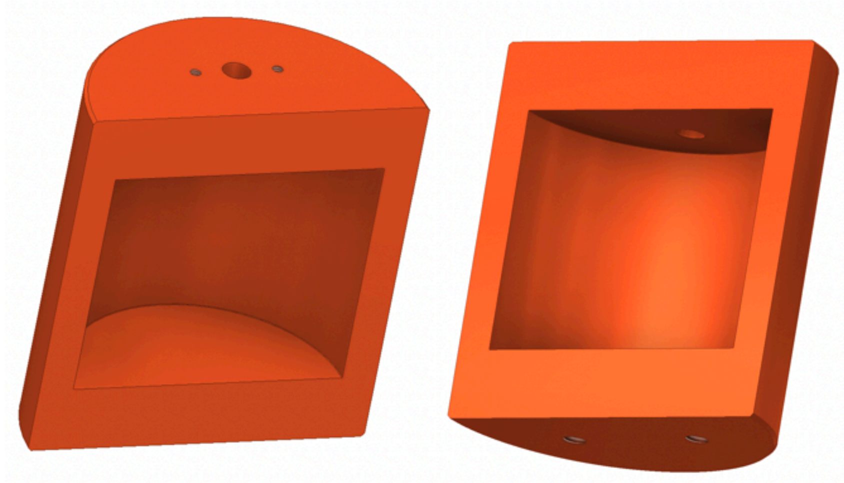


Detail ~

Cavity structure *vs.* contact problem

Horizontal cut

Vertical cut



Lathe machining based

Knife edge
Indium gasket

Milling machining based cavity structure

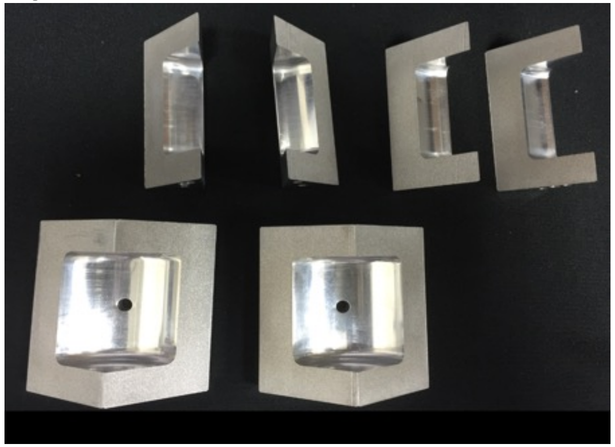
➔ **Cutting in electron oscillating direction**

➔ **No additional resistance or leak**

No contact issue w/ vertically split cavity

2 pieces

6 pieces

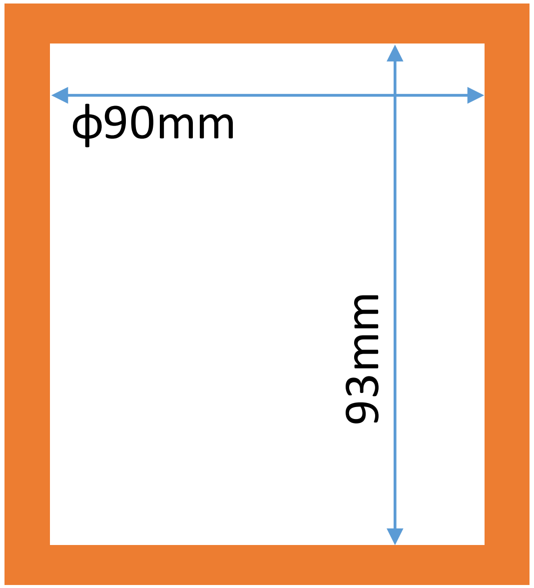


Type	Normal design Al6N	Vertical Cut 2pieces Al6061 (blended)	Vertical Cut 6pieces Al6061
Q_{TM010}@room (simulation)	10,000 (~ 13,000)	10,200 (10,500)	9,600 (~ 9,800)
Q_{TM010}@20mK	~200,000	**>3,500,000**	**> 1,300,000**
Cf) Q_{TE011} @ 20mK	~ 20,000,000		

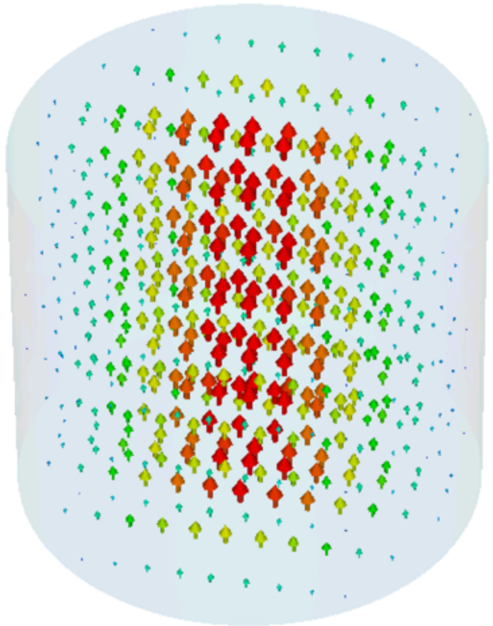
*σ_{Al6061} : 2.3e7 ~ 2.6e7 (S/m) *σ_{Al6N} ~ 3.7e7 (S/m)

RF Cavity design (Prototype, R&D purpose)

Cavity dimension



Important parameters of cavity



F_{010} = 182.9/R GHz/mm
= **2.55 GHz**

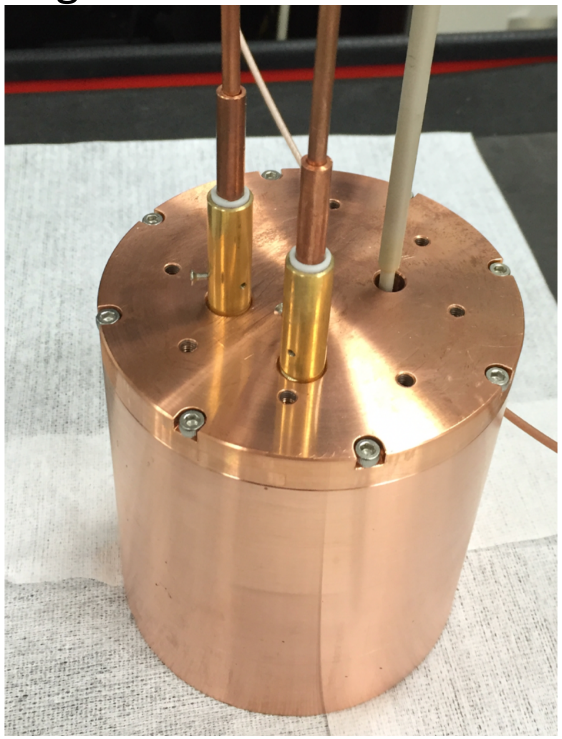
V = ***0.59 L**

Q @room = **22,000**

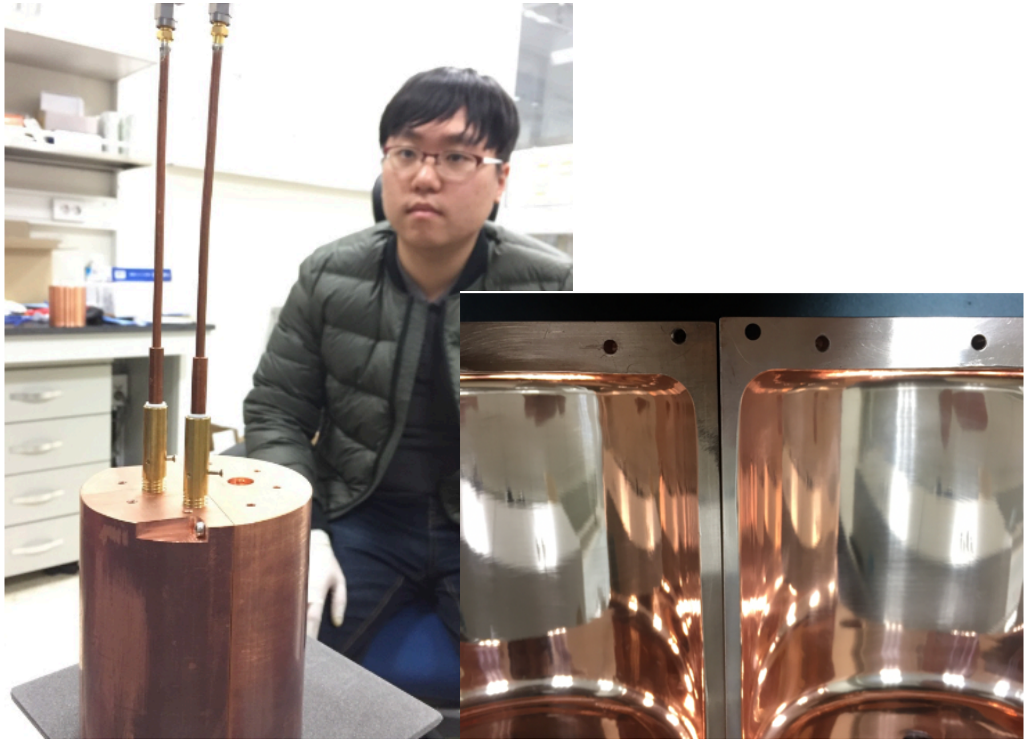
*1.3L would be used in experiment

RF measurements of cavities

Original model

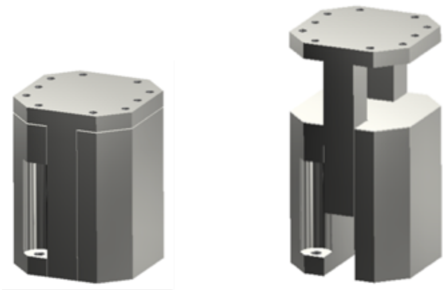


Vertical division



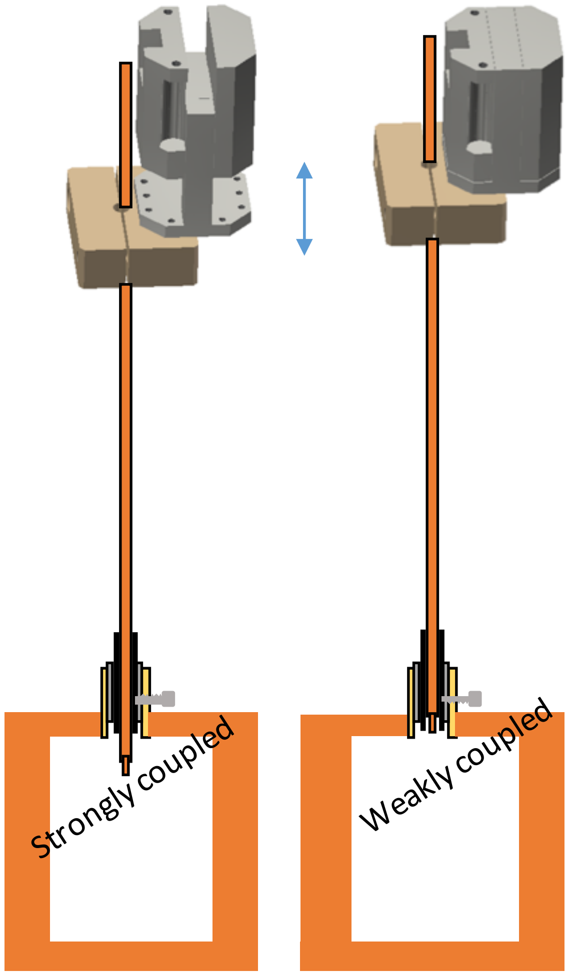
	Room temperature @~293K	Low temperature <4K
Resonant frequency	2.549GHz	2.557GHz
Q factor (HC/VC)	21,000 / **23,000**	50,000 / **80,000**

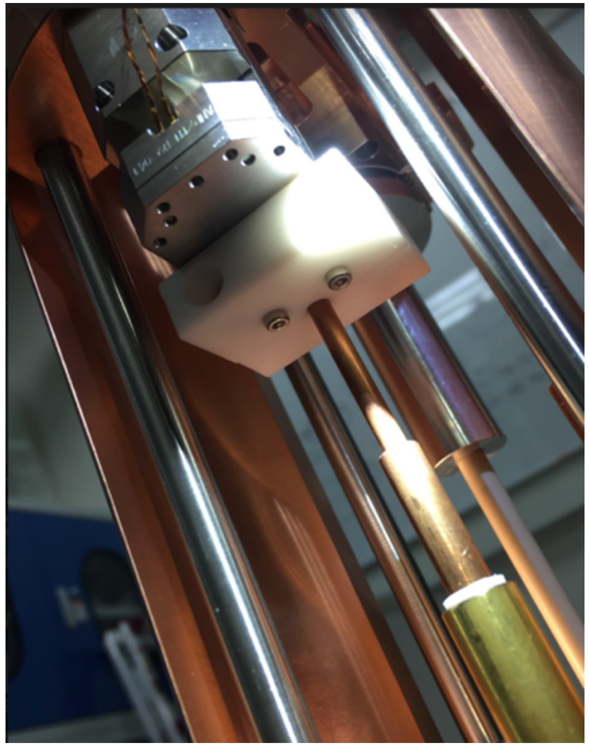
Linear piezo actuator to control the coupling strength



Travel range: 12mm

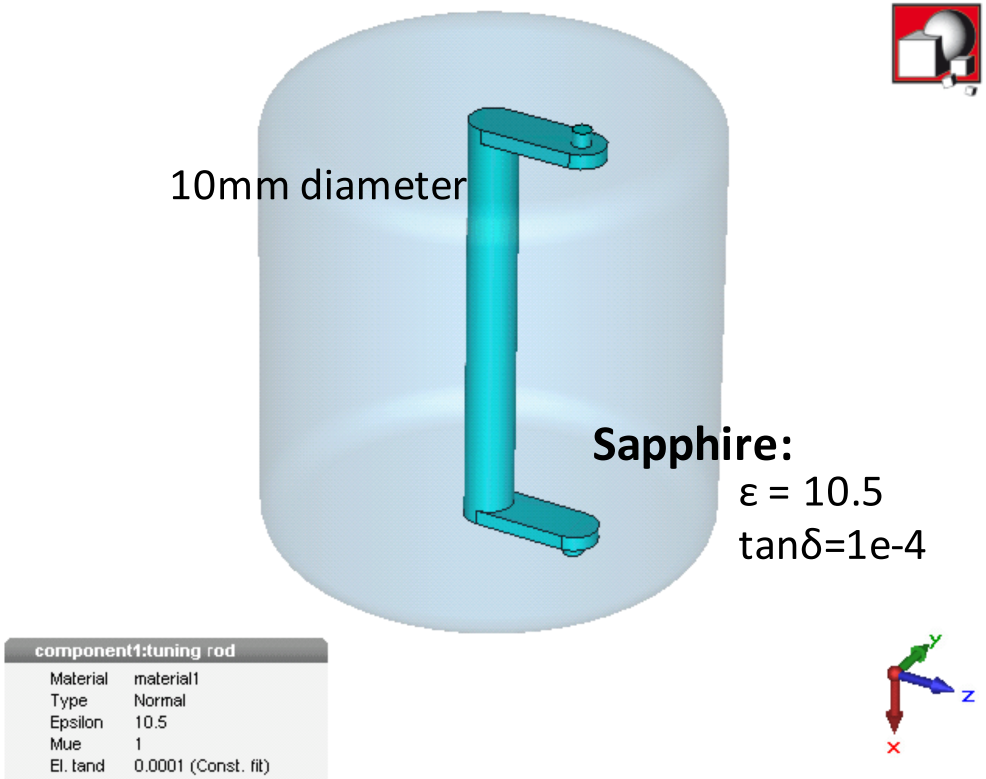
Enough range to control
weak coupling ~ critical coupling



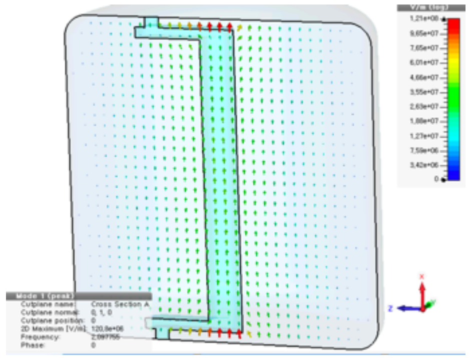


Simulation results

RF cavity tuning: sapphire rod



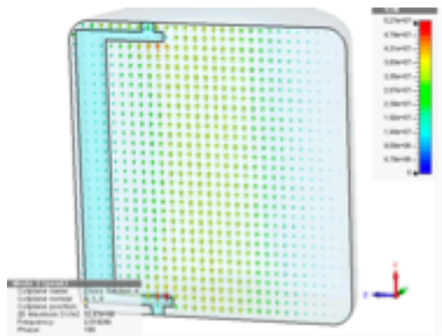
E field pattern when rod is **in center**



Freq
= **2.1GHz**

Q
= **14,000**

E field pattern when rod is **near side wall**



Freq
= **2.51GHz**

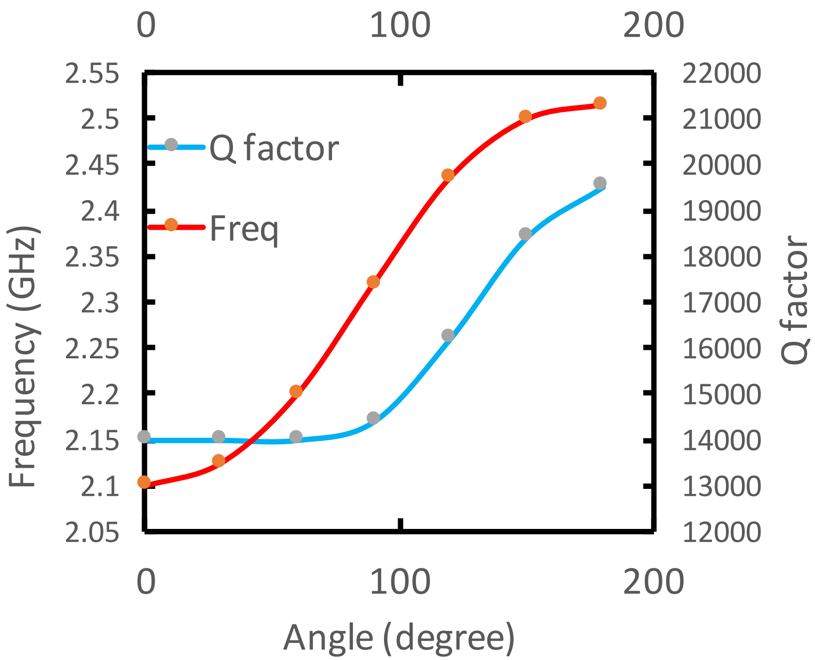
Q
= **19,500**

Rotation → distance from cavity center to rod is changing

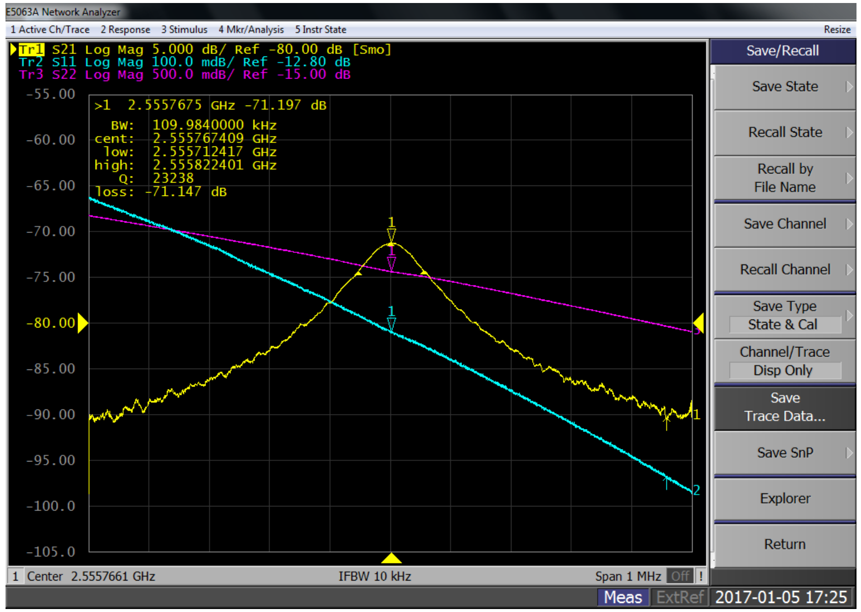
Tuning range: 2.1GHz ~ 2.5GHz (~400MHz range)

RF cavity tuning: sapphire rod

Simulation results



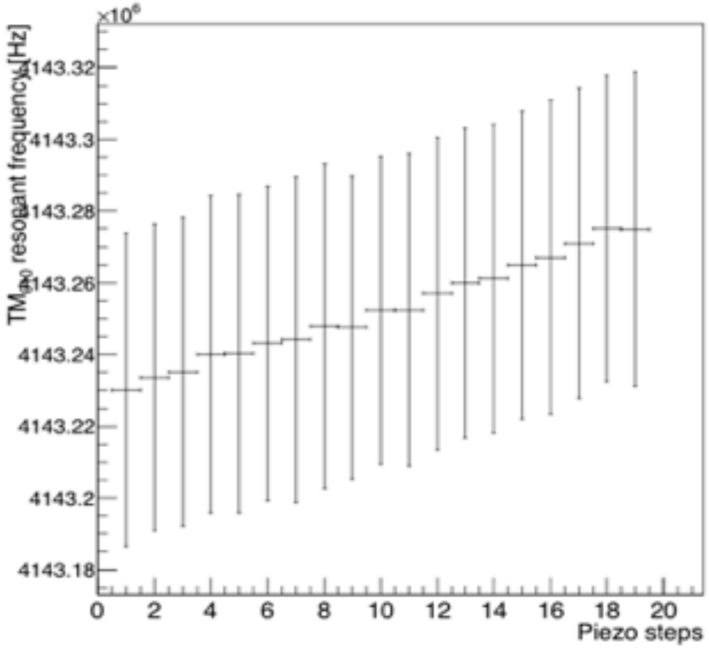
Experimental results

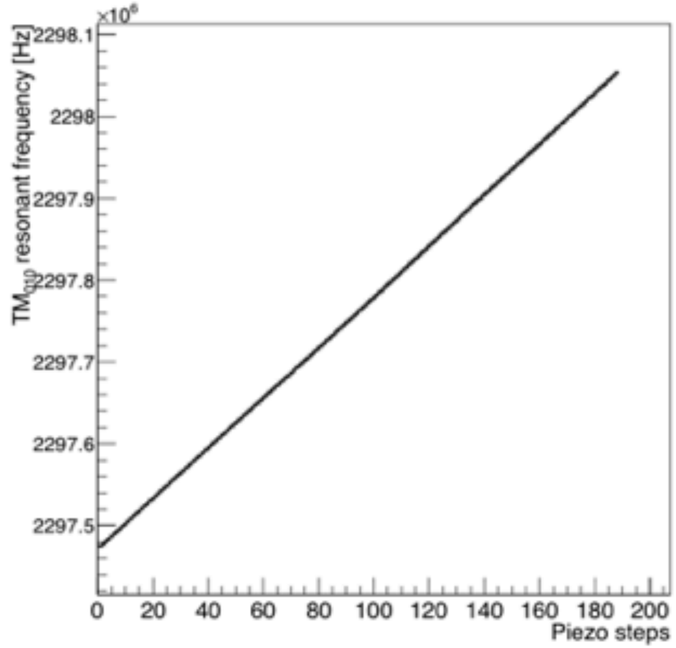


	Tuning rod @ center	Tuning rod @side
Resonant frequency (GHz)	2.047	2.496
Q factor Measurement (simulation)	16,000 (19,000)	12,500 (14,000)

Cf) no Q reduction w/ sapphire @ low temperature

Stability of tuning rod w/ cryogenic bearing





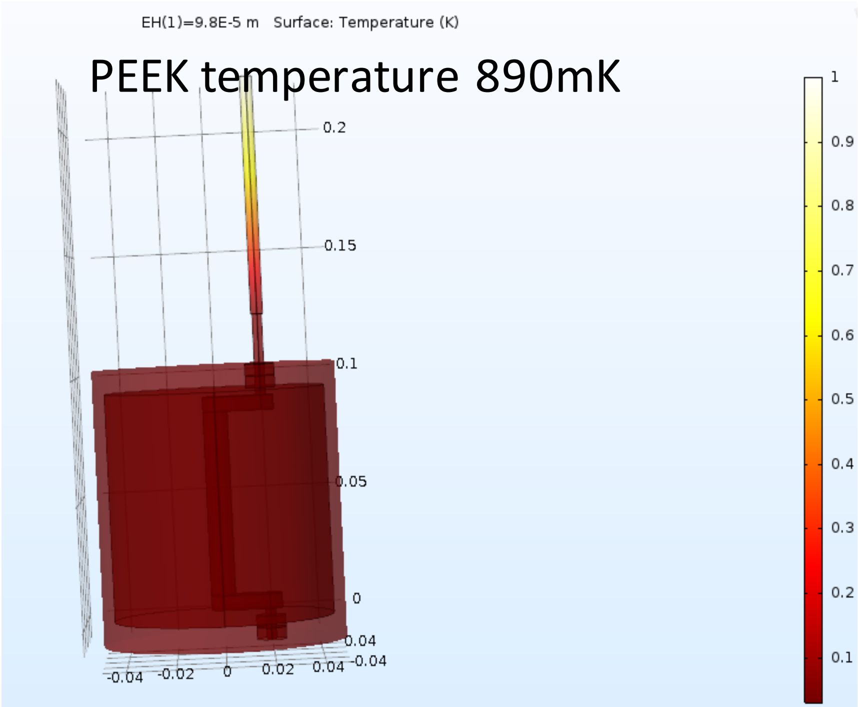
w/o cryogenic bearing
1000 samples per each step
$\Delta f = (2500.74 \pm 14506.5)$ Hz
(error > 500 %)

w/ cryogenic bearing
100 samples per each step
$\Delta f = (3091.2 \pm 153.7)$ Hz
(error ~5 %)

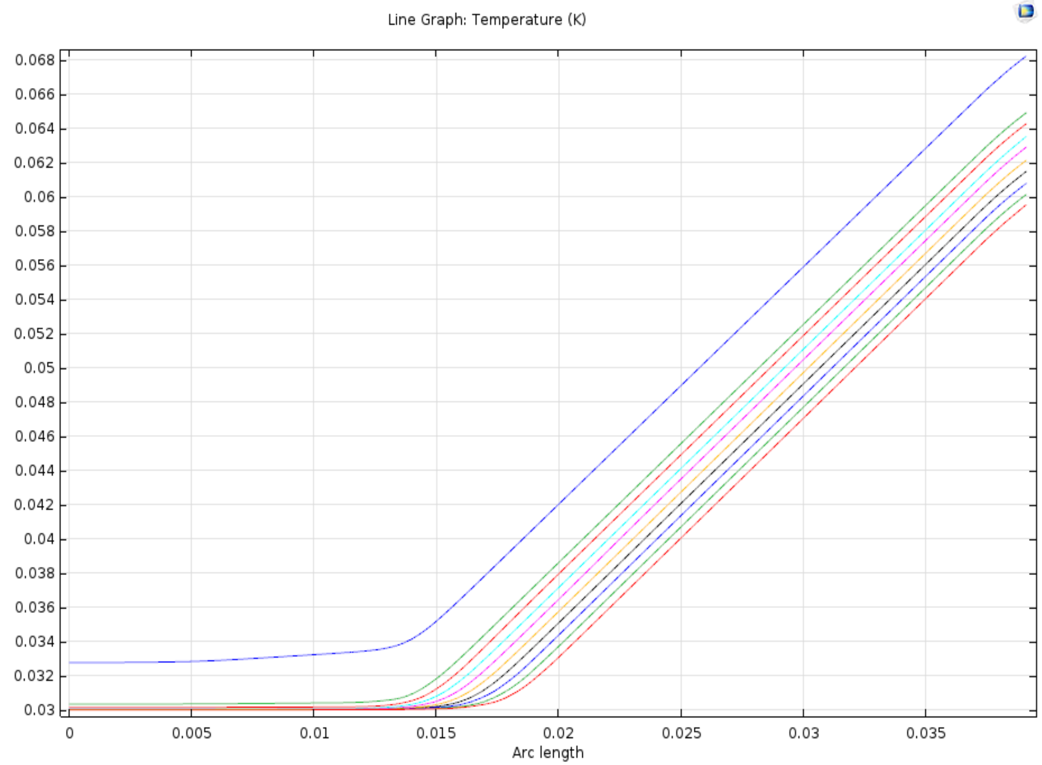
Sapphire is thermally good?

Varying touching area, we simulate temperature of tuning rod

Using COMSOL



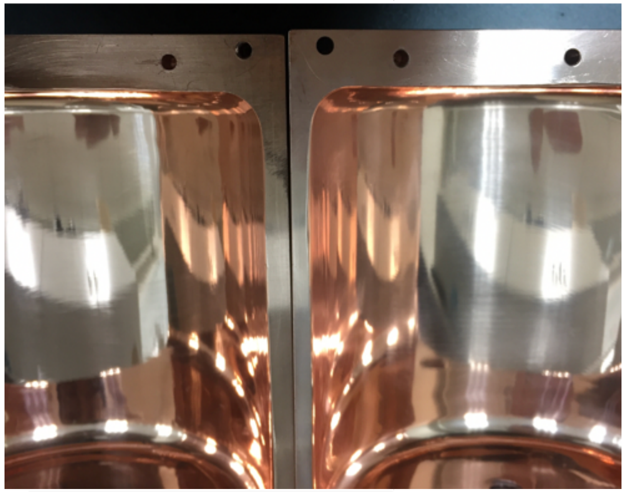
Cavity temp 30mK



Assuming 1% touching (0.04mm x 2π x 4mm) → 32mK

Cf) Assuming 0.01% touching (0. 4um x 2π x 4mm) → ~70mK

Split cavity set with sapphire rod

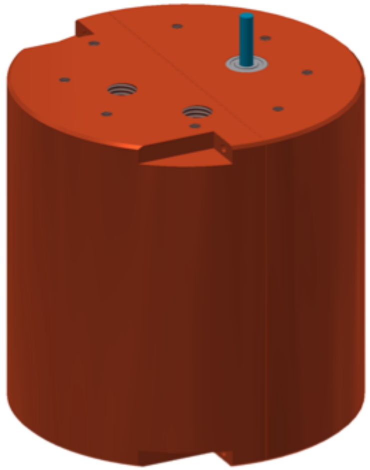


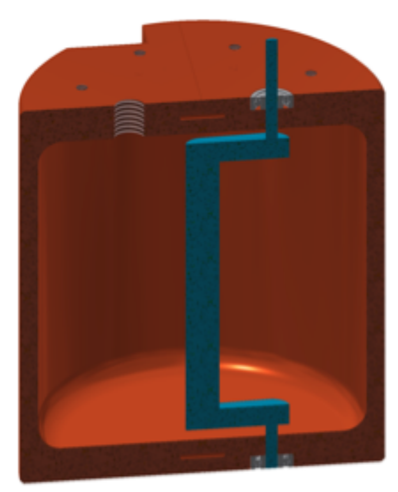
+

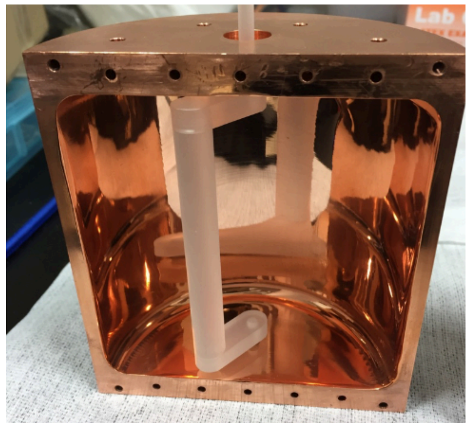
Cryogenic bearings

+

=

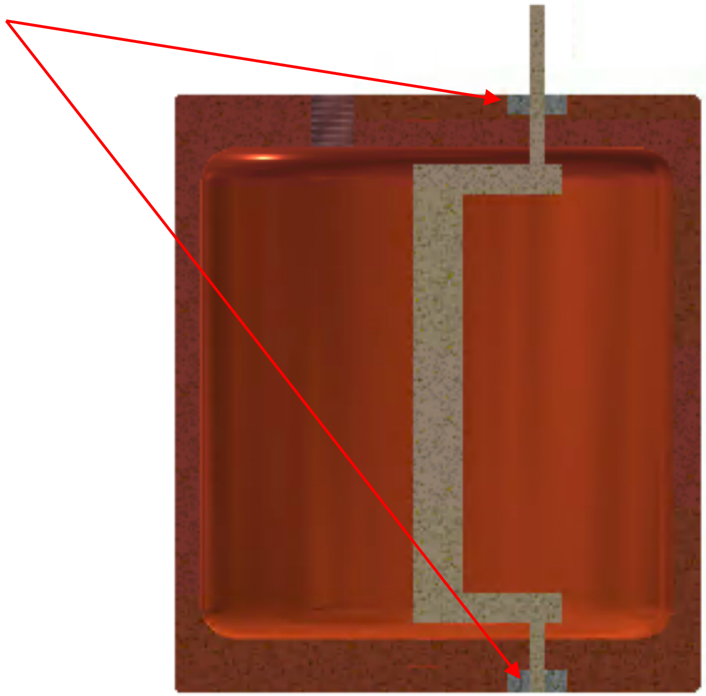






Split cavity with sapphire rod

Cryo bearing (ceramic)



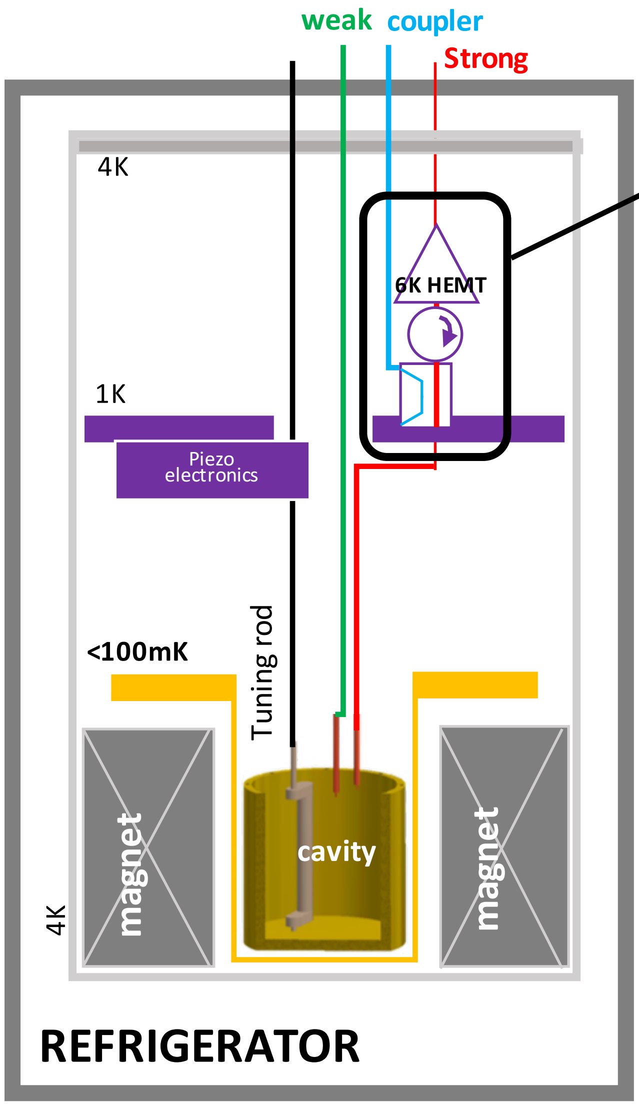
**Sapphire tuning rod assembly

Adjustment using *cryogenic epoxy

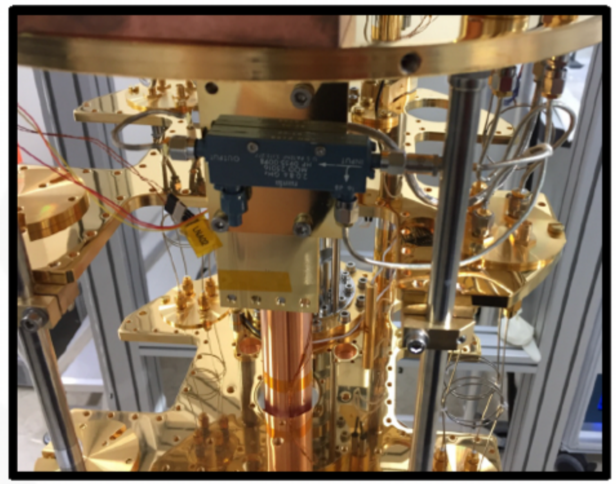
*stycast 2850

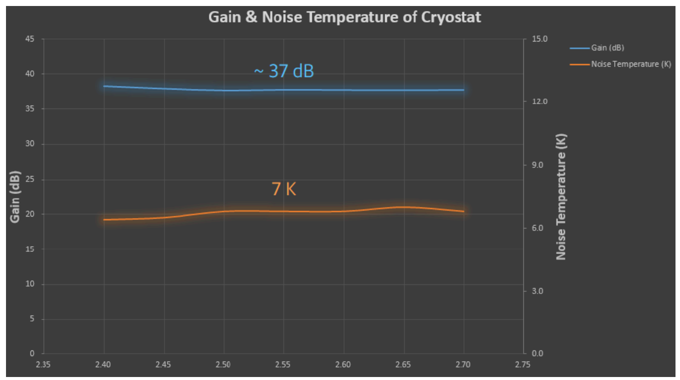
**99.99% pure Al_2O_3

RF Chain in refrigerator (6K HEMT)



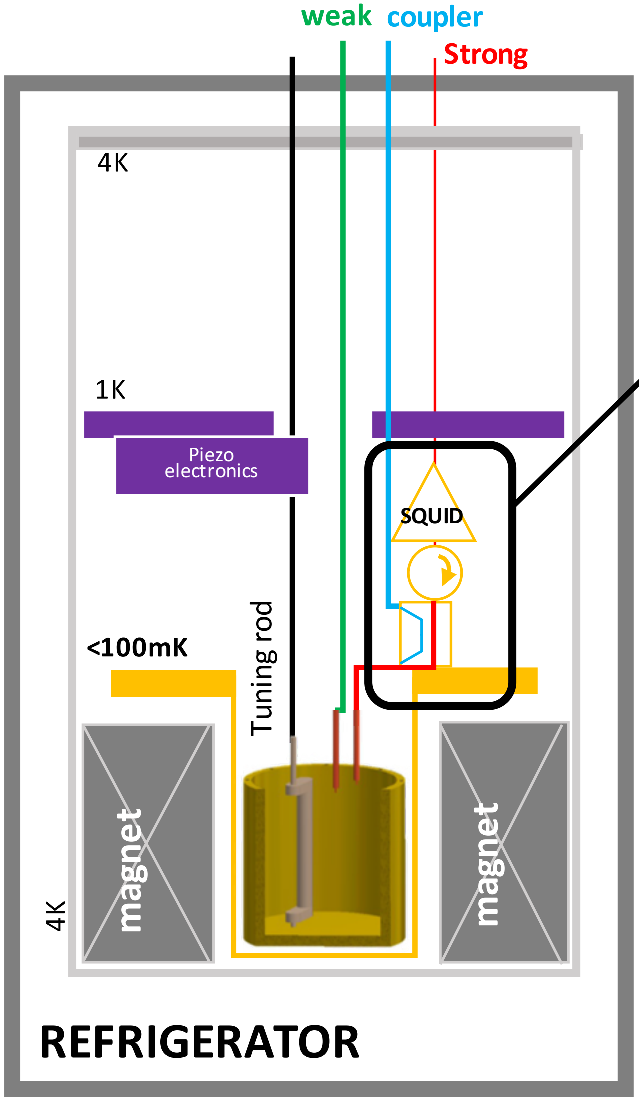
6K HEMT, isolator, coupler installation
: still plate (1K)



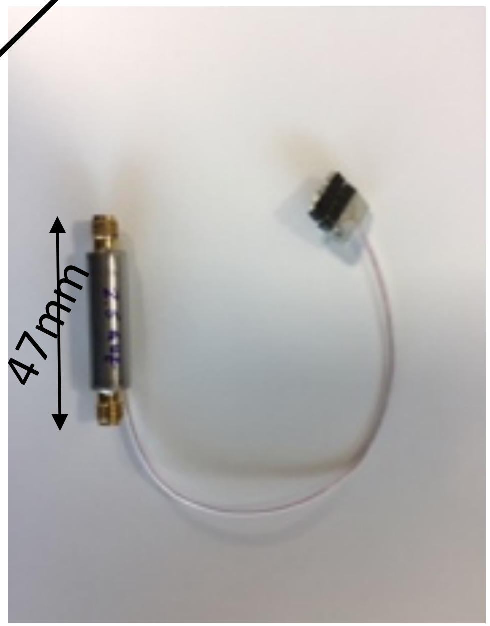


Noise temperature @ 2.5GHz: 8K

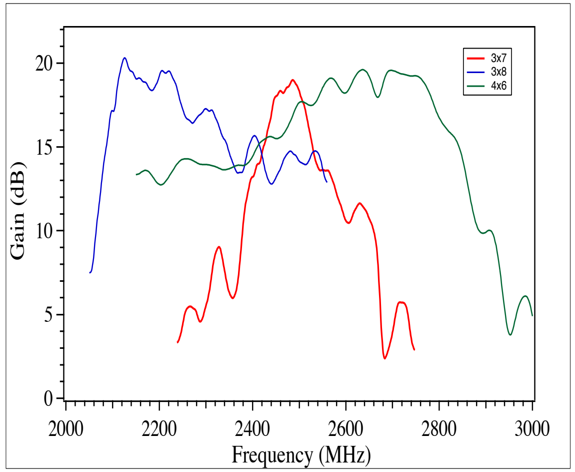
RF Chain in refrigerator (SQUID)



SQUID, isolator, coupler installation
: MXC plate (<30mK)



ez squid (2.5GHz sample)



Test results from vendor

Under test

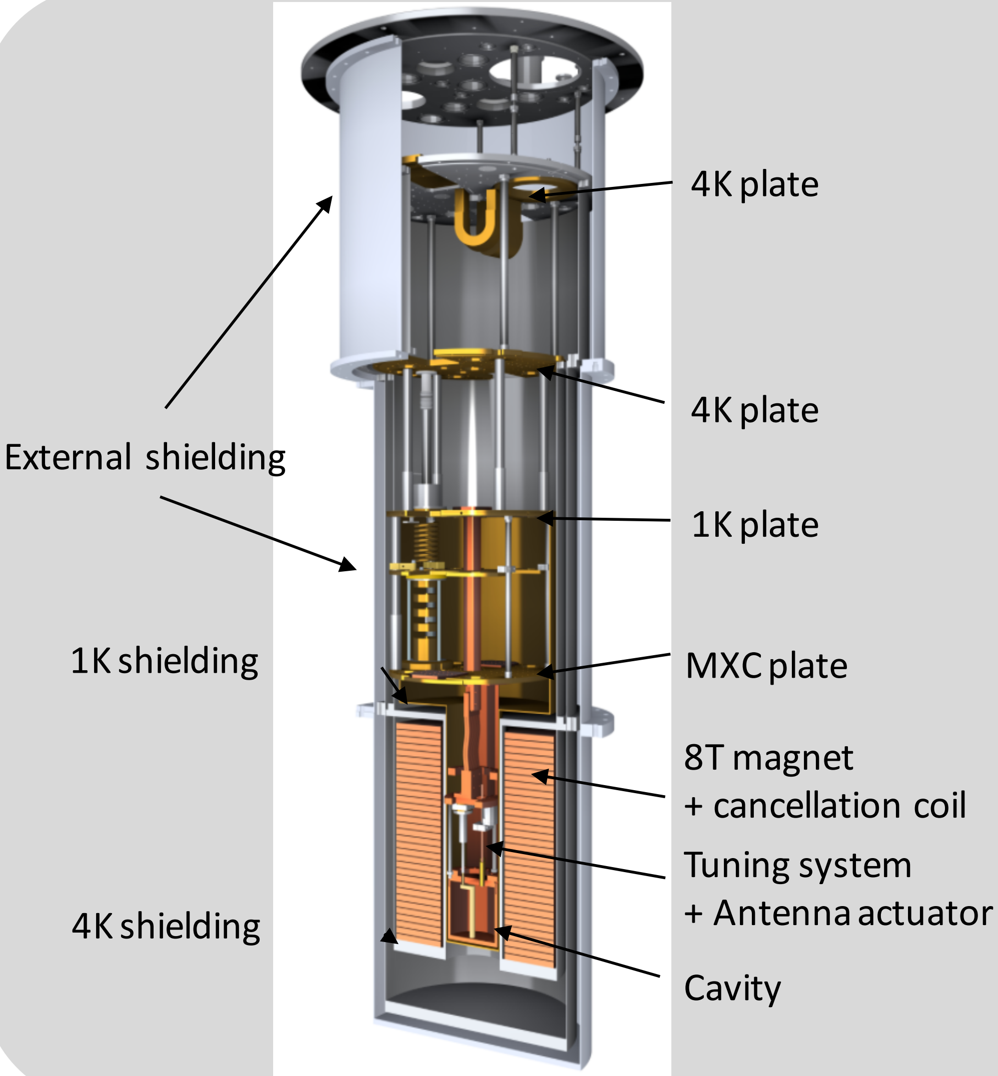
Available amplifiers in CAPP

1st amplifier candidates

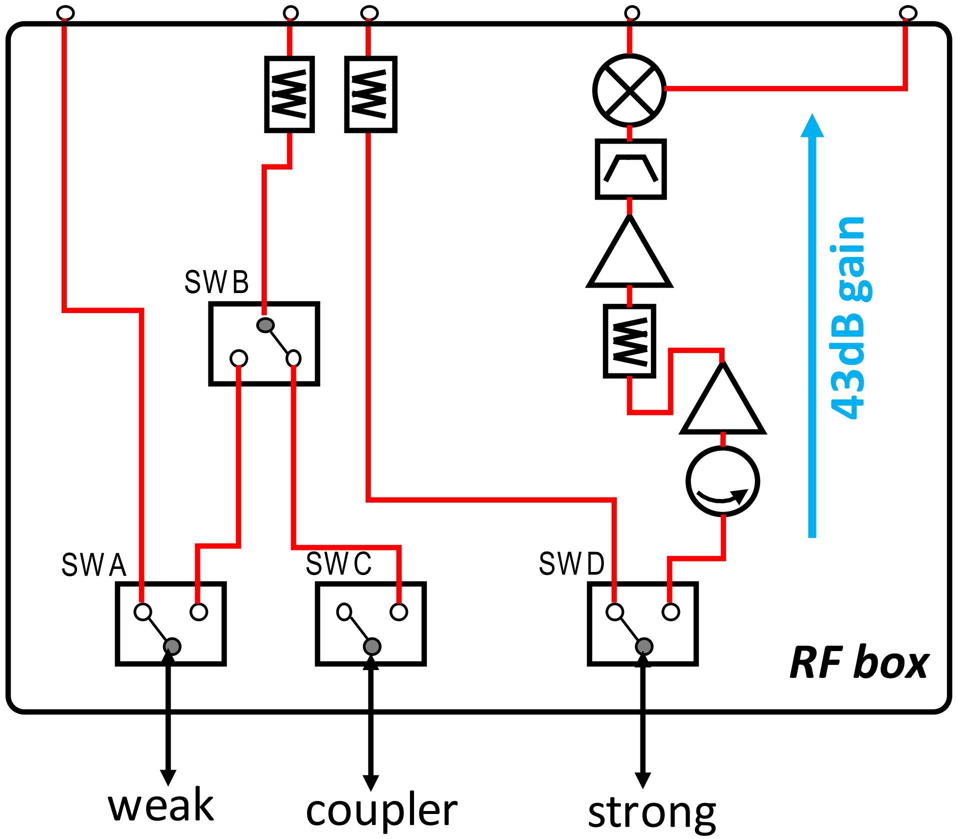
	6K HEMT	***1K HEMT***	***JPA***	***SQUID***
Gain	37dB	36 dB	20dB	<20dB
Noise temp.	8K	<=2K	*0.4K	*0.2K
			4.5-6GHz	2.5GHz

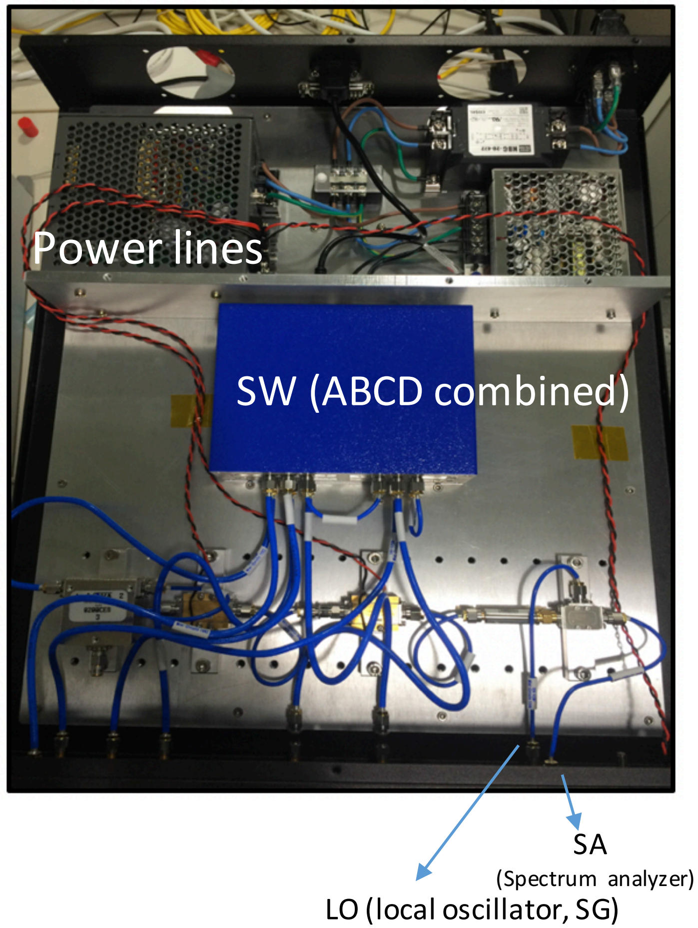
* $T_N \approx \frac{42\nu T}{V_\Phi}$ + @

Entire system for the 1st test run

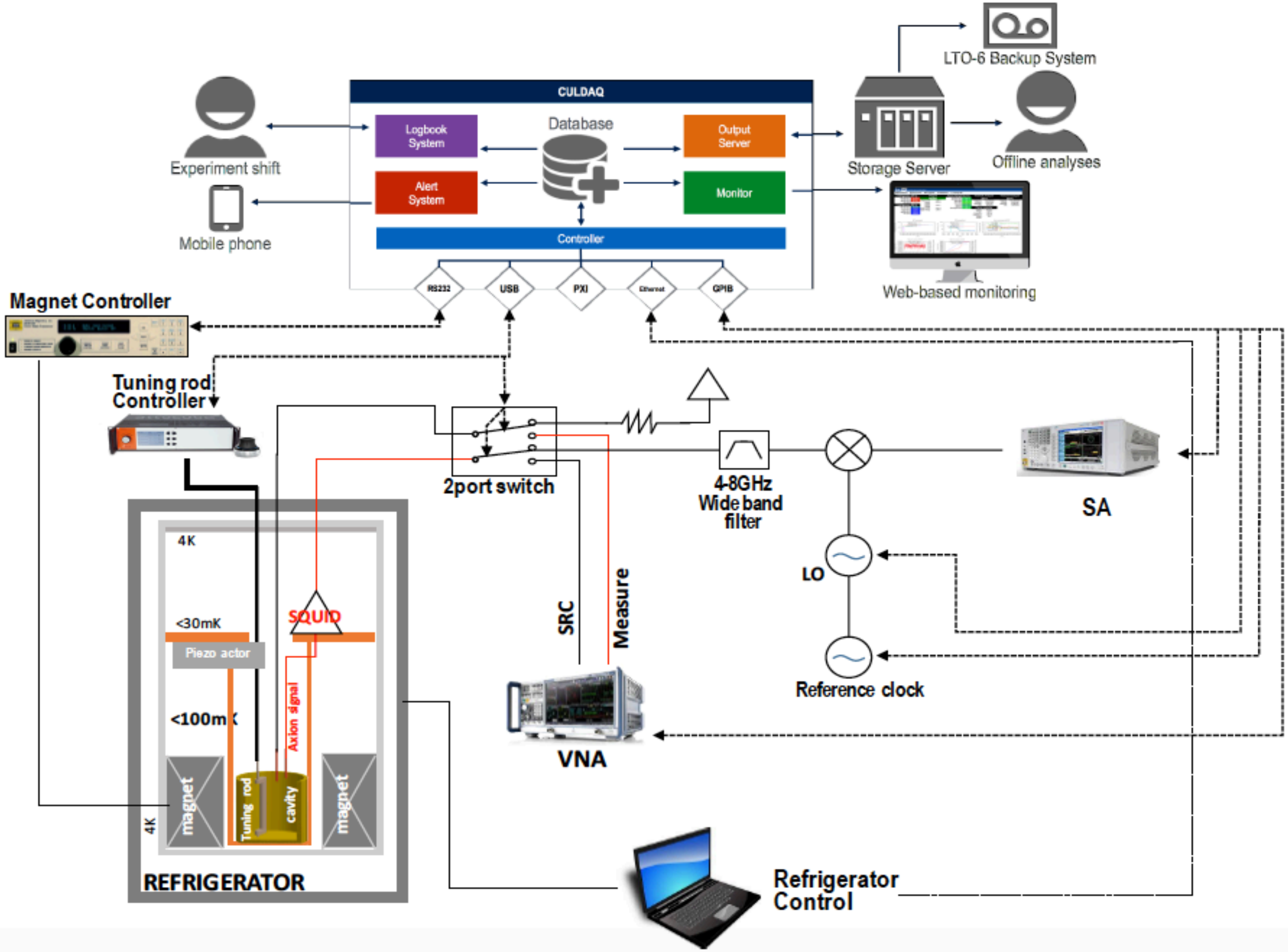


RF box (by Dr. Jihoon Choi)

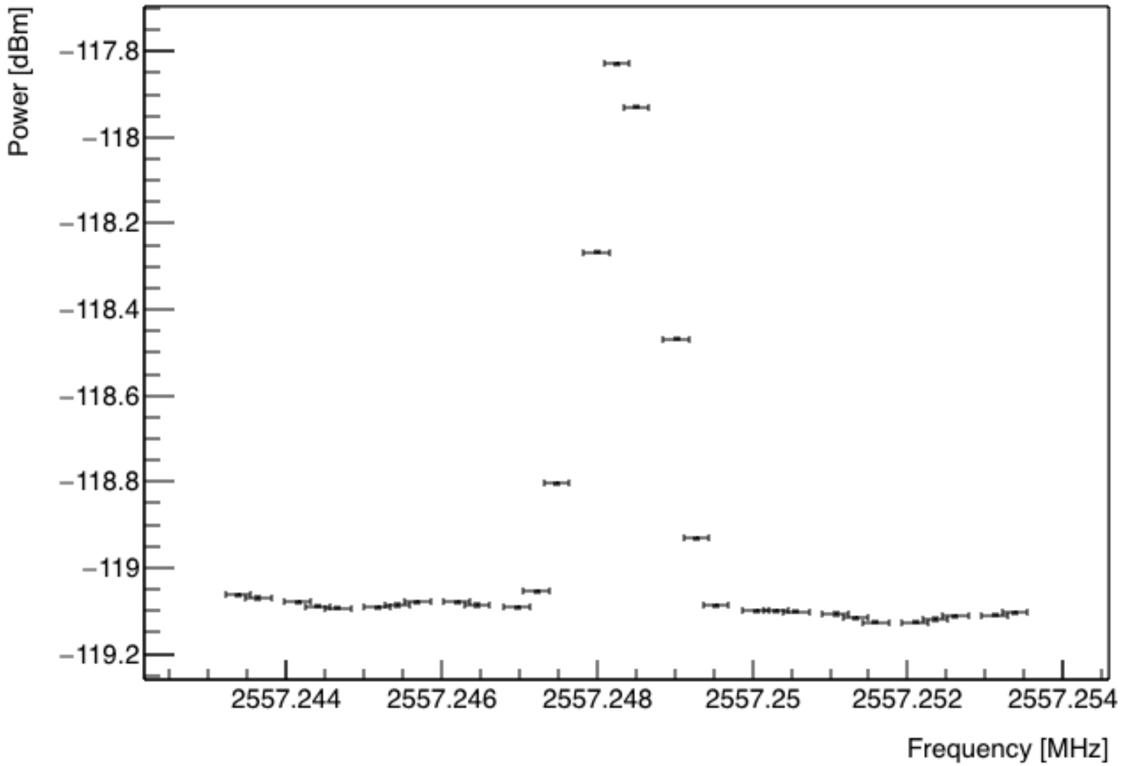




Complete RF chain w/ DAQ



DAQ of fake axion signal



Pinput = -80 dBm,
(cavity loss = -37.8 dB)
No amplifier included in both LT and RT
Ambient temperature = 26 mK
170,000 spectra averaged

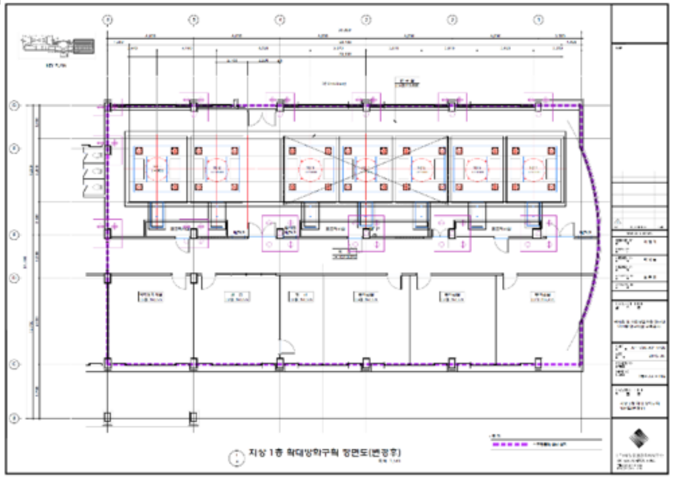
From Dr. Soohyoung Lee

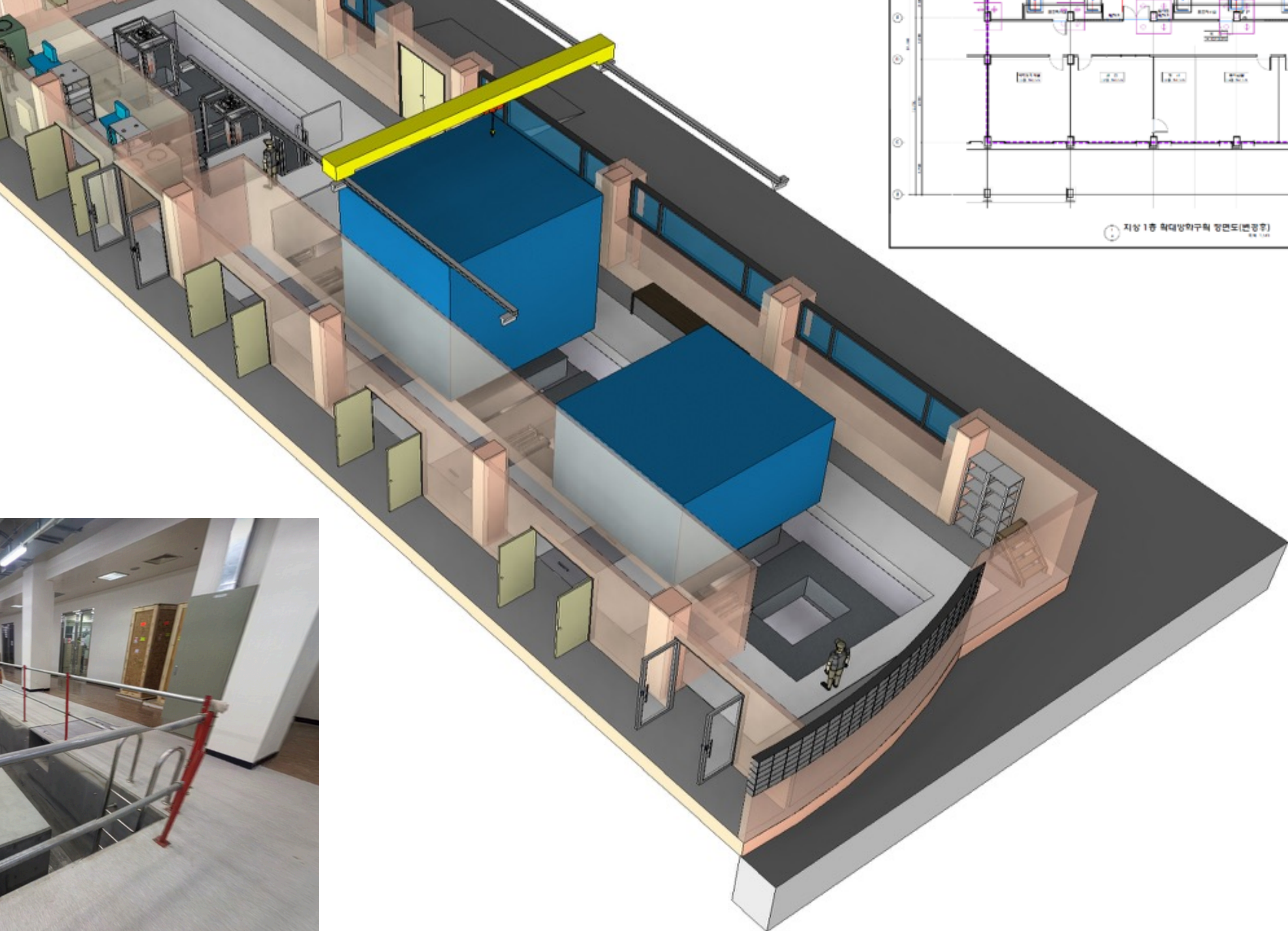
1^{st} test system summary

- Cavity: 9cm ID, 9.3cm height → **2.56GHz, Q=80,000 @ 20mK**
  - To be upgraded to 9cm ID, more than 20cm height
- 1^{st} amp: 6K Noise HEMT
  - (1K HEMT & SQUID under test)
- Total RF gain : 82dB (65dB w/ SQUID)
- Noise temperature: (2K w/ 1K HEMT, 0.13K w/ SQUID)
- Scanning rate(KSVZ): 8K
  - ~20Hz/day (330Hz/day w/ 1K HEMT, 58kHz/day w/ SQUID)
- Scanning rate(DFSZ):
  - ~0.4Hz/day (145Hz/day w/ 1K HEMT, 1.1kHz/day w/ SQUID)

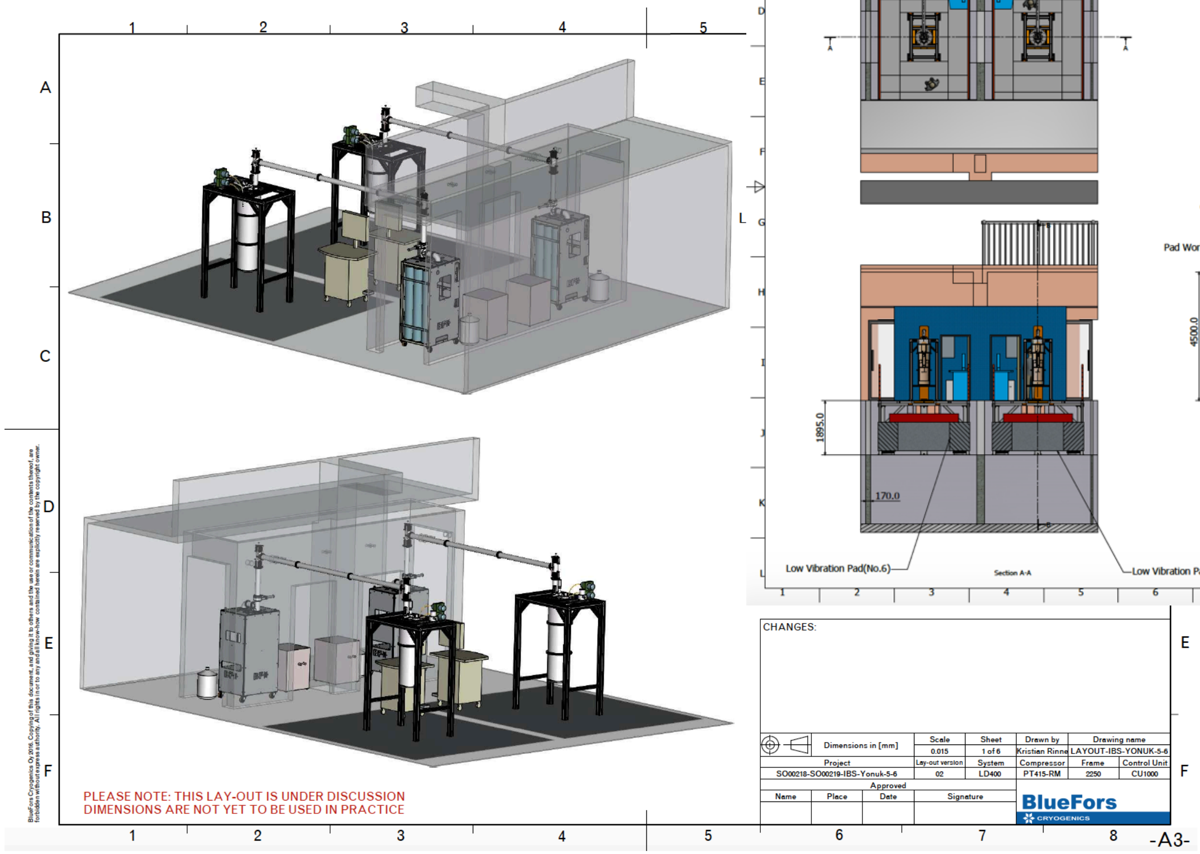
CULTASK 2017
& beyond 2017

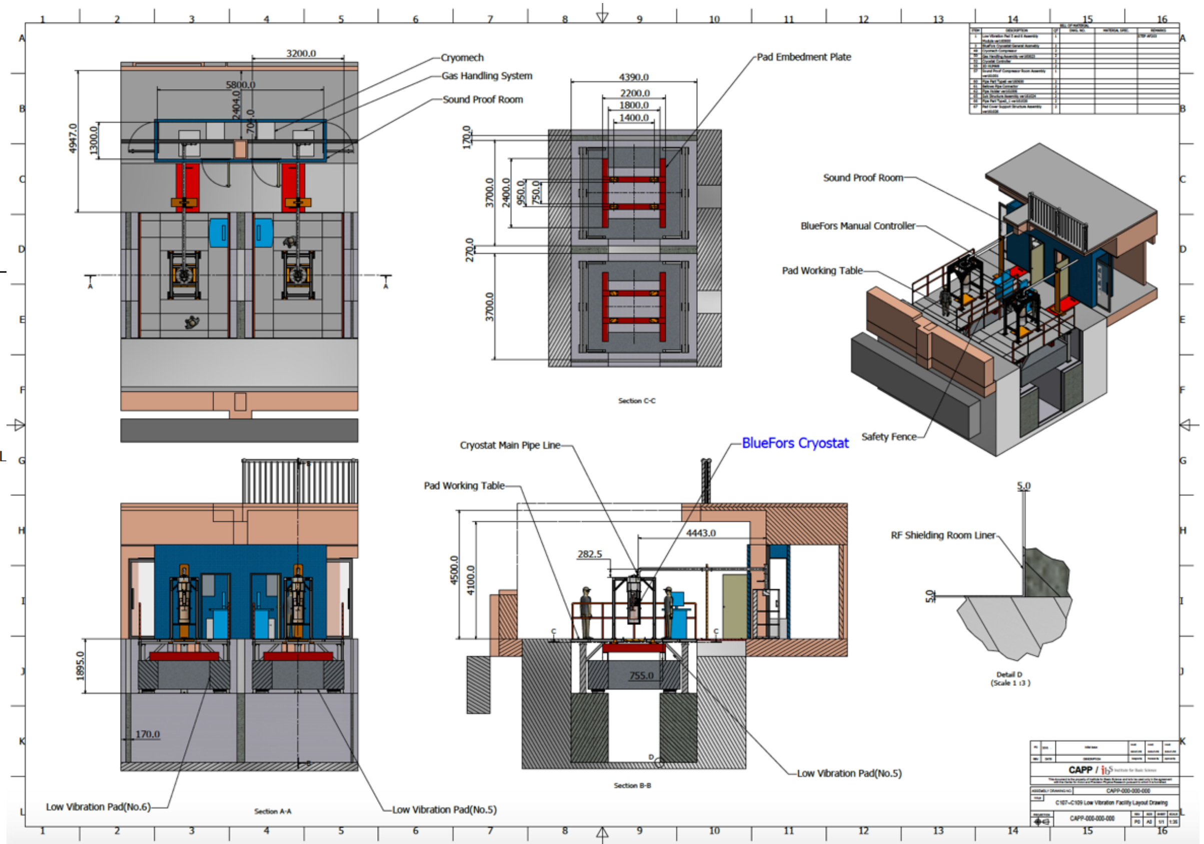
Low vibration pads (LVPs) construction



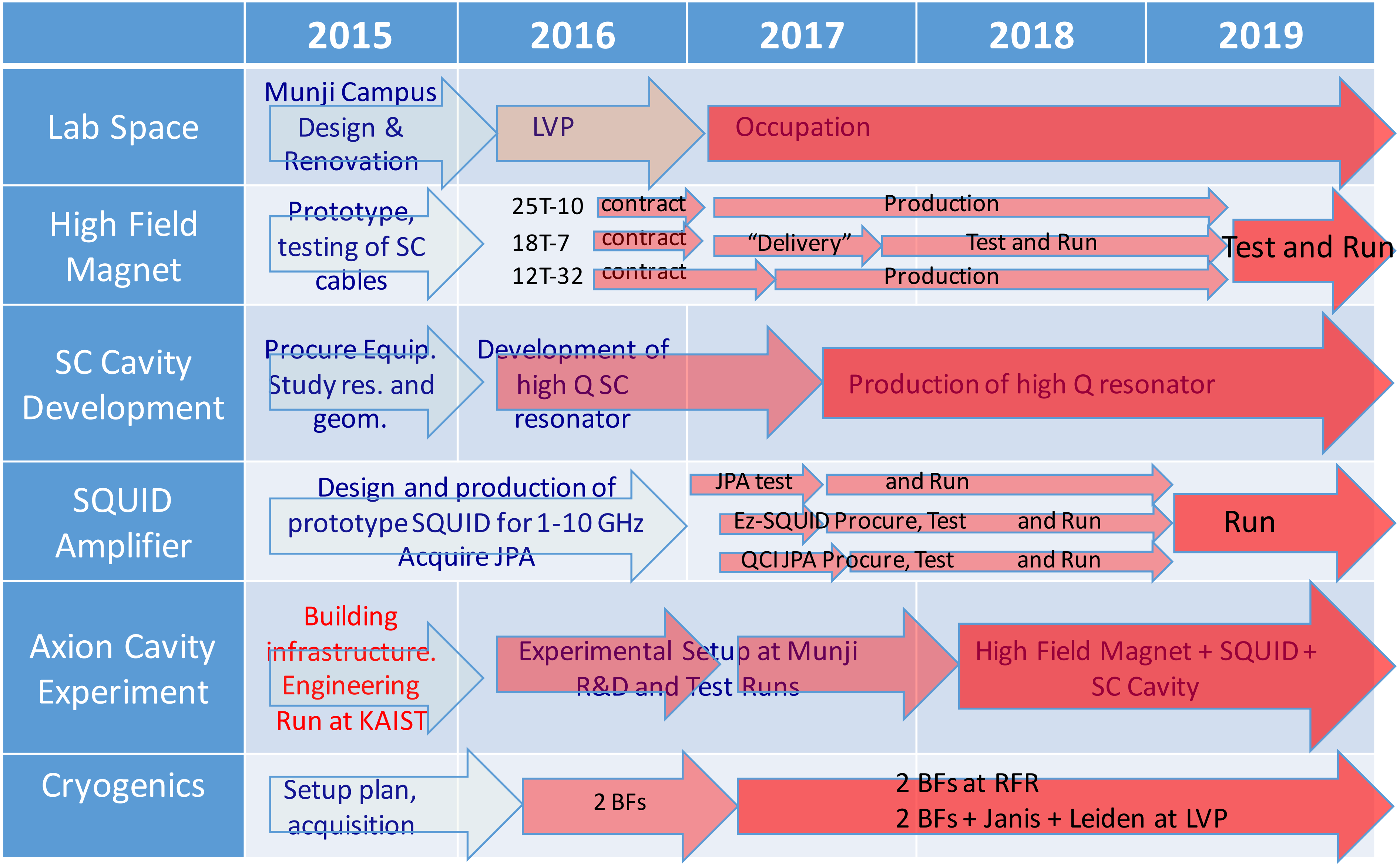


Low vibration pads (LVPs) construction





Milestone


2015
2016
2017
2018
2019
Lab Space
Munji Campus Design & Renovation
LVP
Occupation
High Field Magnet
Prototype, testing of SC cables
25T-10
18T-7
12T-32
contract
contract
contract
Production
"Delivery"
Test and Run
Production
Test and Run
SC Cavity Development
Procure Equip. Study res. and geom.
Development of high Q SC resonator
Production of high Q resonator
SQUID Amplifier
Design and production of prototype SQUID for 1-10 GHz Acquire JPA
JPA test
and Run
Ez-SQUID Procure, Test
and Run
QCI JPA Procure, Test
and Run
Run
Axion Cavity Experiment
Building infrastructure. Engineering Run at KAIST
Experimental Setup at Munji R&D and Test Runs
High Field Magnet + SQUID + SC Cavity
Cryogenics
Setup plan, acquisition
2 BFs
2 BFs at RFR
2 BFs + Janis + Leiden at LVP

Summary

- State of the Art Axion Research at CAPP/IBS in Korea
- Major R&D Efforts
  - Higher B Field: HTS (18T, 25T…) + LTS (12T-32cm)
  - Higher Q Factor with B Field: Factor of >10 Improvement
  - Larger Volume: Toroidal Cavity
  - R&D for Higher Frequencies (>10 GHz)
- CULTASK ready to build a complete experiment
  - ez SQUID test is remained (in 2 weeks)
  - Vertical division promise contactless TM010 cavity
  - Could reach close to QCD Axion Sensitivity soon!
- Major improvement in Axion Experiment in 2 years

BACKUP

Institute for Basic Science (IBS)

IBS HQ

CAPP/IBS at KAIST

KAIST main campus

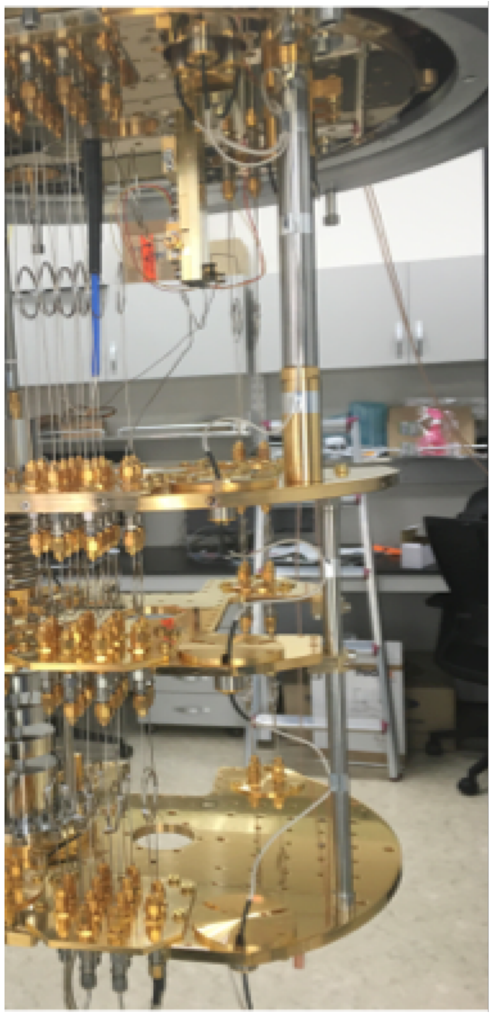
CAPP/IBS at KAIST Munji campus

KAIST Munji Campus

CAPPers

35+ members and growing

Bluefors refrigerator w/ 8T magnet



When 20mK @MXC plate,
cooling power >20μW

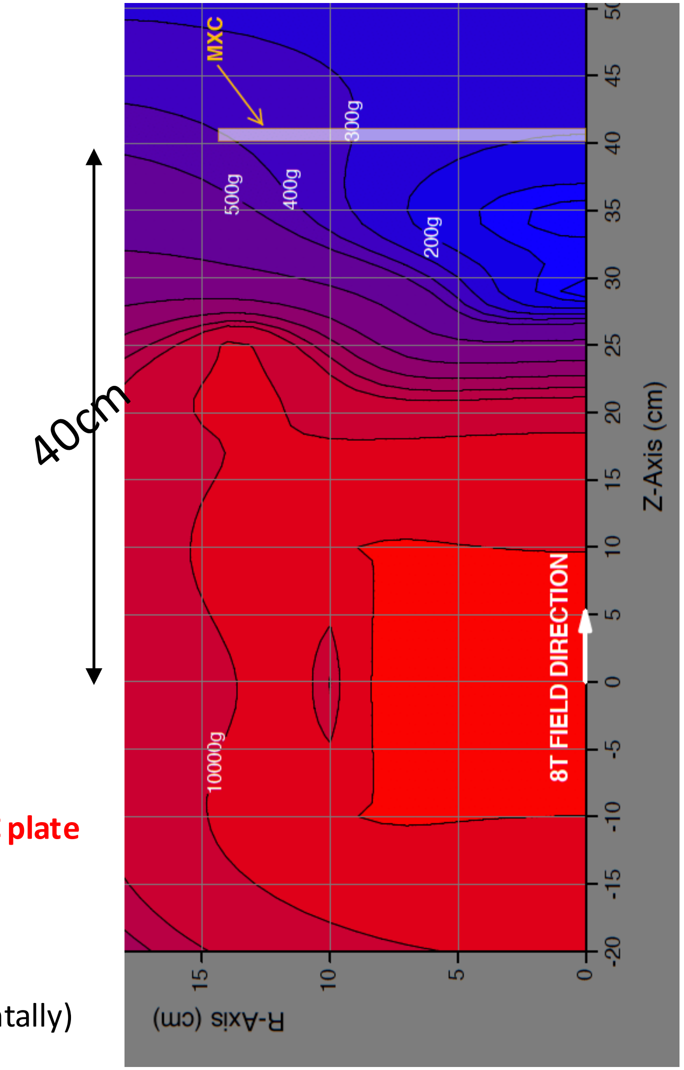
To reach <30mK,
>= 2days (w/ magnet)

To warm up from <30mK,
>= 2days (w/ magnet)

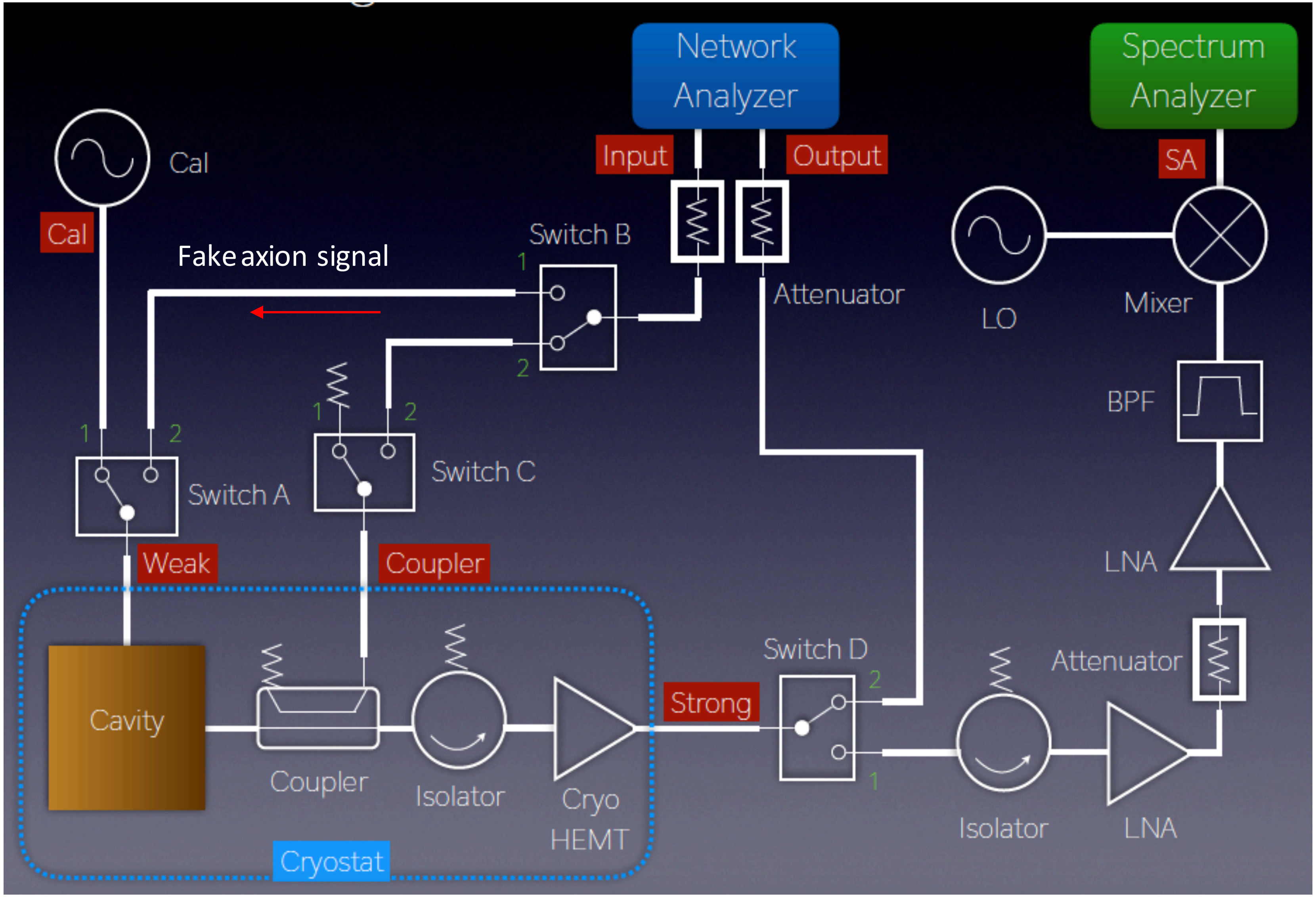
Magnetic field: 8T

Magnet center:
40cm below from MXC plate

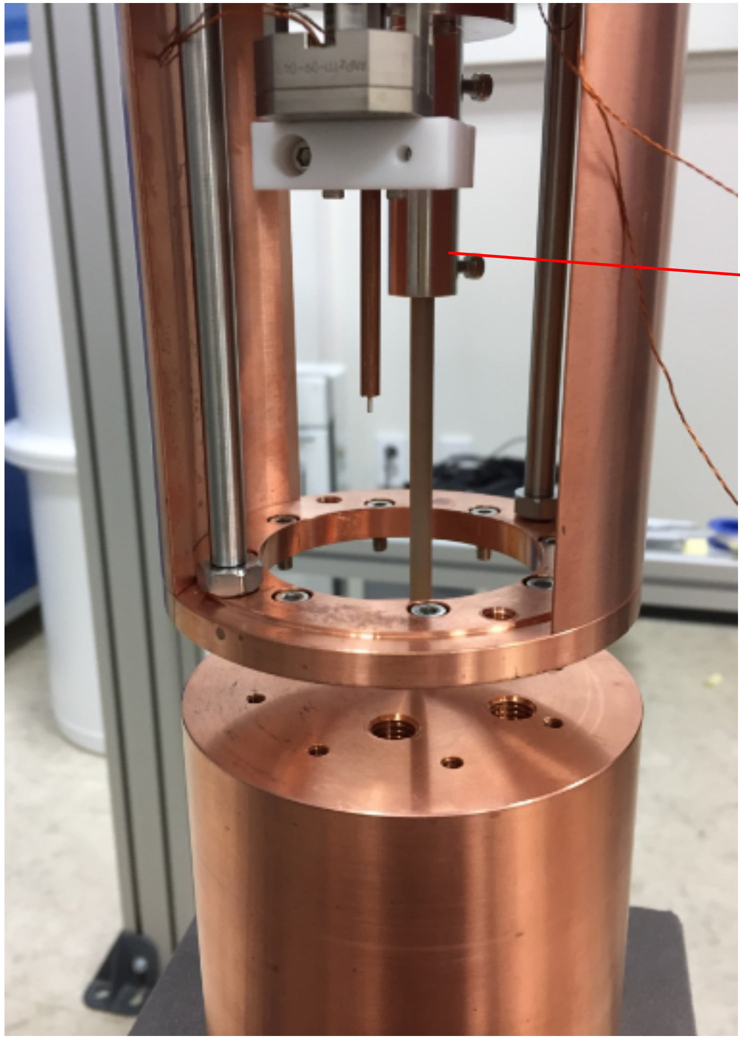
8T coverage??
Within **20cm** (vertically)
15cm diameter (horizontally)

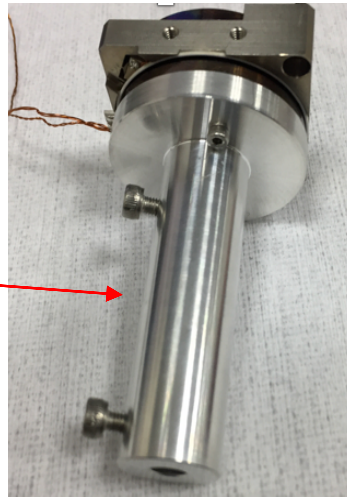


Schematic of 1st axion searching experiment

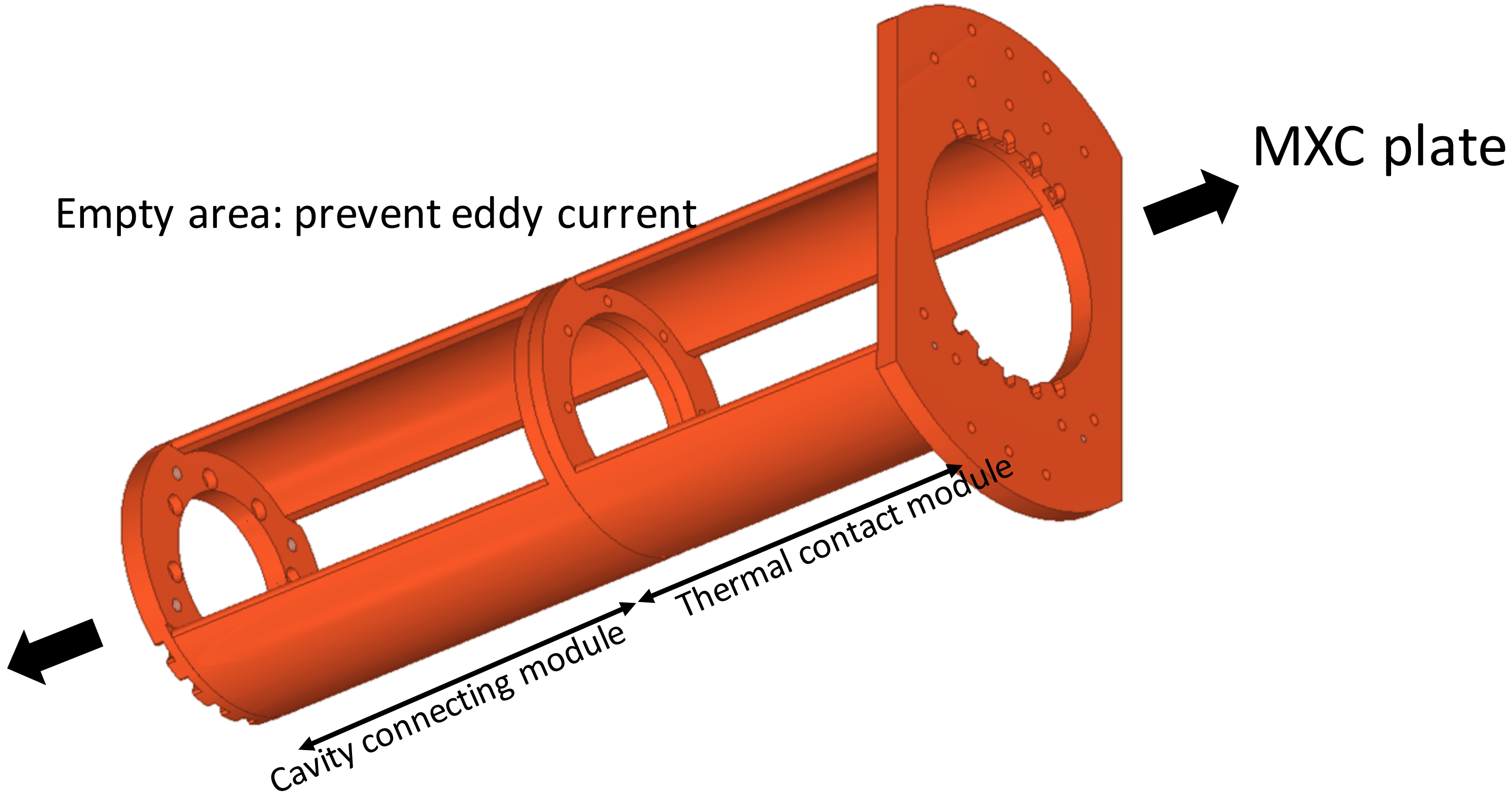


From Dr. Jihoon



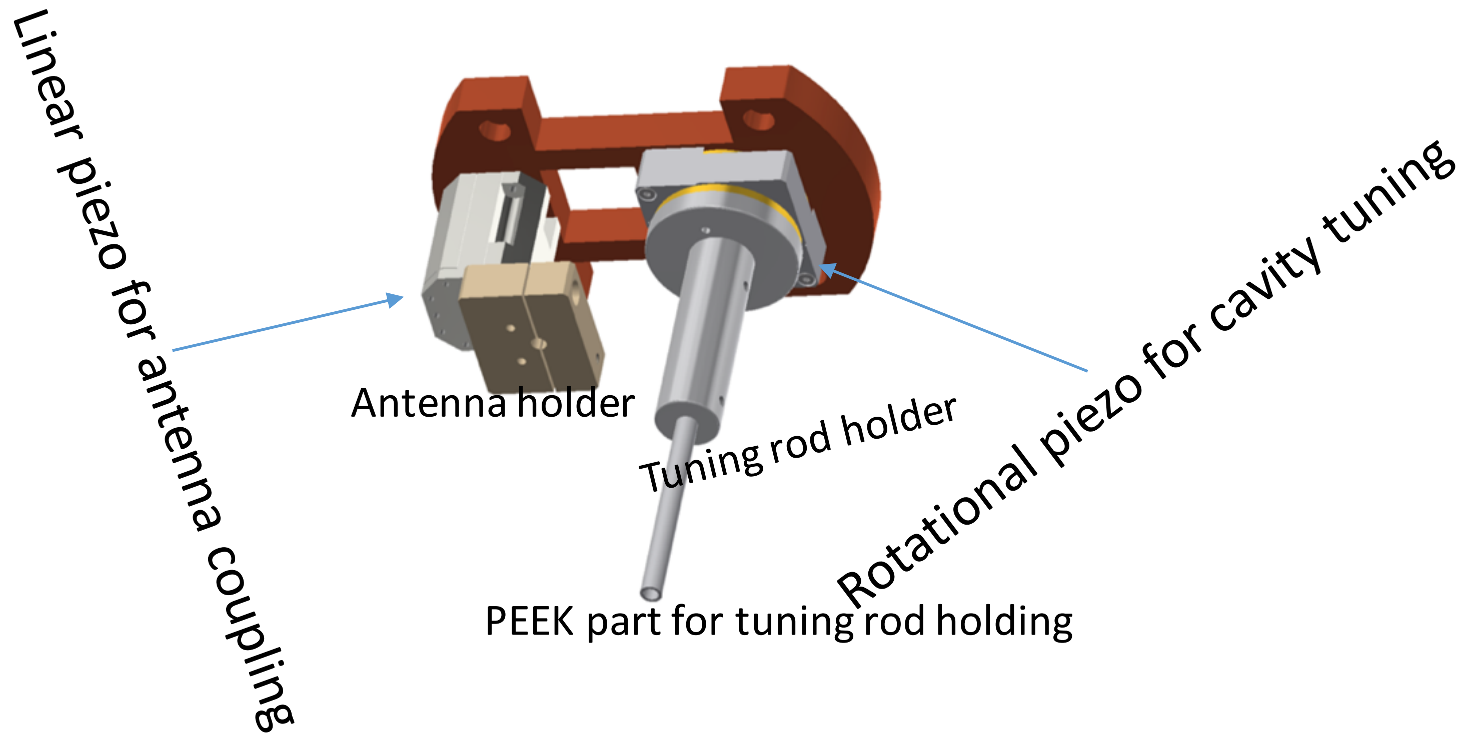


Cavity supporting structure



Modular structure → replacing available

Piezo holder (thermally isolated)

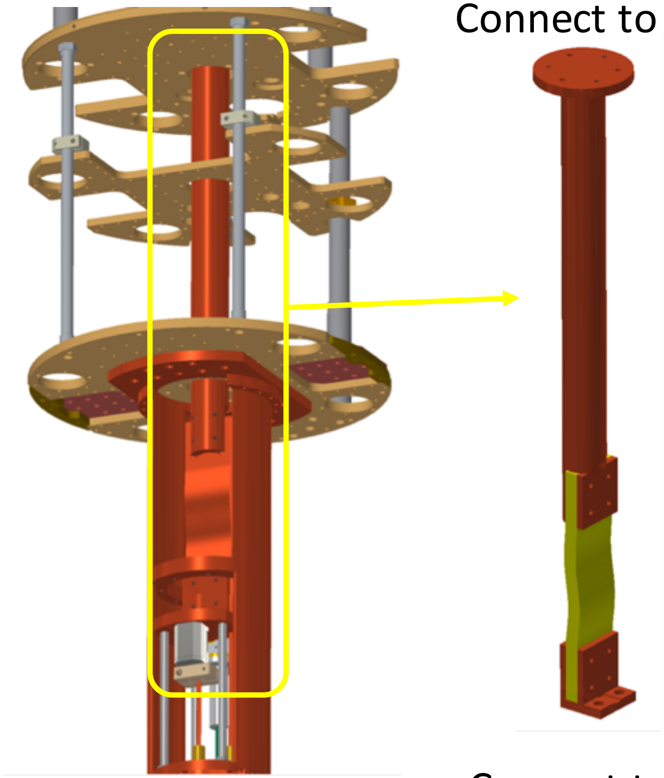


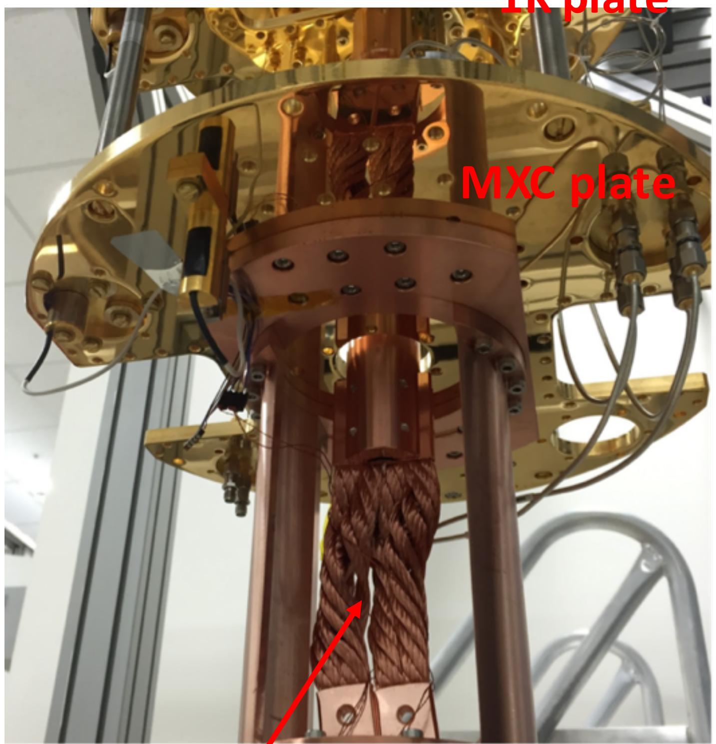
Thermal braiding

Main purpose:

To thermally contact the piezos to 1K

(to avoid critical thermal load from piezos on cavity)





Breakthrough

- Use average function in the spectrum analyzer
  - Spectrum-by-spectrum measurement

Sweep (3.3 ms)	Waiting (~200 ms)	SA→PC (~20 ms)	MEM→HDD (~40 ms)
Sweep (3.3 ms)	Waiting (~200 ms)	SA→PC (~20 ms)	MEM→HDD (~40 ms)

. . .

10,000 measurements: 2,600 sec. for 33 sec measurements **Deadtime = 98.7%**

  - Averaged spectrum measurement (e.g. flushing at 1,000 measurements)

Sweep (3.3 ms)	Sweep (3.3 ms)	. . .	Sweep (3.3 ms)	Sweep (3.3 ms)

Waiting (~32 s)	SA→PC (~1.1 ms)	MEM→HDD (~0.3 ms)

10,000 measurements (1k avg.): 320 sec. for 33 sec measurements **Deadtime = 89.7%**

Spectrum analyzer N9010A can average up to 10,000 spectra

10,000 measurements (10k avg.): 48 sec. for 33 sec measurements **Deadtime = 31.3%**