CULTASK, Axion Experiment at CAPP in Korea

Woohyun Chung

Center for Axion and Precision Physics Research (CAPP)
Institute for Basic Science (IBS)

OUTLINE

- Introduction
  - IBS/CAPP
  - Axion & Dark Matter
- CAPP's Plan
  - Axion Detection Scheme (Haloscope)
  - R&D projects
- CULTASK 2017 (CAPP's Ultra Low Temperature Axion Search in Korea)
  - Cavity + FTS Development & RF Receiver
  - Engineering Run with DAQ (complete RF chain) in 2017
- Plans beyond 2017
  - Low Vibration Pads (LVP) with Six Refrigerators in 2017
  - Physics Data by 2018
- Summary

IBS/CAPP

Center for Axion and Precision Physics Research (CAPP)

Funded by the Institute for Basic Science (IBS)

- Led by Director, Yannis Semertzidis
- Annual Budget of ~ $10M
- 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 and growing

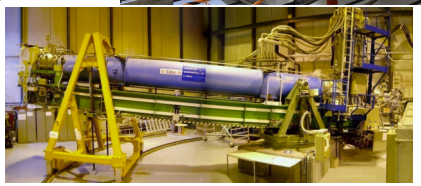
CAPP's Axion Research

Axion Research at CAPP

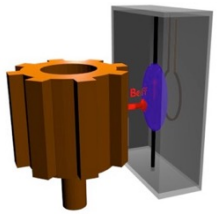
- CULTASK
- CAPP/CAST
- ARIADNE
- Large Toroid

Lead: Woohyun Chung
4 DRs installed and operational
Complete RF chain (w/ DAQ)
2 more frig. in 2017 at LVP

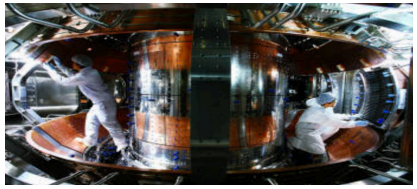
Lead: Lino Miceli
First installation at CAST



Lead: Yunchang Shin
NMR based
R&D in progress



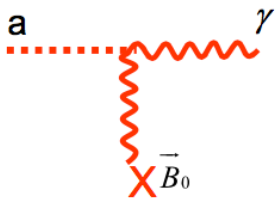
Lead: Byeongrok Ko
Requires big collaboration
R&D in progress



Axion & Dark Matter

- 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
  - $\beta \sim 10^{-3} \rightarrow Q_a \sim 10^6$



$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

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

Axion Detection Scheme

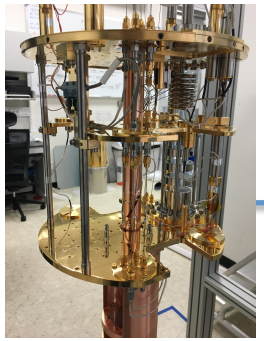
P. Sikivie's Haloscope:

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

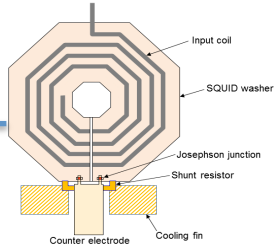
Scan rate: $$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

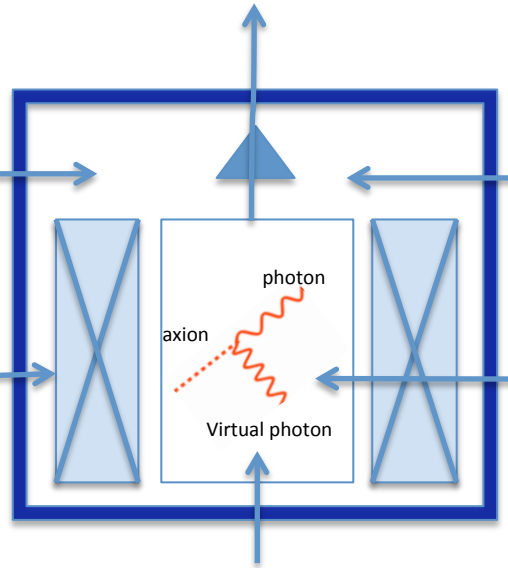
Cryogenics
<50mK



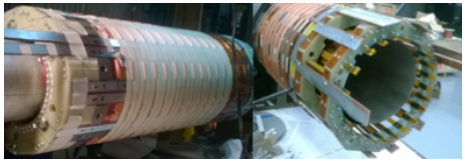
To RF Receiver

Quantum Limited Amplifier
SQUID or JPA (commercial?)

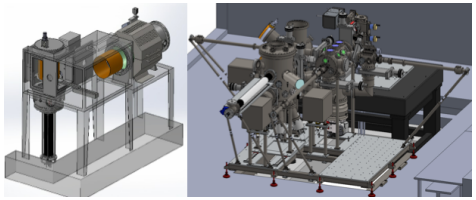




High Field SC Magnet
25T and then 35T
BNL (HTS Technology) Design



High Q Tunable Cavity
Superconducting Coating
Prof. Jhinhwan Lee of KAIST



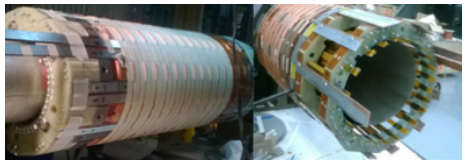
(Reverse) Primakoff Effect

CAPP's R & D

R&D for Axion Research

High Field SC Magnets

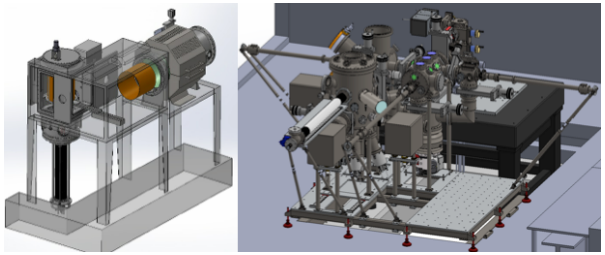
HTS 25T-10cm (->35T) by BNL 2019
HTS 18T-7cm (SuNAM) in Aug 2017
HTS 26T-3.5cm (SuNAM:WR)



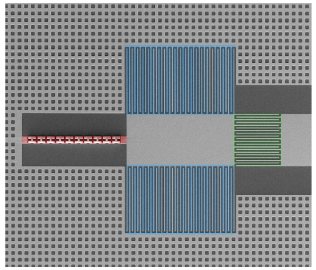
Small Toroid 12T, V=80 L
Giant Toroid 5T, V=9900 L

SC High Q Cavity

Jhinhwan Lee
Equipment setup complete
First Sputtering Sc coating

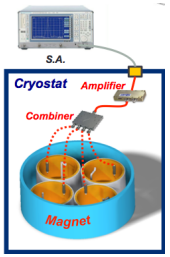


SQUID Amp



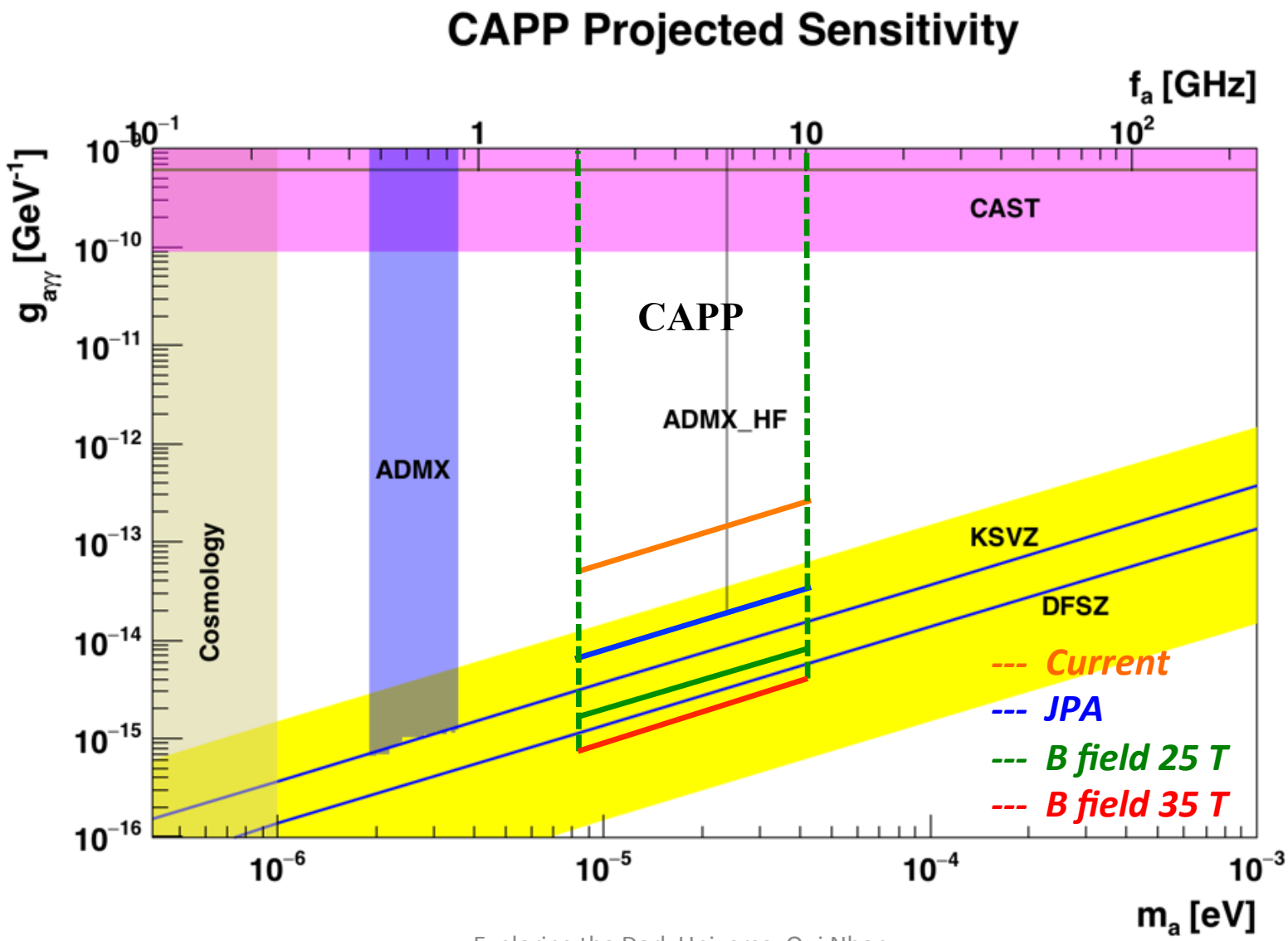
Andrei Matlashov
JPA from K. Lehnert (JILA)
MSA from M. Mueck (ez-SQUID)
JBA/JPC from Yale (QCI)
SQUID from IPHT

Higher Frequencies



SungWoo Youn
Multiple cavities
Phase locking
Photonic crystal
R&D in progress

R&D: Sensitivity



CULTASK 2017 w/ Four DRs

	BF3	BF4	BF5	BF6
Model	BlueFors LD400	BlueFors LD400	BlueFors LD400	BlueFors LD400
Magnet	None	8T (AMI), 12cm	None	8T (AMI), 16cm
RF lines	24	8	24	8
DC lines	72	72	72	72
Cool down to <10 mK	24 hours	48 hours	24 hrs	48 hrs
Base temp at MXC	9 mK	7 mK w/ SC magnet	7 mK	10 mK w/ SC magnet
MXC temp w/ Load	11 mk w/ Al cavity (4cm id) and HEMT amp	28 mk w/ 10 kg OFHC copper support structure and cavity + HEMT amp + Network Analyzer + Piezo Controller	Superconducting RF lines	Superconducting RF lines

CULTASK 2017 w/ Four DRs

- New Lab space in
  - KAIST Munji Campus Creation Hall (RF room + LVP) completed
- Installed two more Dilution Refrigerators (total of 4 running now) in Feb.
- "minAxion" is about to take data:
  - 8T 12.5 cm bore NbTi magnet (dry)
  - 9cm ID Cu cavity (~2.5 GHz)
  - FTS (freq. tuning system) with Sapphire rod
  - 1K HEMT LNA as a preamp
  - Cryo RF noise figure measurements: $T_{system} \sim 1.4$ K
  - Complete RF chain set-up with DAQ
  - Fake axion signal injection (blind test)
  - Take reasonable sensitivity DATA in 2017
  - Will boost DAQ efficiency
  - SQUID or JPA test
  - SC Cavity?
- "CAPP8Tb" is being ready
  - 8T 16.5 cm bore NbTi magnet (V~3.5 liter)
  - 15 cm cavity (~1.5 GHz) w/ FTS (being fabricated)

- 2 More refrigerators and 2 magnets in 2017 (LVP)

CULTASK 2017 w/ Four DRs

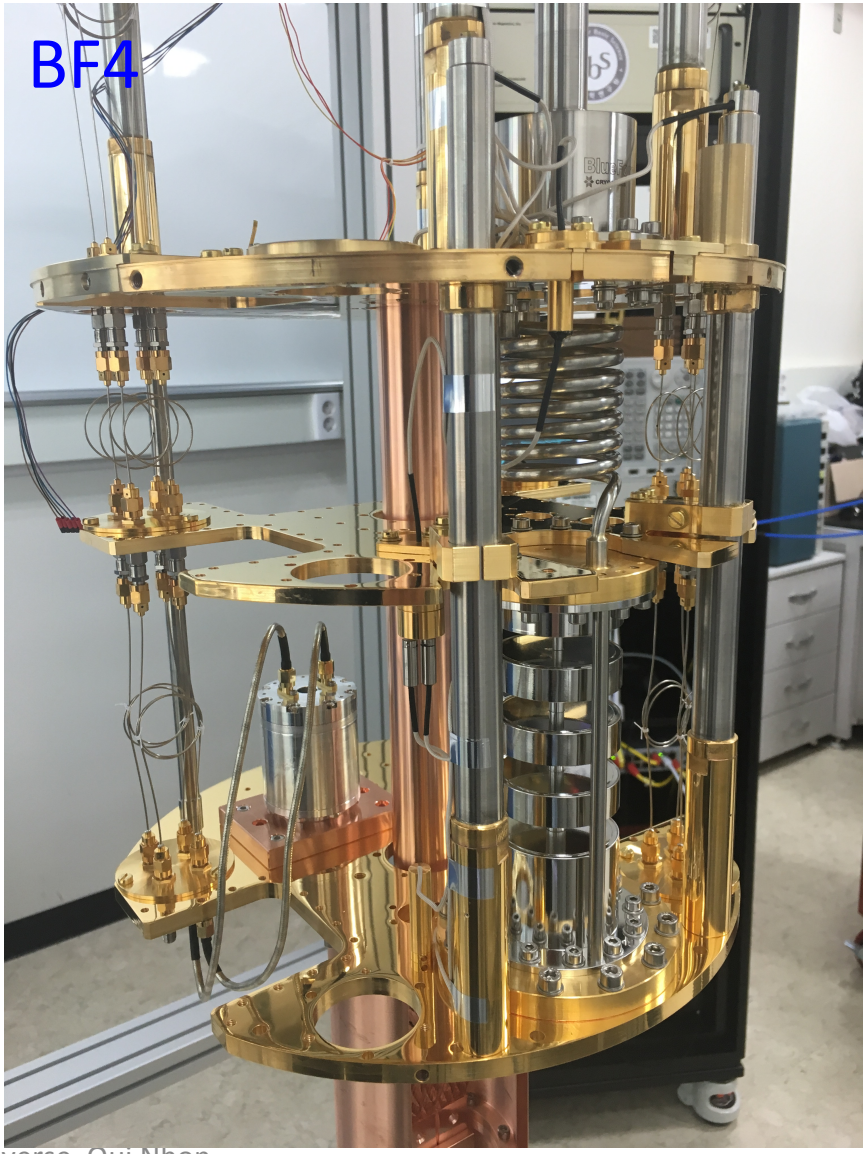
BF3 (RFR)

BF4 (RFR)

BF5 (LVP)

BF6 (LVP)

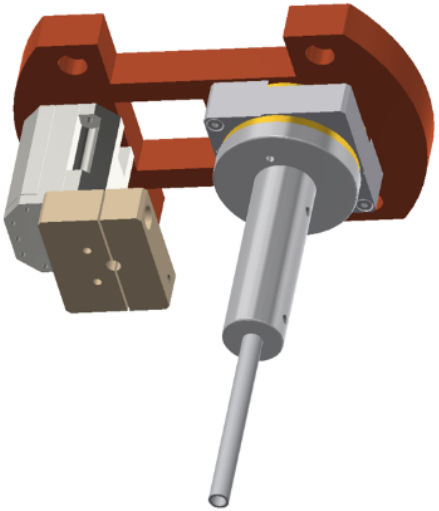
CULTASK 2017 w/ Four DRs

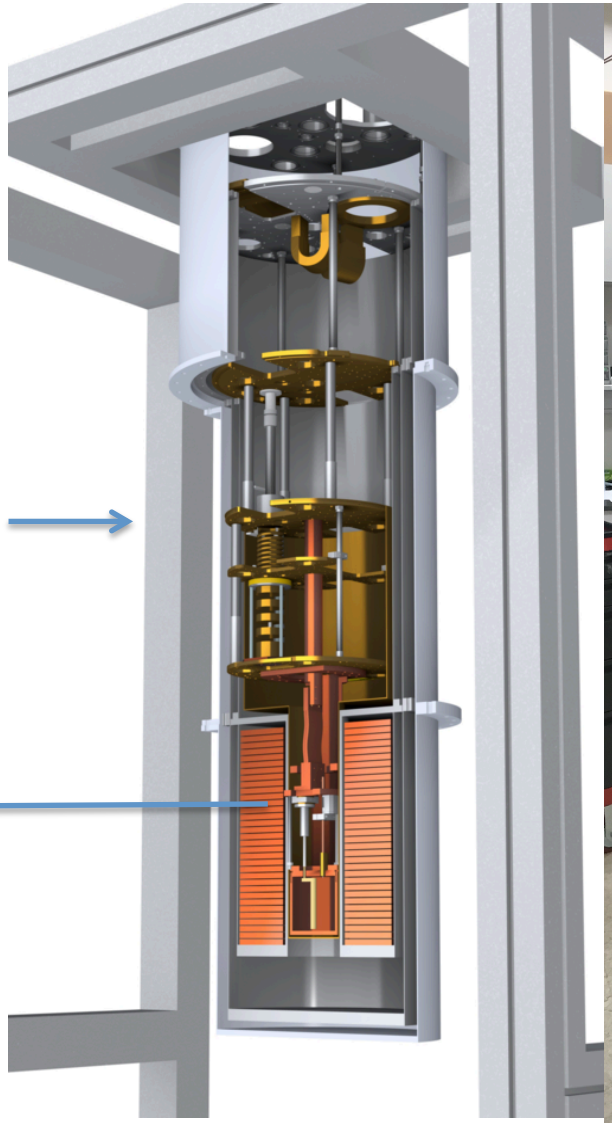


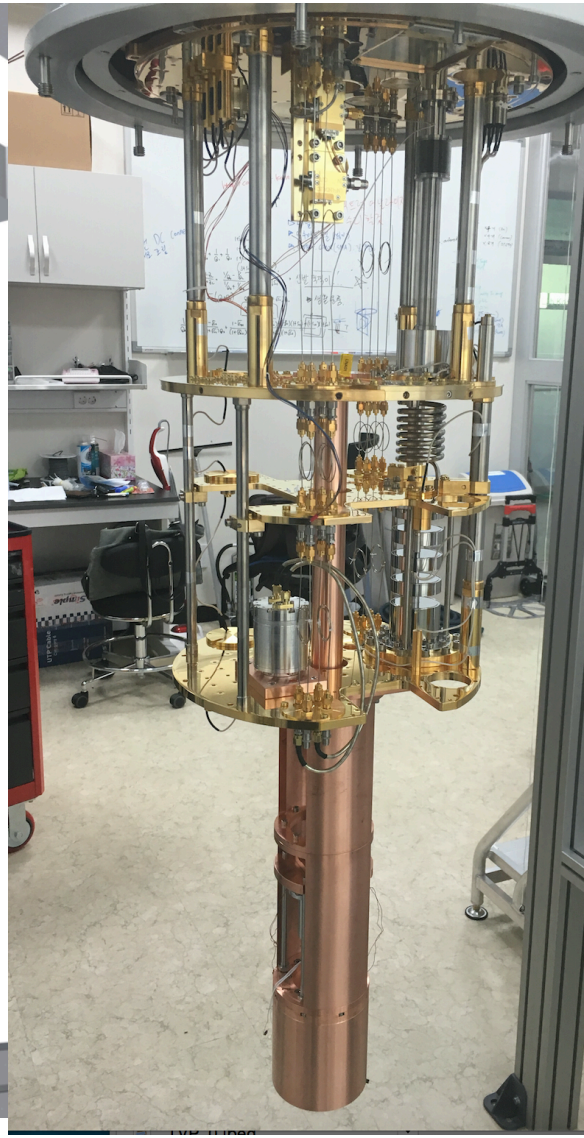
CULTASK 2017 w/ Four DRs

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



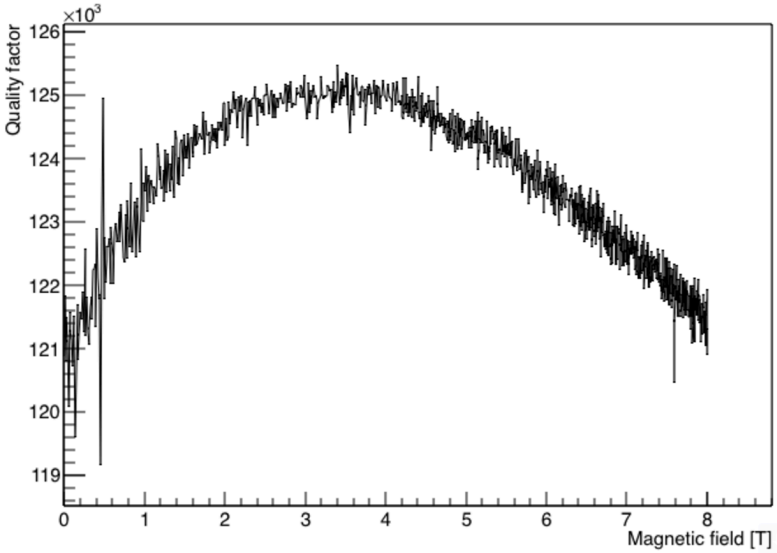


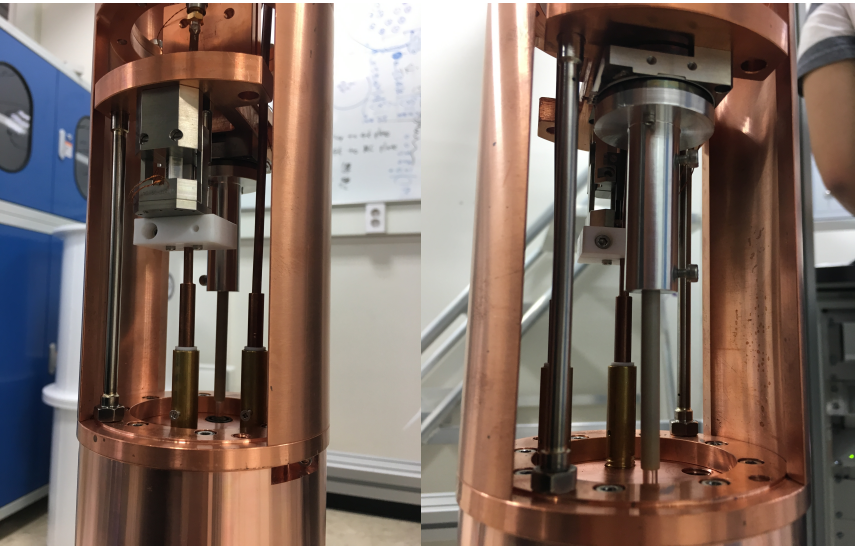


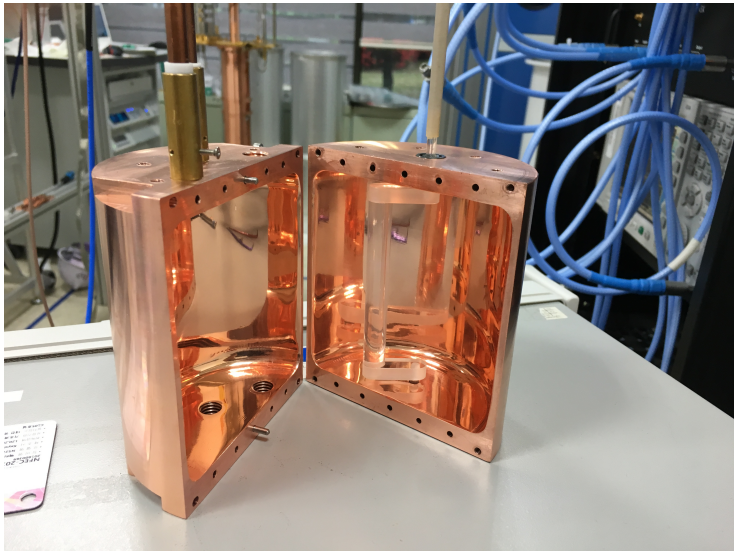
CULTASK 2017 w/ Four DRs

Cavity: OFHC Cu split type
Unloaded Q-factor of ~120,000 w/ Sapphire rod
Pure (6N) Cu and Al (annealed) will be fabricated

FTS: Attocube piezoelectric actuators
Thermal link to 1K plate
→ Sapphire rod to cavity by cryo bearing
Rotator resolution of 1/1000 deg → 2.5 ~ 5 kHz step







CULTASK 2017 w/ Four DRs

Cavity Delivered!

BF6

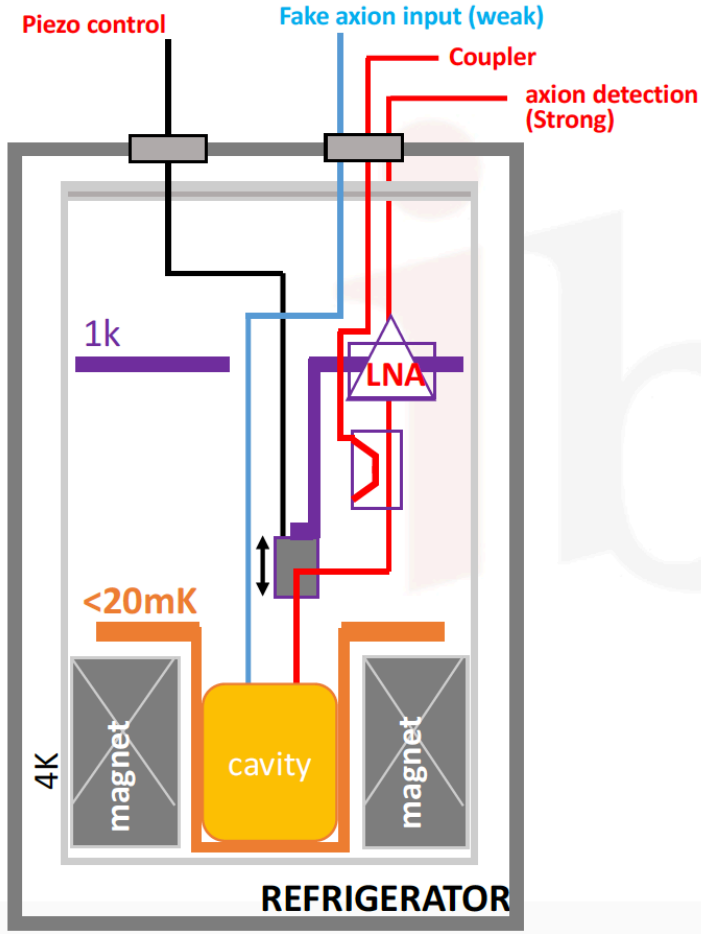
- Two cavities [conventional and split] (ID=134 mm, H=246 mm) have been delivered on May 26

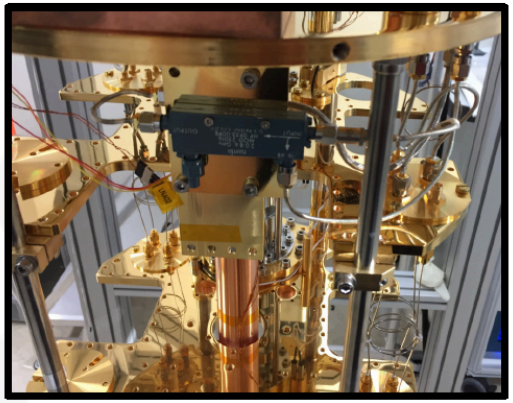
June 28 2017, MinAxion and CAPP8TB Joint Meeting 2 Soohyung Lee (IBS/CAPP) *on behalf of CAPP8TB team*

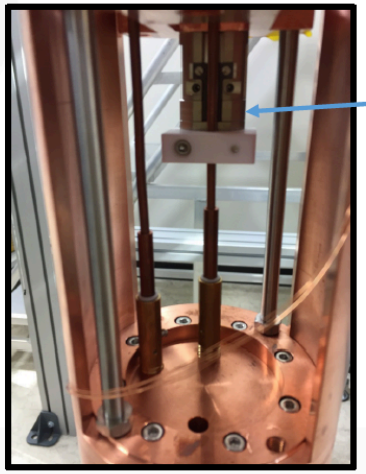
CULTASK 2017 w/ Four DRs

Inside Cyrostat

Institute for Basic Science — CAPP/ Center for Axion and Precision Physics Research



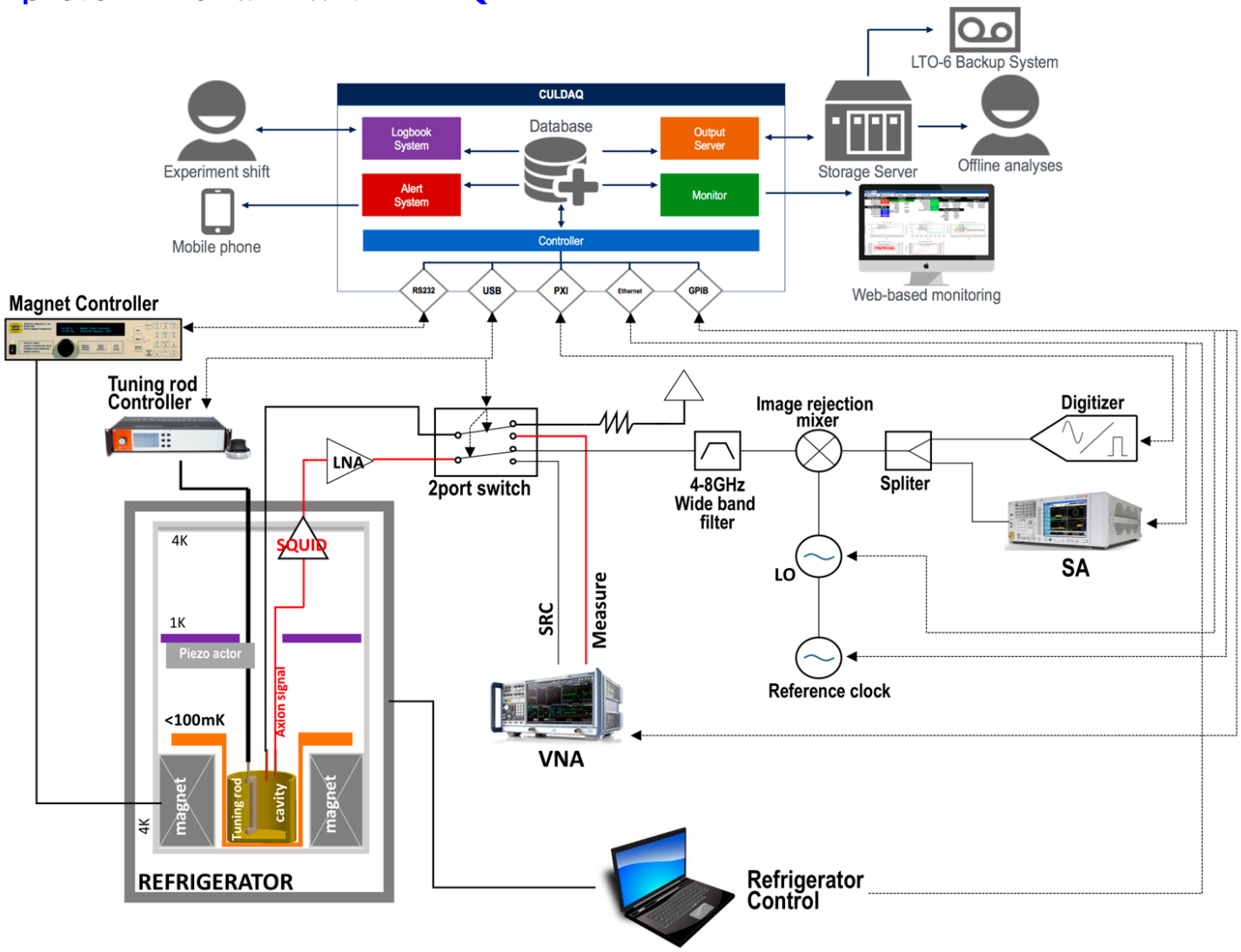




Linear piezo (control antenna

CULTASK 2017 w/ Four DRs

Complete RF chain with DAQ



Refrigerators & SC Magnets

Manufacturer	Model	Installation	Usage	Location
BlueFors	LD400	Installed 2016.02	RF and SC cavity test	RF room
BlueFors	LD400	Installed 2016.02	Mini Axion: DAQ and RF chain	RF room
Janis	HE3	Installed .2017.03	Magnet tests	LVP 4
BlueFors	LD400	2017.02	Axion Exp JPA test DAQ	LVP 6
BlueFors	LD400	2017.02	Axion Exp Muti-cavity	LVP 7
Leiden	DRS1000	2017.08	Axion Exp HFmagnet	LVP 3

Material	Manufacturer	Field Strength	Bore Size	Installation/ Delivery
NbTi	AMI	8T	12cm	2016.02
NbTi	AMI	9T	12cm	2017.01
NbTi	AMI	8T	16cm	2017.01
HTS	SuNAM	18T	7cm	2017.08
HTS	BNL	25T	10cm	2018.12
HTS	SuNAM	26.4T	3.5cm	2017.01

CULTASK 2017 Plan

Ingredients for reasonably sensitive axion experiment

B^2: Ultra high magnetic field → 25 T 10 cm bore HTS magnet (delivery in early 2019)
18 T 7 cm bore HTS magnet (one week from today)
12 T 32 cm bore LTS magnet (sometime in 2019)

V: B^2V matters, but higher freq. means small volume →
Multi-vane cavity, photonic crystals, Bragg reflectors and so on

Q: Superconducting coating (NbTi, NbSn, YBCO….) + Vortex pinning
Superconducting film (HTS tapes)
Pure metals (6N Cu, 7N Al) + proper annealing technique to increase RRR

Ultra low temperature T_s : $Ts = T_{physical} + T_{noise}$

$T_{physical} < 50$ mK (done), T_{noise} (mostly pre-amp) : 1 K HEMT → SQUID or JPA
Pushing standard quantum limit (50~75 mK per GHz)
Quantum squeezing for higher frequencies

CULTASK 2017 Plan

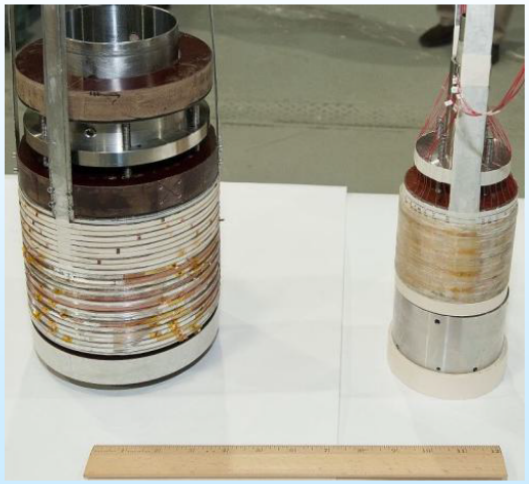
Ultra High Field Superconducting HTS Magnet(s)

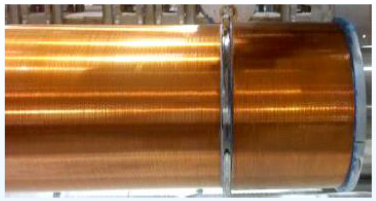
- R&D Program with BNL's Superconducting Magnet R&D Group (Dr. R. Gupta)
- Compact design: 10 cm inner bore 25T (35T even 40T w/ out-cert) with HTS tape
- SuNAM is delivering 18 T 7cm bore HTS magnet in one week
- Commercial (Oxford) 32cm bore 12 T LTS magnet will be ordered

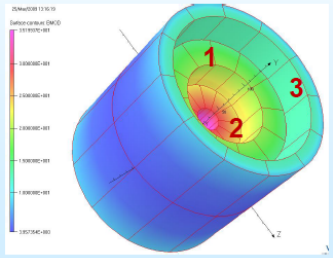
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Status of High Field MAP Solenoids

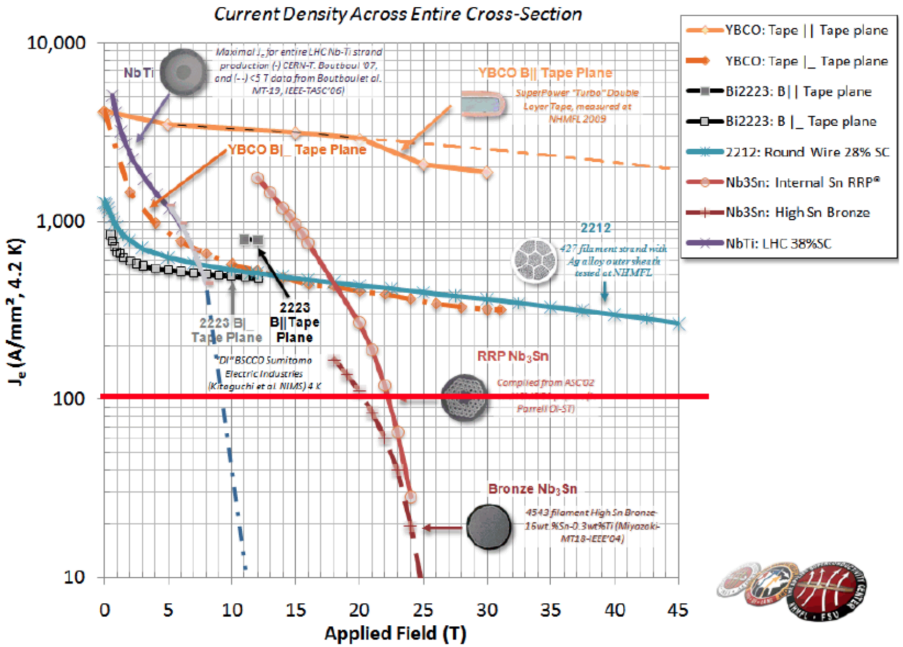
Two HTS coils together made with SuperPower HTS is expected to create 20-25 T, if successful







~30 T with NbTi outer
(40 T with Nb_3Sn or more HTS)

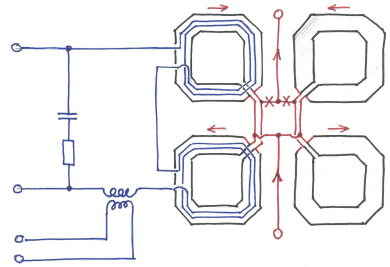


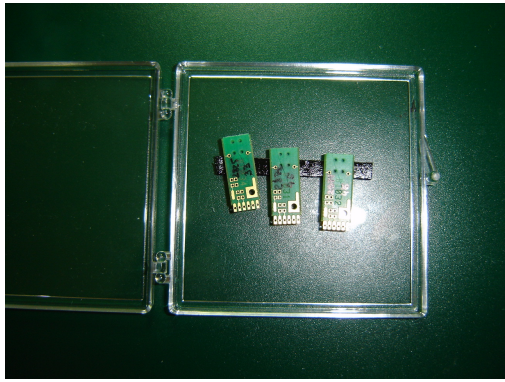
Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

CULTASK 2017 Plan

SQUID + JPA Options (Andrei Matlashov)

SQUID from KRISS (Korea)
EZ SQUID (commercial, Germany)
CE1K2 SQUID (IPHT, Germany)





JPA from JILA(Konrad Lehnert)
- We have it (shielding and flux coil being fabricated)

JPC by QCI of Yale (Commercial)

JPA at WMI (TUM)
- from U. of Tokyo (Y. Nakamura)
- Quantum squeezing now

JTWPA used by Jan Goetz (Aalto U. of Finland)
- from MIT (Lincoln Lab: W. Oliver)
- broadband (> 1 GHz) with gain more than 20 dB

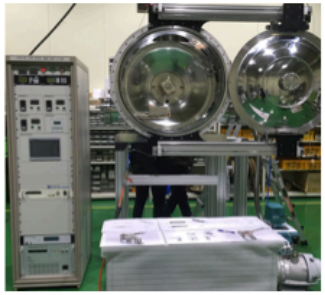
Quantum Limited Amp.
50 ~ 75 mK of noise temp per GHz

CULTASK 2017 Plan

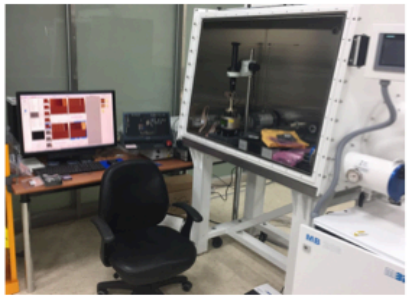
Process for manufacturing of superconducting cavity

R&D of recipe for Nb_3Sn or FeSe film on small substrate
1. Molecular beam epitaxy system (Growth of Nb_3Sn film)
2. LEED & RHEED (Characterization of Nb_3Sn film)
3. Low temperature UHV-STM (Superconductivity)

Application of growth of Nb_3Sn film on cavity
1. Molecular beam epitaxy system (Growth of Nb_3Sn film)
2. Radiative thermal heater (Superconductivity)
3. 4 probe measurement (Superconductivity)



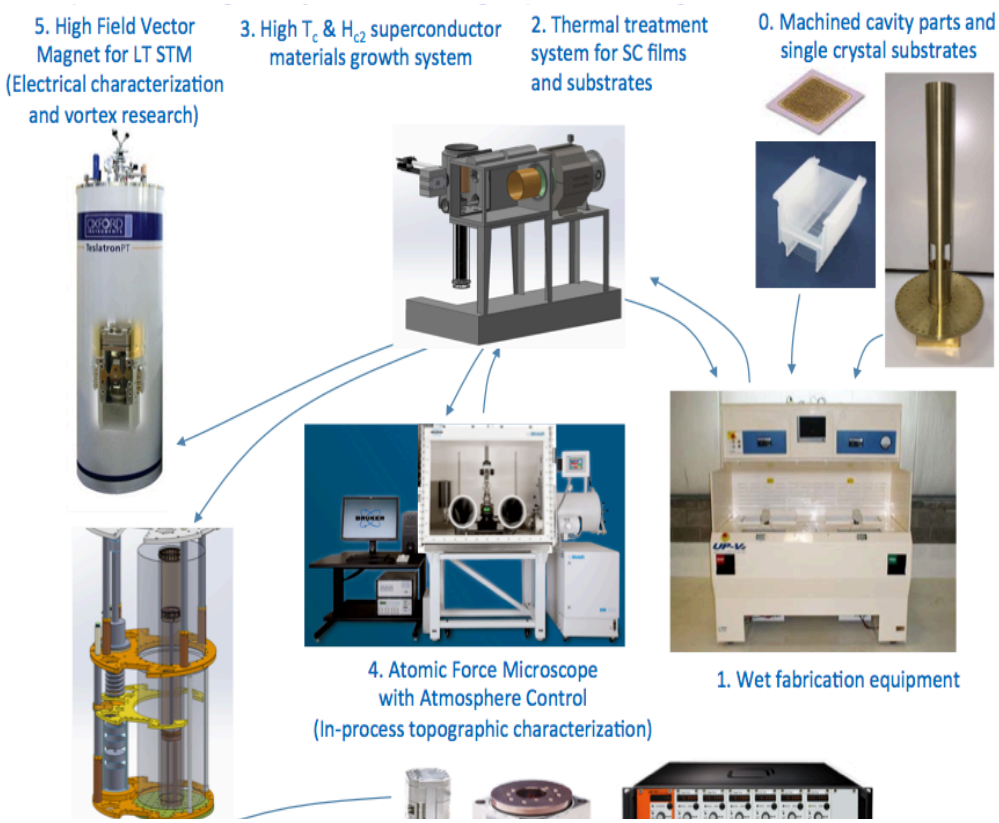
Anodized Al oxide for vortex pinning
1. Chemical etching system (Growth of AAO surface)
2. Atomic force microscope (Characterization of AAO surface)

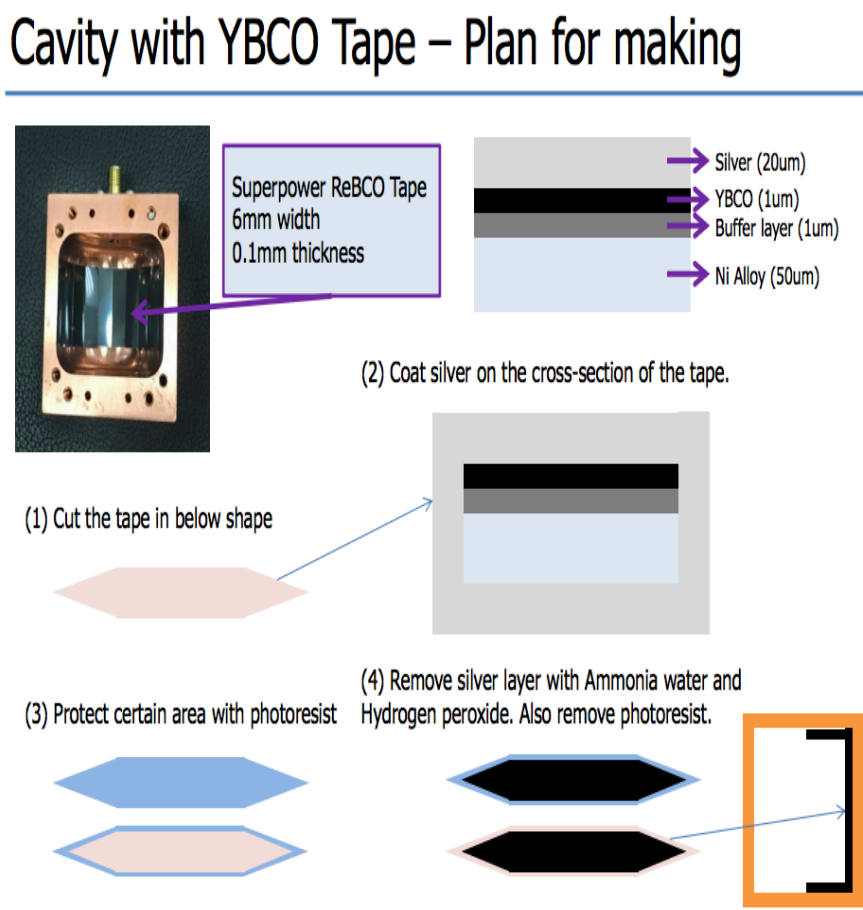


By Won-Jun Jang

CULTASK 2017 Plan

Superconducting Cavity Development





CULTASK 2017 Plan

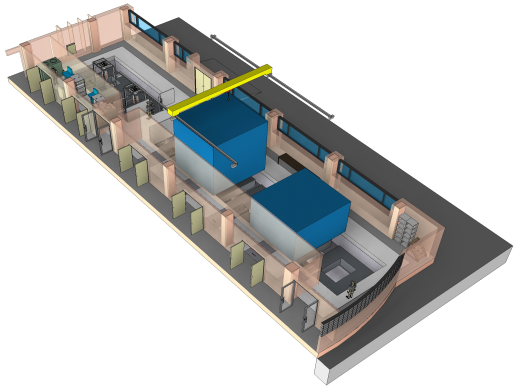
Scanning Speed :

$$\frac{d\nu}{dt} = \left[\eta \cdot \frac{4}{5} \cdot Q_L Q_a \cdot \frac{1}{SNR^2}\right] \cdot \left[g_\gamma^2 \frac{\alpha^2}{\pi^2}\right]^2 \cdot \left[\hbar^3 c^3 \frac{\rho_a}{\Lambda^4}\right]^2 \cdot \left[\omega_0 \frac{1}{\mu_0} B_0^2 V \frac{1}{k_B T_S}\right]^2 \cdot \left[\frac{\beta}{1+\beta} C_{nlm}\right]^2$$

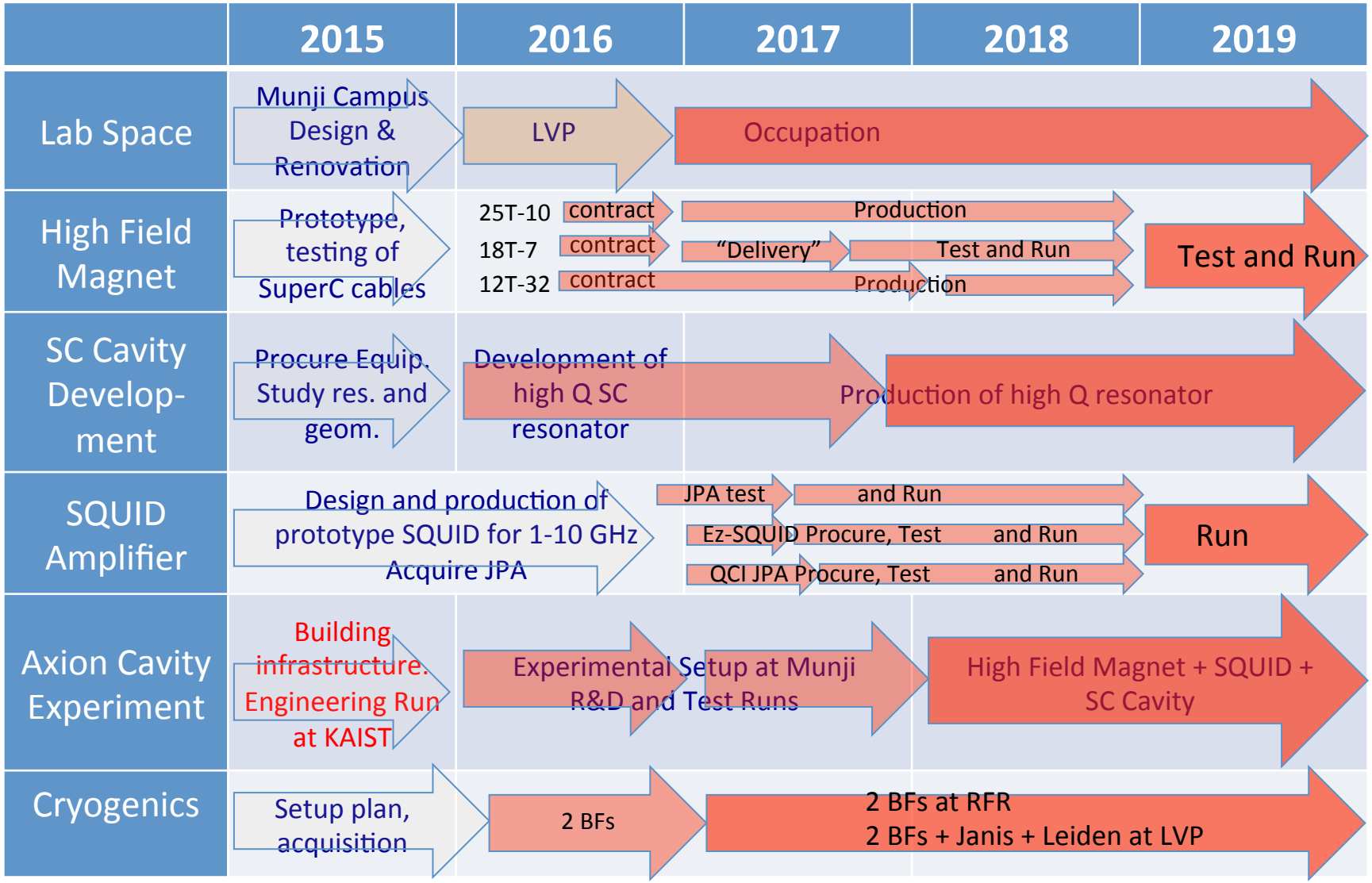
		KSVZ (MHz/yr)	100 MHz (months)	g(gamma)	2017							2018
					J	J	A	S	O	N	D	
ADMX-HF		11.223	2.737	2.5KSVZ								
MinAxion-Now	n=0.25	0.091	21.201	5.0KSVZ								
MinAxion-Heff	n=0.9, V=0.5	0.326	5.889	5.0KSVZ								
MinAxion-Heff-LV	V=1.5, T=2.0	2.093	0.917	5.0KSVZ								
MinAxion-Heff-LV-SQ	V=1.5, T=1.0	8.372	143.333	KSVZ								
MinAxion-Heff-LV-SQ-300	V=1.5, T=0.3, B=8	93.024	12.900	KSVZ								data taking
CAPP8Tb	V=3.5, T=0.3, B=8	215.414	5.571	KSVZ								data taking
CAPP18T	V=1.0, T=0.3, B=18	7210.878	0.166	KSVZ								data taking
CAPP25T	V=1.0, T=0.3, B=25	11925.474	0.101	KSVZ								

Plans beyond 2017

Axion Lab with 7 Low Vibration Pads in KAIST Munji campus



Timeline


2015
2016
2017
2018
2019
Lab Space
Munji Campus Design & Renovation
LVP
Occupation
High Field Magnet
Prototype, testing of SuperC cables
25T-10
contract
Production
18T-7
contract
"Delivery"
Test and Run
12T-32
contract
Production
Test and Run
SC Cavity Develop-ment
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…)
  - Higher Q Factor with B Field: Factor of >10 Improvement
  - Adding SQUID or JPA
  - Larger Volume: Toroidal Cavity
  - R&D for Higher Frequencies (>10 GHz)
- CULTASK 2017 ready for a complete experiment
  - Cavity R&D and Cryo-RF testing
  - DAQ running now
  - Testing Quantum Amplifiers
- Stay Tuned: We will take physics quality data Soon!

CAPP
Center for Axion and Precision Physics Research

Thank You For Your Attention!