The Coldest Axion Experiment at CAPP/IBS/KAIST in Korea

Woohyun Chung

Center for Axion and Precision Physics Research (CAPP)/KAIST

Institute for Basic Science

CAPP
Center for Axion and Precision Physics Research

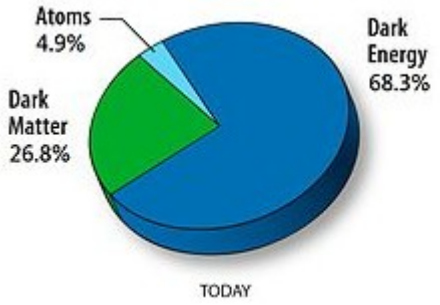
OUTLINE

- Introduction
  - Axion and Dark Matter
  - Detecting Axions
  - ADMX and CAPP
- CAPP's Axion Research
  - New Lab Space at Creation Hall
  - High Field Magnet
  - SC Cavity
  - SQUID Development
- CULTASK
  - Cavity Development
  - Cryogenic RF Integration
  - RT Electronics/DAQ
- Summary

Axion & Dark Matter

- Strong CP Problem of QCD in Standard Model
- In 1977 Peccei and Quinn postulated an elegant solution by adding a new global symmetry
- Weinberg and Wilczek pointed out that the existence of a field implied a corresponding particle
- Hypothesized new particle called “Axion” (named after a popular brand of detergent)
- What is Axion?
  - Pseudo Goldstone Boson
  - No Electric Charge
  - Small Mass ($1\mu eV<m_a<100\mu eV$)
  - Very Weakly Interacting

- Dark Matter: A kind of matter to account for gravitational effects that appear to be the result of invisible mass
  - 84.5% of total matter in the universe
  - Doesn’t interact with light
  - Not the matter we know



Axion is an excellent Dark Matter Candidate!

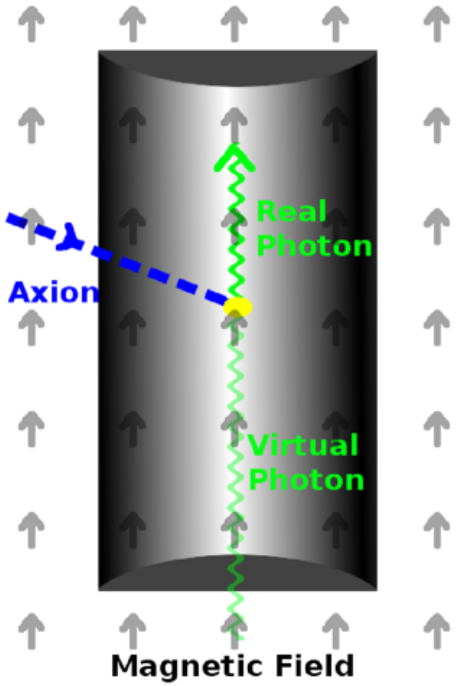
Detecting Axions

- Axion Haloscope (on earth): P. Sikivie's Scheme (Phys. Rev. Lett. 1983)
  - Axions will convert to photons in a strong magnetic field
  - Reverse Primakoff Effect
  - Enhanced (as much as Q of Cavity) signal if photon's frequency corresponds to the cavity's resonant frequency
  - Tunable, resonant cavity immersed in a strong B-field
  - Conversion Power: $P_a \propto VB_0^2Q$ (~ 10^{-22} Watt)
  - Signal power is so small: a great challenge to experimentalists
  - Sensitivity of the detector: Signal to Noise Ratio

$$\mathrm{SNR} = (P_a/P_N)\sqrt{bt} = (P_a/k_B T_S)\sqrt{t/b}.$$

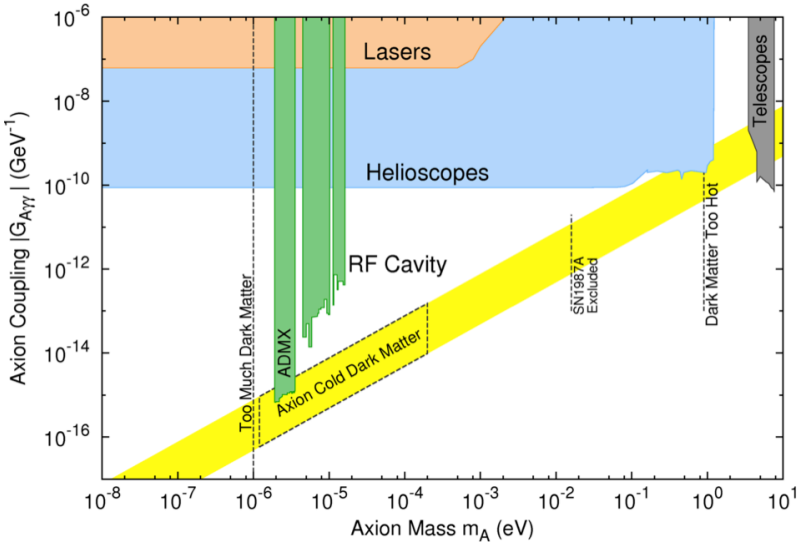
  - Mass scan rate: 10 times cooler means 100 times more data!

$$dm_a/dt \propto (B_0^2 V)^2/T_S^2$$

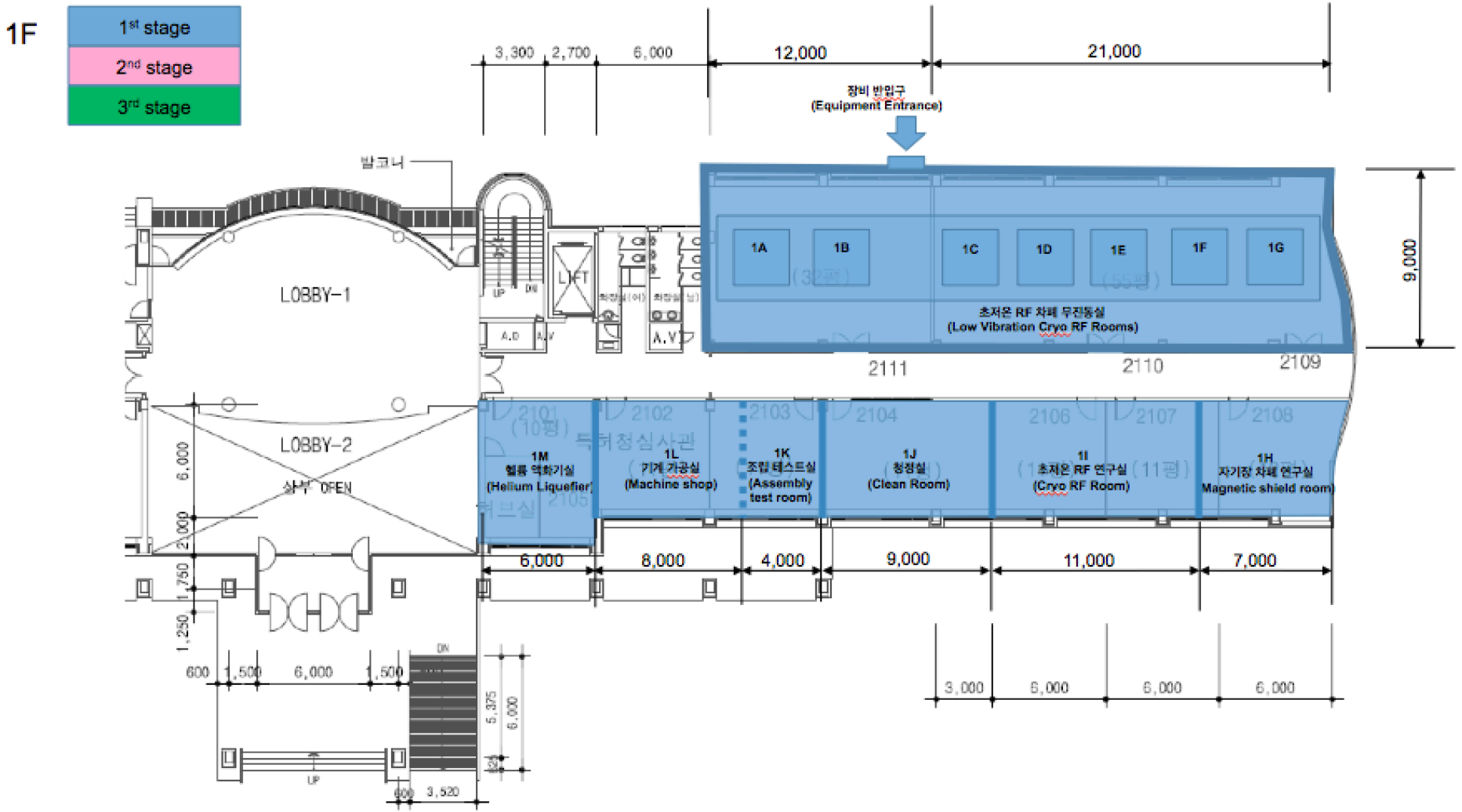


Axion Dark Matter eXperiment and CAPP

- ADMX Gen2 (US DOE and NSF program)
  - Dilution Refrigerator
  - New JPA from UC Berkeley
  - Will explore higher mass range
  - Collaboration with CAPP
  - Separate Setup w/ Stronger Magnet (>20T) (CAPP/ADMX)
- CAPP: What's there to improve?
  - Higher B^2, Q and V
  - New Superconducting Magnet (>25T)
  - Cavity with Superconducting Walls
  - Running Colder (<100mk): scan faster!
  - New SQUID from KRISS
  - R&D for higher frequencies (higher mass range)
  - Giant Toroidal Cavity



CAPP's Axion Research (Lab Space)



CAPP's Axion Research (R&D: Cryogenics)

From Dr. Yonuk Chong (KRISS)

	2014	2015	2016	2017	2018	.....
Essential Equipments	CF-DR(RF1) CF-DR(magnet) Wet-He3(large bore)					
Quantum Amplifier Research		CF-DR(RF2)				
Small-sclae Integration			CF-DR(testbed)			
Low-noise Experiments			Wet-DR1(precision) Wet-DR2(precision)			
AxionDetector main				Main DR (Axion Detector)		

Example of a 7T-190mm cryogen free AMI magnet integrated with a BF-LD system (Protective aluminum magnet cover shield not shown in picture)

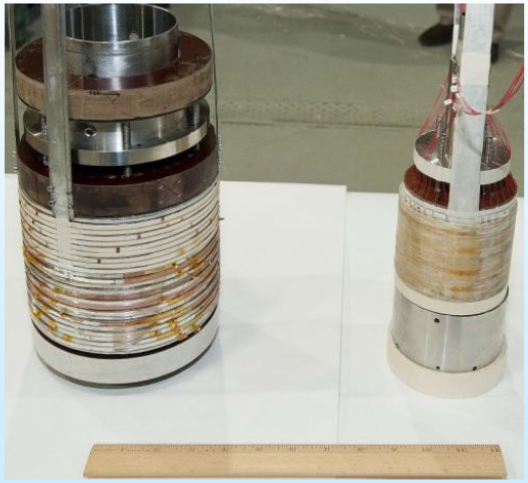
CAPP's Axion Research (R&D: Magnet)

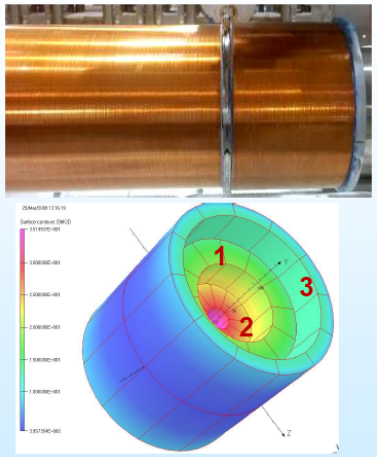
- R&D Program with BNL's Superconducting Magnet R&D Group (Dr. R. Gupta)
- 3-5 year Program
- Goal is 10 cm inner bore 25T and then 10 cm inner bore 35T (even 40T)
  (Current Axion experiments are using <10T)
- Based on HTS(High Temperature Superconductor) cable (SuNAM, Korean Company)

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

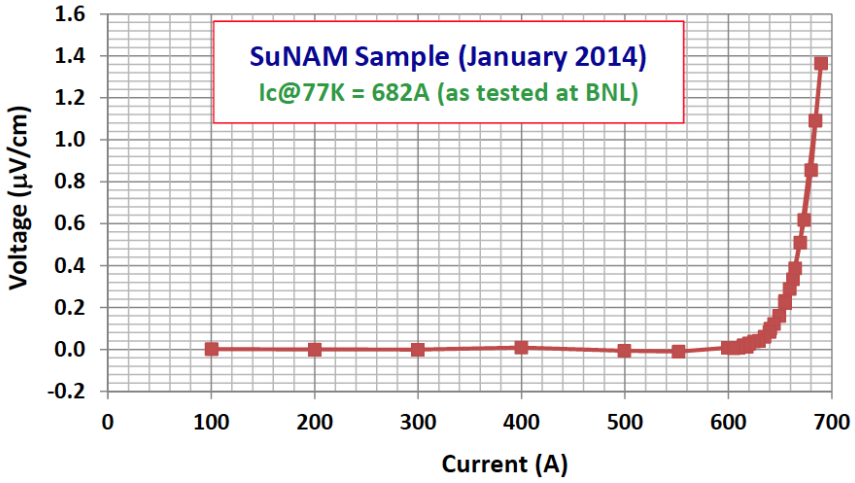
Status of High Field MAP Solenoids

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)



CAPP's Axion Research (R&D: Cavity)

- Started an R&D Program to achieve high Q (>10^6) in high B-field
- Cavity with SC walls including special top/bottom plates
  (by Prof. Jhinhwan Lee of KAIST/IBS)
  - Two to Three year plan
  - Acquiring equipment to develop SC cavities
- Multiple Cavities in-phase
  - Dr. Sungwoo Youn of IBS (Young Scientist Program) will develop with CAPP
  - 5 year Program
- Giant Toroidal Cavity
  - 10 year Program
  - Large Volume for Low Frequencies
  - Opportunity for large collaboration

CAPP's Axion Research (R&D: Primary Amplifier)

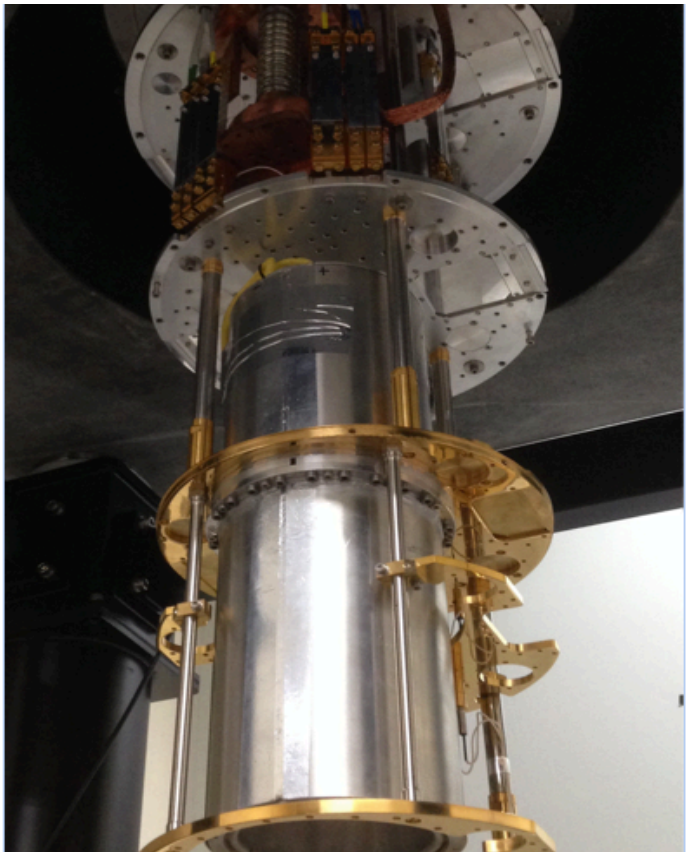
- SQUID Amplifier at KRISS (Dr. Yong-Ho Lee's Group)
  - Started a development program for Quantum Noise Limited SQUID Amplifiers in the 1-10 GHz range
  - Testing Prototypes begins in summer of 2015
  - Physical temperature aiming for 50 mK
  - Evaluate method for higher frequency
  - 5 year program
- Josephson Parametric Amplifier from UC Berkeley (Prof. Irfan Siddiqi)
  - ADMX has JPA
  - Top notch amplifier with broad bandwidth and tunable frequency range
  - Agreement on Collaboration with CAPP/ADMX in progress

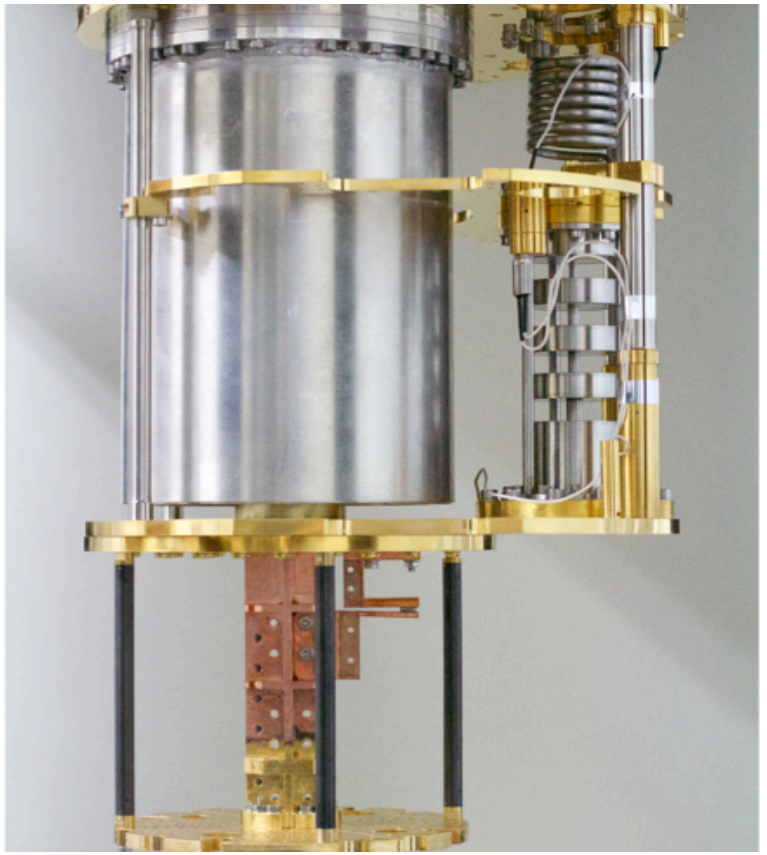
CAPP's Axion Research (Summary)

	2015	2016	2017	2018
Lab Space	Munji Campus Design & Renovation	Occupation		Occupation
Magnet	Prototype, testing of SuperC cables	25T, 10cm bore SuperC Magnet design	Work on 35T, 10 cm bore SuperC magnet	Magnet Delivery
Cavity Development	Procure Equip. Study res. and geom.	Development of high Q SC resonator	Production of high Q resonator	
Amplifier	Design and production of prototype SQUID for 1-10 GHz Acquire JPA and test		SQUID delivery from KRISS Develop higher freq. amplifier	
Axion Cavity Experiment	Building infrastructure. Engineering Run at KAIST	Experimental Setup at Munji Test Runs		High Field Magnet + SQUID + SC Cavity

CAPP Ultra Low Temp Axion Search in Korea

- DR(BlueFors LD400) + SC Magnet (9T, 6cm bore)
  from Prof. Hyoungsoon Choi of KAIST/IBS (4 months)





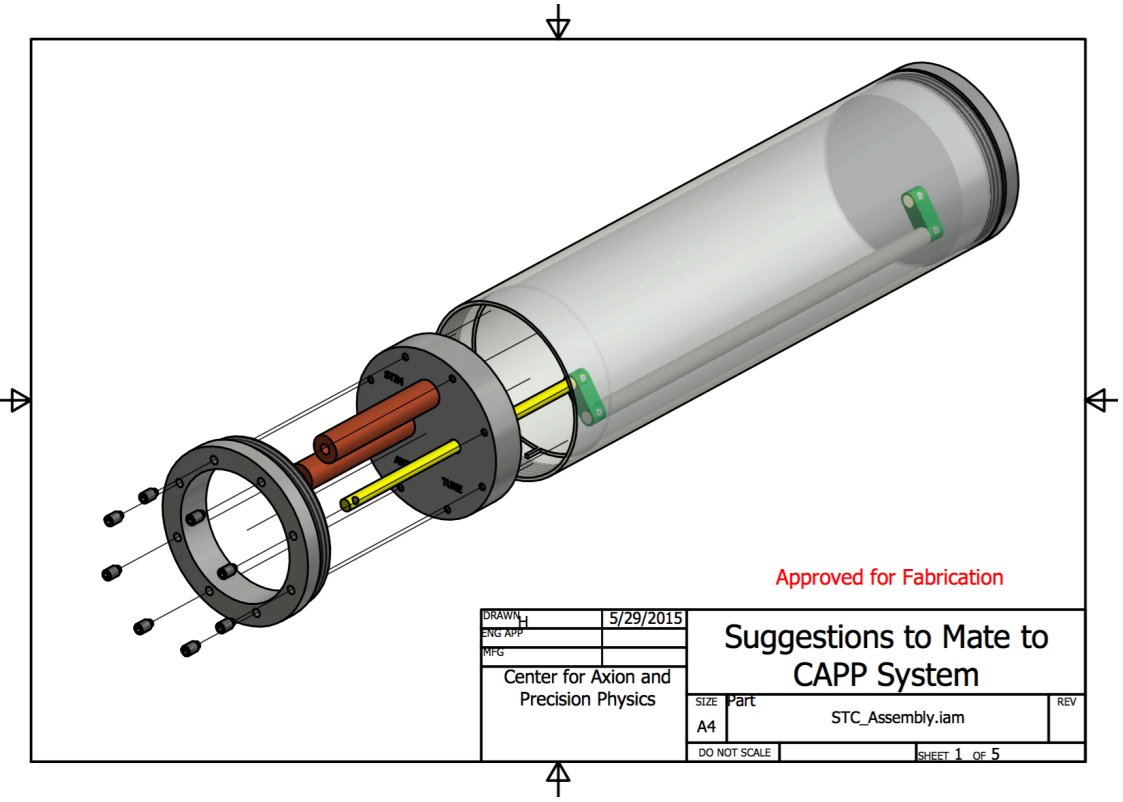
CAPP Ultra Low Temp Axion Search in Korea

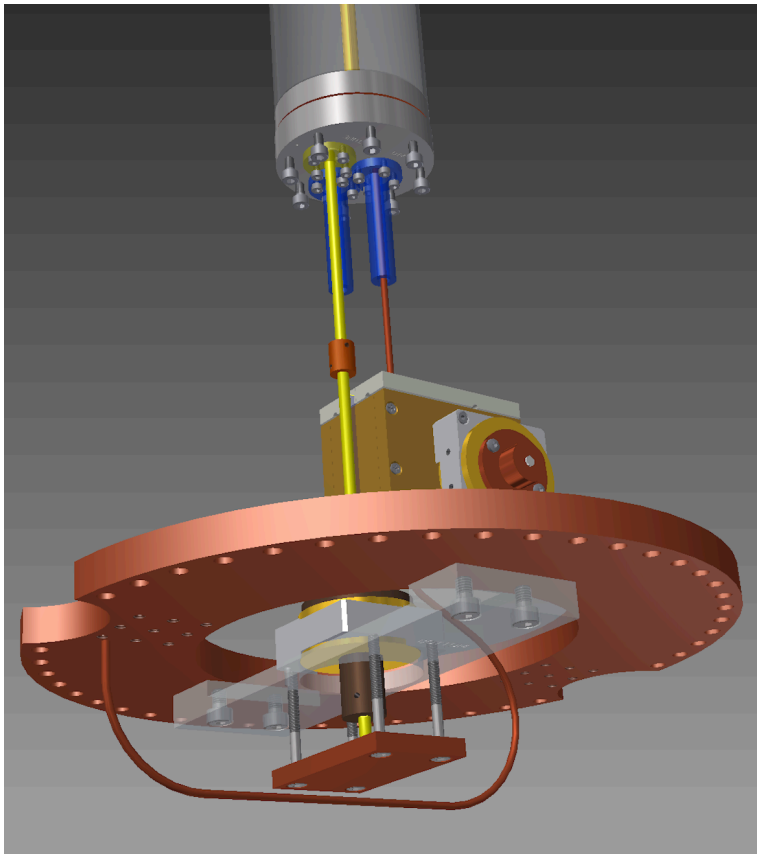
- Great opportunity to prepare ourselves before Creation Hall completion
- "ENGINEERING RUN", building Infrastructure for upcoming experiment
- The coldest axion experiment (base temp. <10 mK)
- Start with ~5 GHz (4.5 cm id) freq. range
- Designing cavities with frequency tuning systems
  - Different inner surface coating techniques (ultra pure Cu and Al >6N)
  - Tuning rod and antenna use piezoelectric actuators
- Cryogenic RF (circulators, HEMT and couplers…)
- Complete RT Electronics/DAQ will be ready
- SQUID amp and SC cavity will not be ready for this run

CULTASK (Cavity Development)

- High Q-Factor Cavity
  - Will try anything except superconductor (Mostly pure Cu and Al)
  - Sputtering pure Cu and Al from TUM (Technical U. of Munich): in July
  - Pure Cu and Al sheet roll inside SS (brazing) from STC (Seoul Teracom): in July
  - Electroplated cavity (annealed) for practice
  - More on Tuning system + simulation
- Cavity in DR
  - Support Structure: Designed to improve sub 100mK: need thermal analysis
  - Seamlessly integrate Piezo Actuator(s)
- Monitoring, Control and Measurement
  - Measuring Q correctly (and consistently) : Thanks, Fritz!
  - Has to improve Piezo + Network Analyzer Control and Monitoring
  - RRR measurement and RF Q

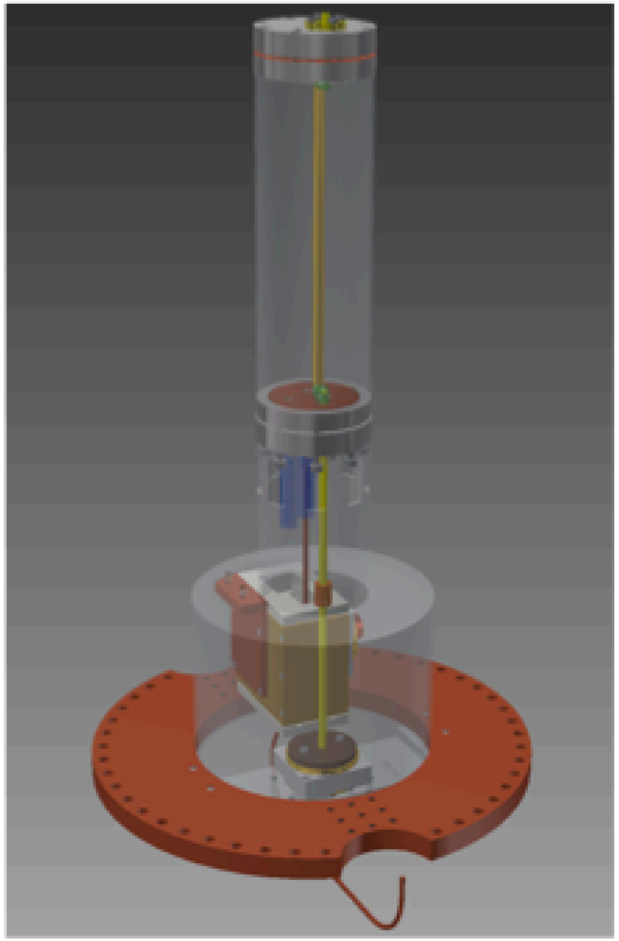
CULTASK (Cavity Development)

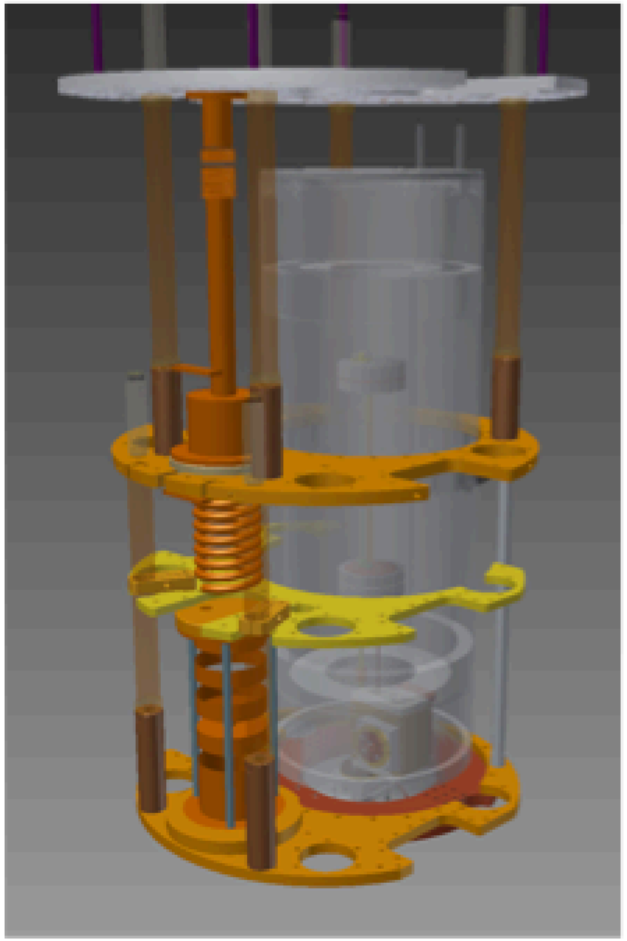




CAPP
Center for Axion and Precision Physics Research

CULTASK (Cavity Development)

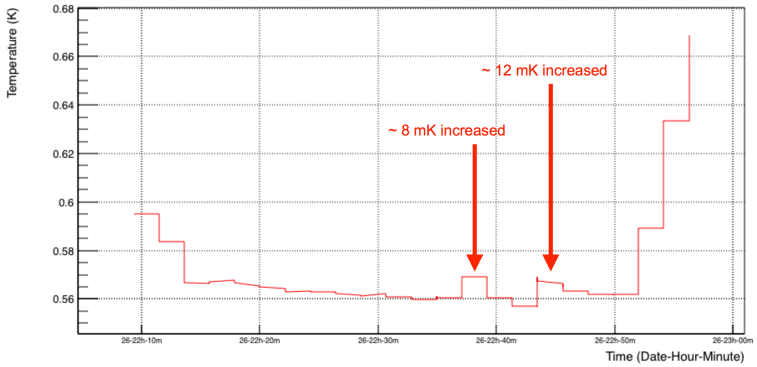


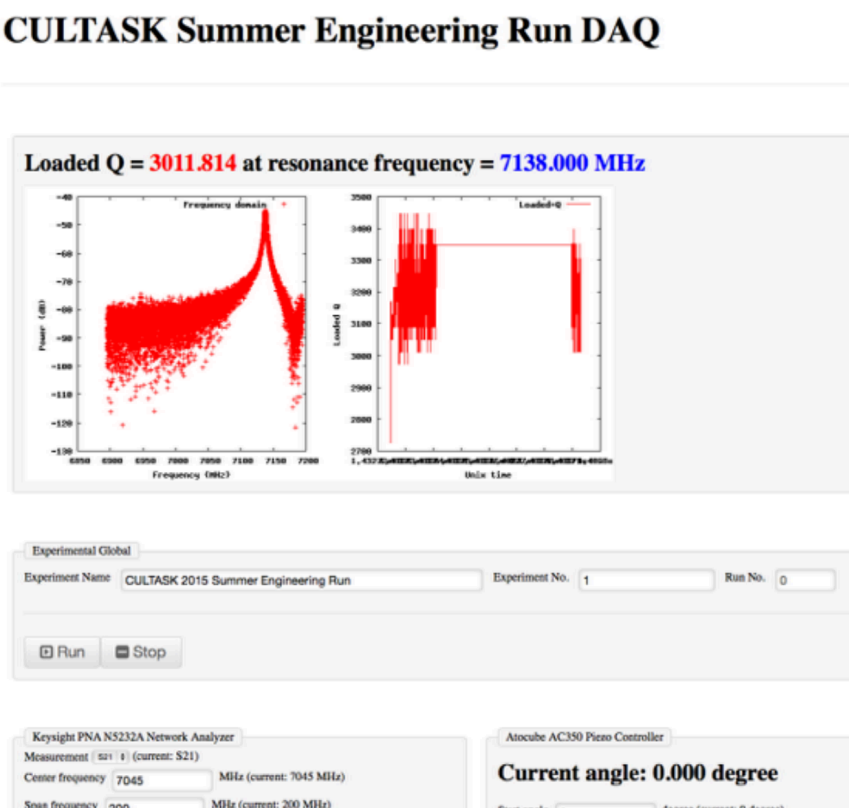


CULTASK (First Cool-Down in May)

- Cavity in DR

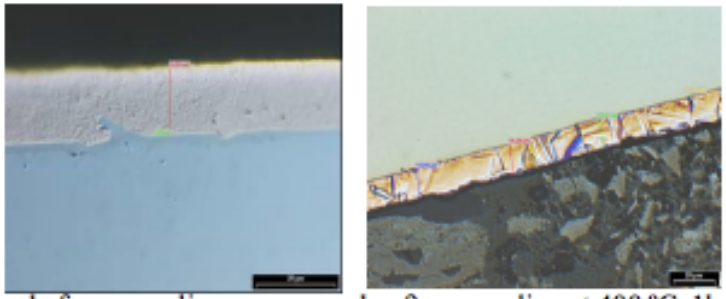
- We've just touched to ~500 mK region
  - Piezo is confirmed to work at this temperature and under 4T B field
    - But we need better experience with complete configuration
  - Piezo doesn't ruin the temperature very much
    - Few mK level found
  - Loaded Q gets better as expected
    - x2.5 enhancement
  - Confirm the relation between B and loaded Q
    - We need a decent cavity with a decent rod for more precise result





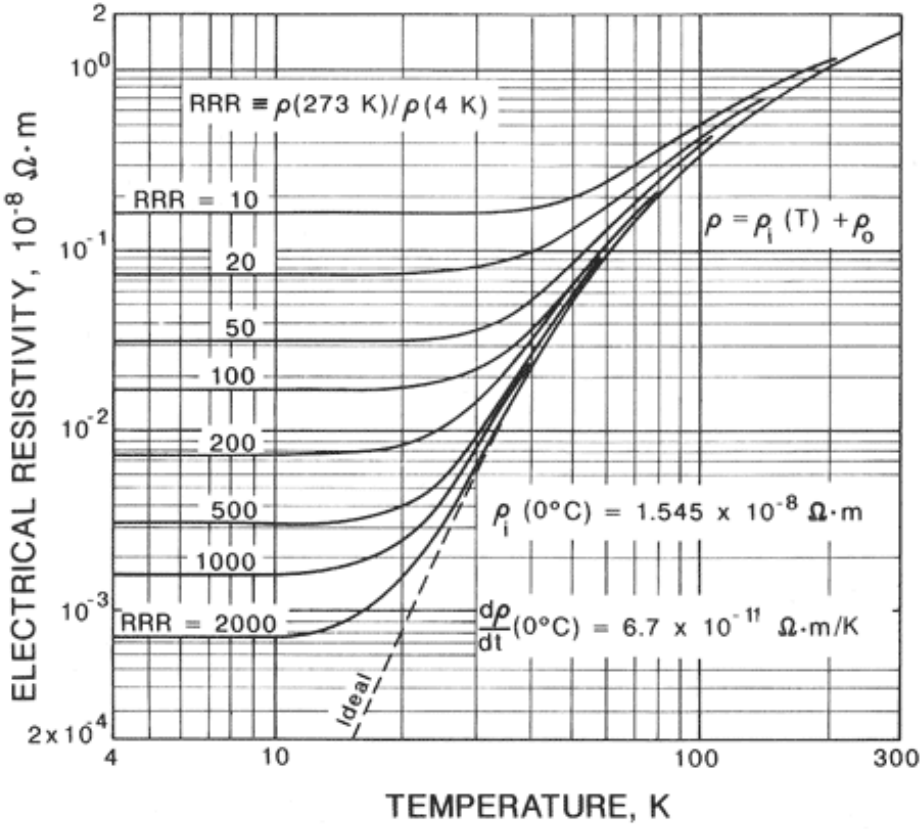
CULTASK (Cavity Development>RRR)

- Residual-Resistance Ratio (copper wire's RRR: 40-50)
- Strongly depends on Impurities and Crystallographic Defects
- Pure Sample → large RRR
- Good Candidates: Cu, Al, Ag, Au
  - 4N, 5N, 6N, 9N Cu
  - 5N, 6N Al
- Annealing Technique is essential
  - 773C for Al
  - 400C and 923C for Cu



a. before annealing b. after annealing at 400 °C, 1h

Figure 1: Microstructure of NiFl20μmCuPyro samples (as received and after heat treatment) magnification 500:1.



CULTASK (Cavity Development>RRR&Q)

$$Q_0 = Q_c = \frac{2V}{S\sqrt{\frac{2}{\omega\mu\sigma}}}$$

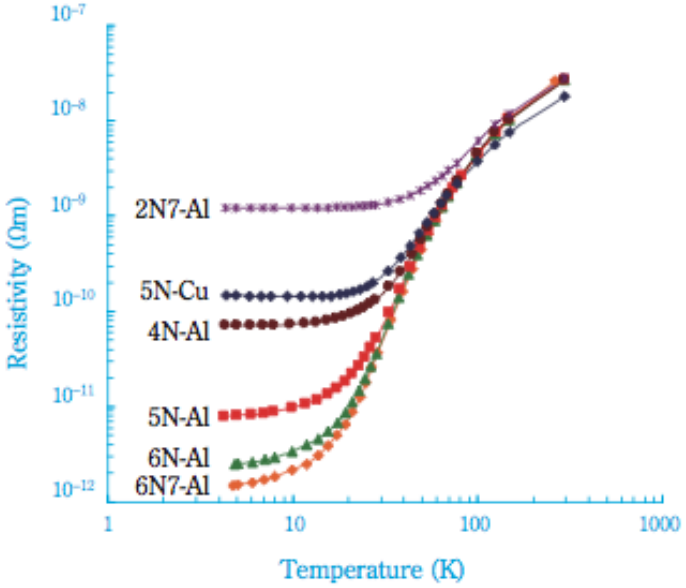


Fig. 9 Measured specific resistivity for high purity aluminium and copper using 0.5 mm thickness sheet annealed at 773 K

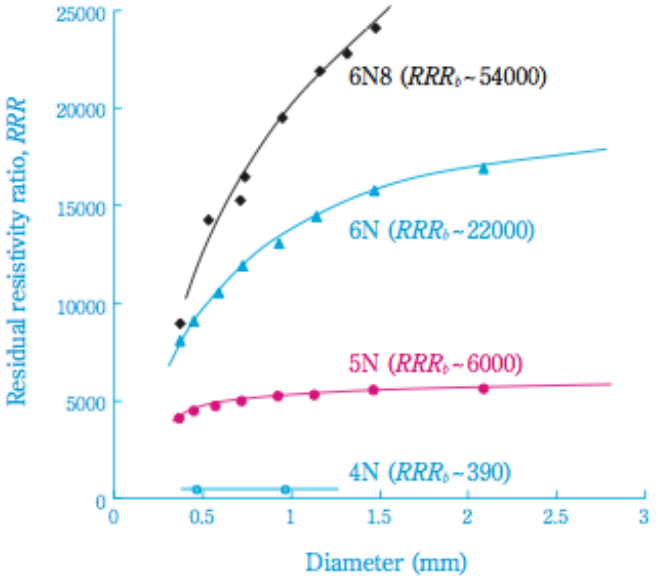


Fig. 12 Measured *RRR* values using high purity aluminium wire specimens annealed at 773 K

CULTASK (Cavity>MAGNET ATTACK!!!)

- Magnetoresistance
  - More than skin depth needed
  - Spiral motion of electrons
  - SUMITOMO(Japan) data used
  - Investigate surface smoothness effect
- Al's Tc =1.2 K, Bc =10 mT

Table 2 *RRR* of high purity aluminium and copper at 0 T and 15 T [12]

purity	diameter (mm)	transverse		longitudinal	
		0 T	15 T	0 T	15 T
5N-Al	0.5	4100	1300	3700	2500
	1.0	3800	1000	5800	3000
6N-Al	0.5	6400	2200	7600	7000
	1.0	7300	2300	11000	7800
6N8-Al	0.5	6600	2500	8100	9400
	1.0	8600	3600	11000	9000
5N-Cu	0.5	1100	36	1100	240

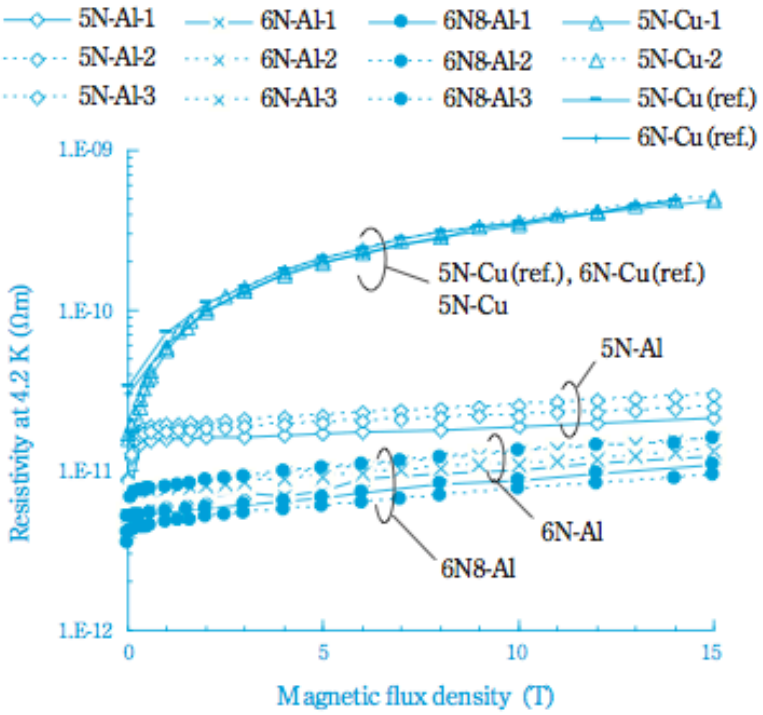
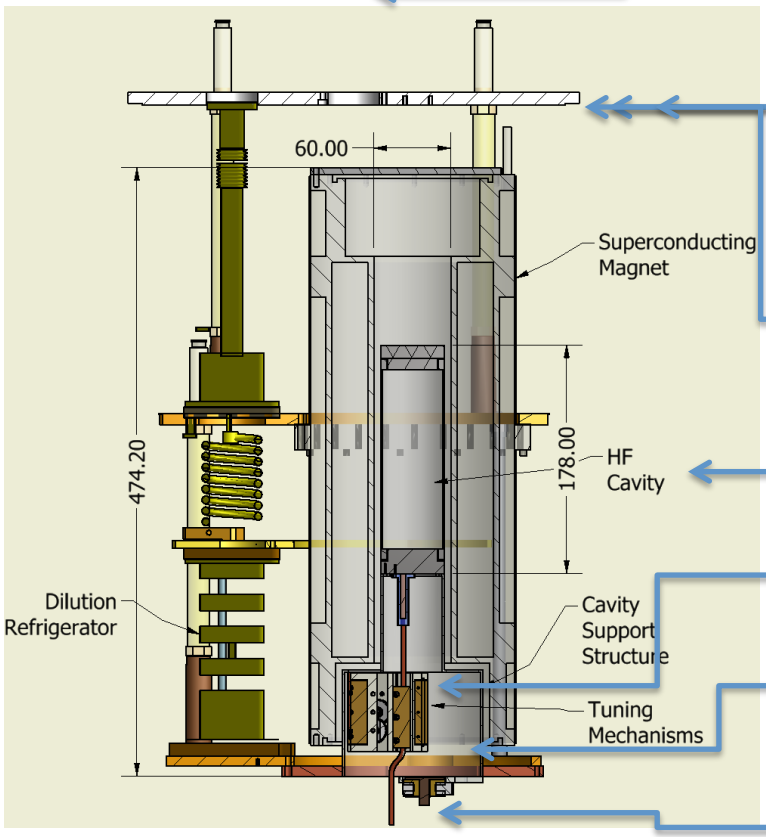


Fig. 11 Transverse magnetoresistance at 4.2 K of 0.5-mm-diameter-specimens. Dashed lines show the results obtained using the delta mode method, while solid lines show the results obtained from the use of a DC current source. The literature data are also plotted for comparison as 5N-Cu (ref.) and 6N-Cu (ref.).[12]

CULTASK (Cavity + Cryo RF)



SMA Vacuum Feedthrough

+

Cryo HEMT(1-12 GHz)

Cryo Circulator(1-10 GHz)

Directional Coupler(1-10 GHz)

+

None SC Cavity (from ITS + STC + TUM)

Piezo Actuators (2 rotary type)

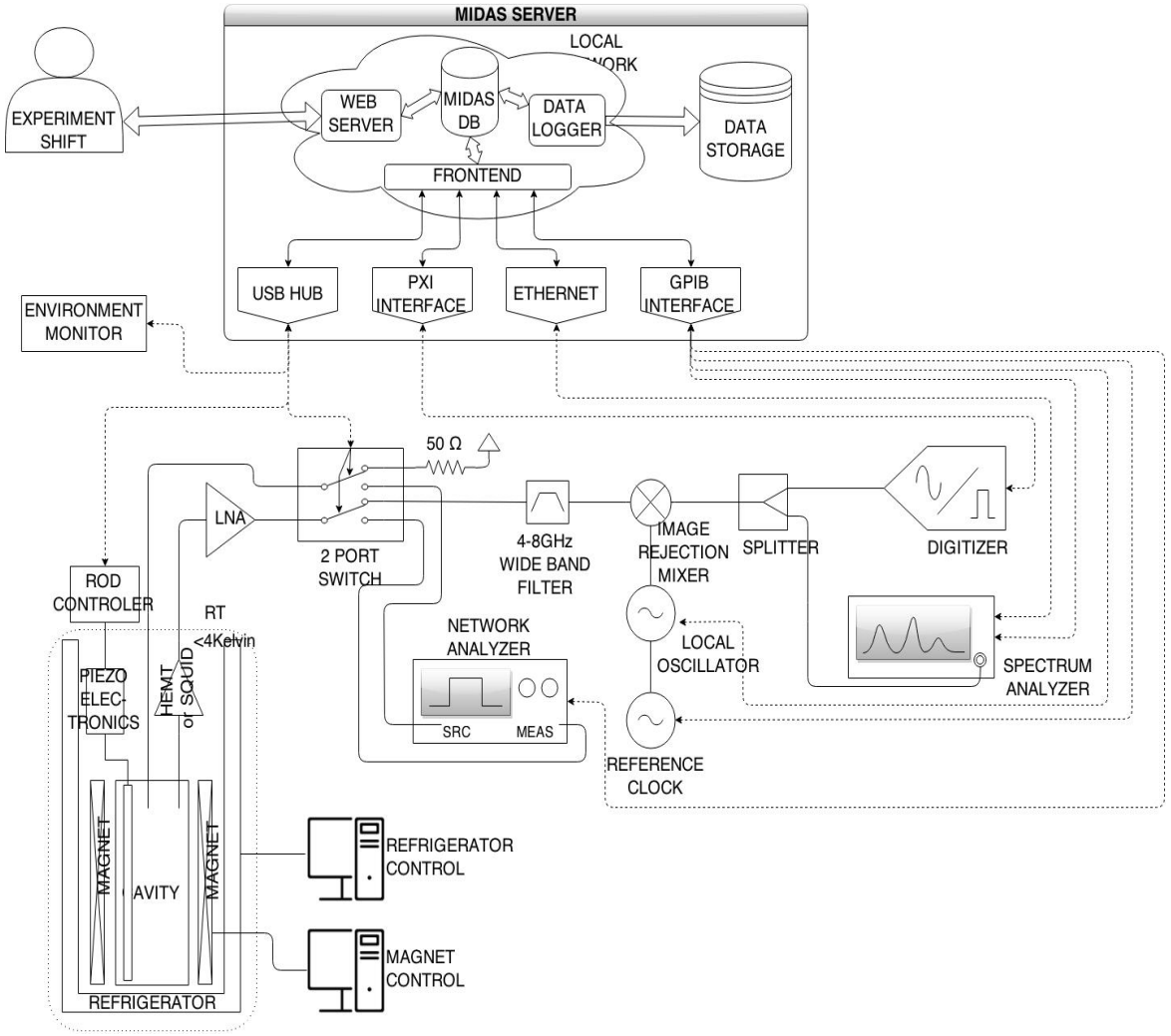
Support Structure(OF copper+machining)

+

ULT05 Cables

Dr. Yonuk Chong (KRISS) is testing Cryo RF chain now and will integrate them into our system in July.

CULTASK (RT Electronics/DAQ)

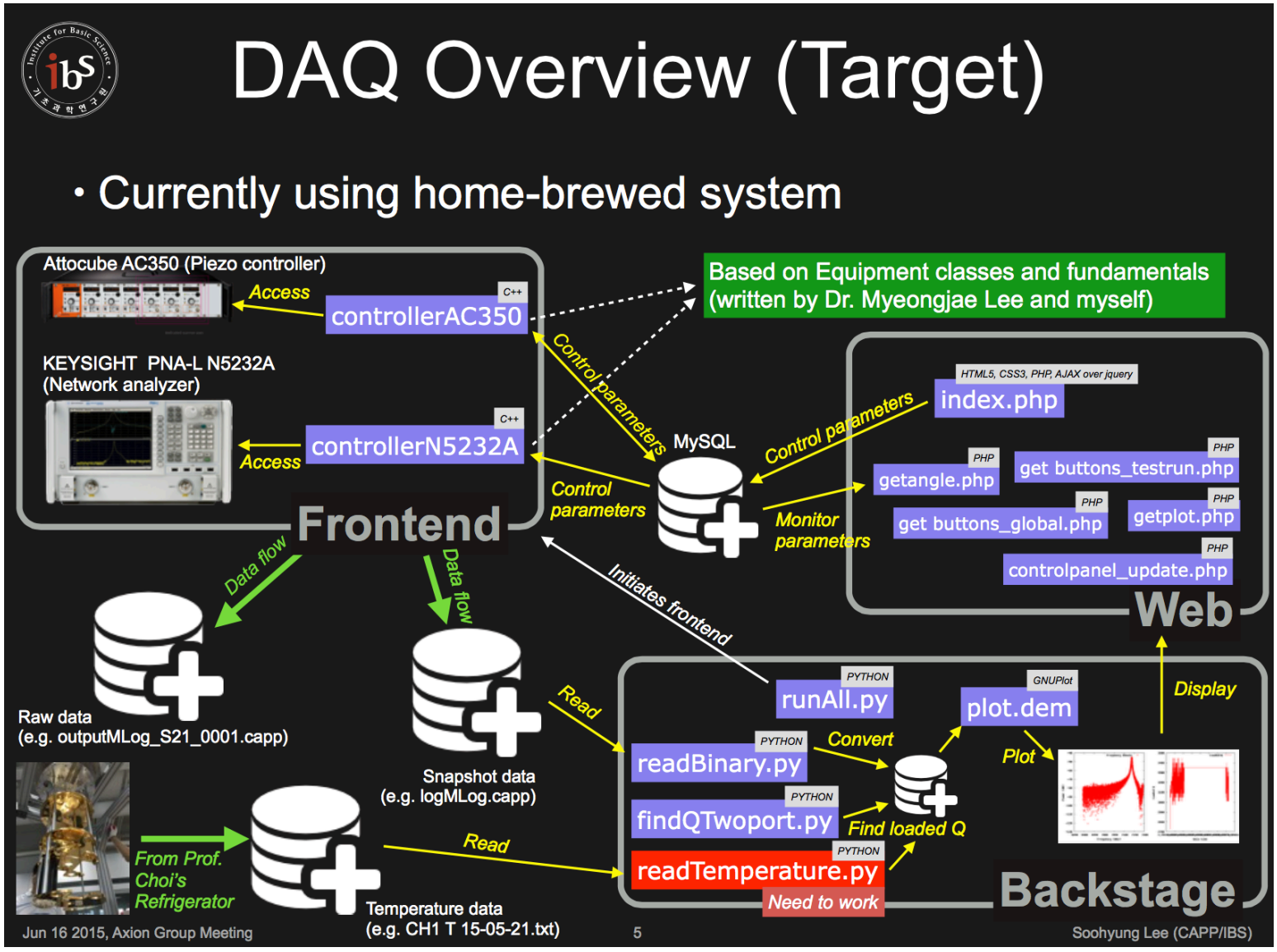


- Network Analyzer
- Spectrum Analyzer
- **Switch (USB-2SPDT-A18)**
- Digitizer (4 GHz)
- Signal Generator
- RT HEMT Amplifiers
- Mixers
- Filters
- RF Cables

+

Rack (temp controlled)

CULTASK (RT Electronics/DAQ)



CAPP
Center for Axion and Precision Physics Research

Summary

- State of the Art Axion Research at CAPP/IBS
- Major R&D Effort on improving Axion Dark Matter eXperiment
  - Higher B Field: 25T and then 35T-40T
  - Higher Q Factor with B Field: Factor of >10 Improvement
  - Larger Volume: Toroidal Cavity (>50)
- CULTASK in summer as Engineering Run to build Infrastructure
  - Cavity R&D
  - Could reach close to QCD Axion!
- Major improvement in Axion Experiment as early as in 5 years

CAPP
Center for Axion and Precision Physics Research

Thank You For Your Attention!